Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire
Canada

Regulatory Research on Thermo-Hydro-Mechanical-Chemical Processes

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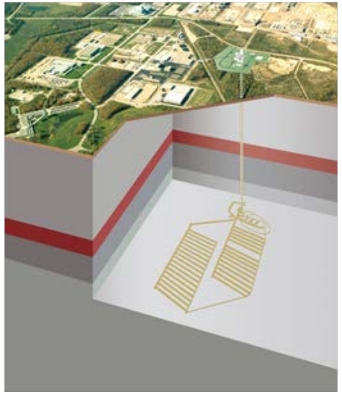
Content

- Canadian Nuclear Safety Commission (CNSC)
- Current CNSC research projects on coupled thermo-hydro-mechanical-chemical (THMC) processes
- Conceptual and mathematical model for coupled thermo-hydro-mechanical-chemical processes
- Examples of coupled THMC processes and their modelling:
  - heater experiment at Mont Terri underground laboratory
  - water and gas injection experiment at Mont Terri
  - past glaciation on a sedimentary rock basin

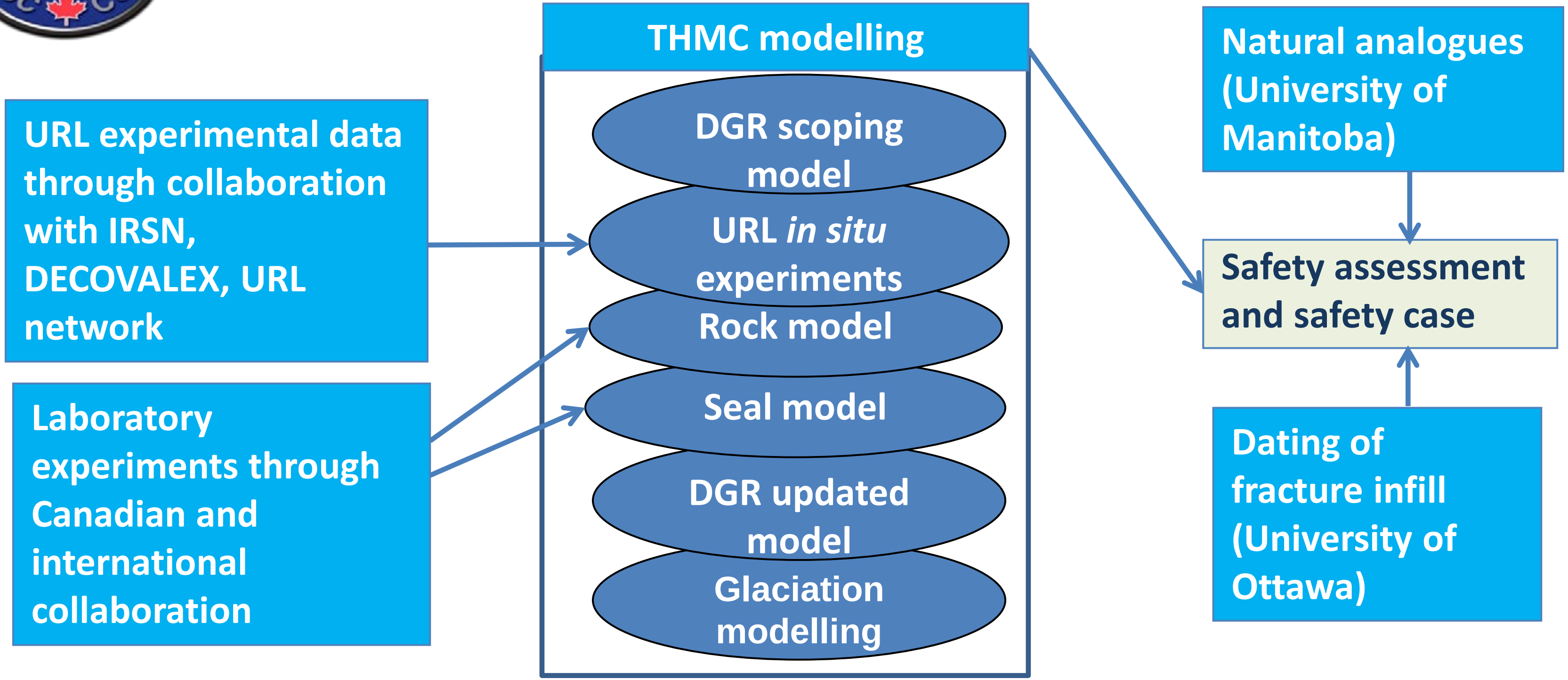
Canadian Nuclear Safety Commission (CNSC)

- The CNSC
  - regulates the use of nuclear energy and materials to protect health, safety, security and the environment
  - implements Canada's international commitments on the peaceful use of nuclear energy
  - disseminates objective scientific, technical and regulatory information to the public
- The CNSC regulates all nuclear facilities and activities in Canada throughout the whole lifecycle



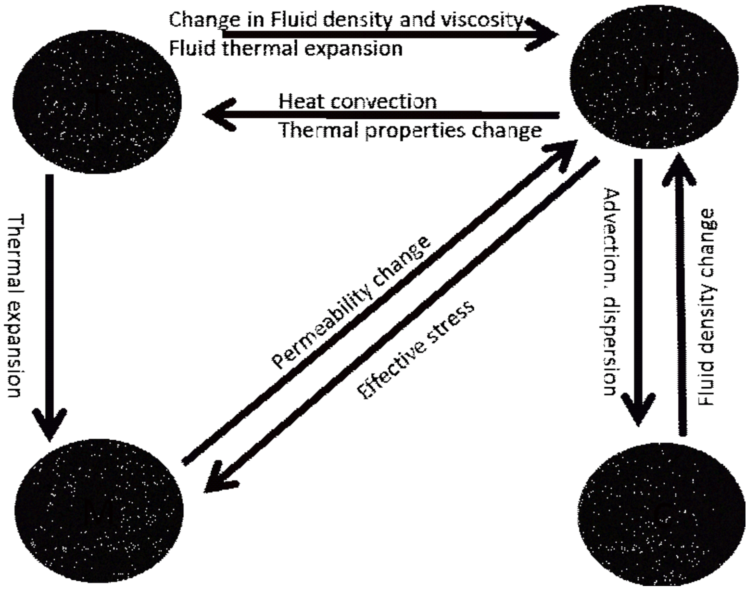
The CNSC conducts research to build independent expertise in order to make well-informed regulatory decisions

Current Research Projects



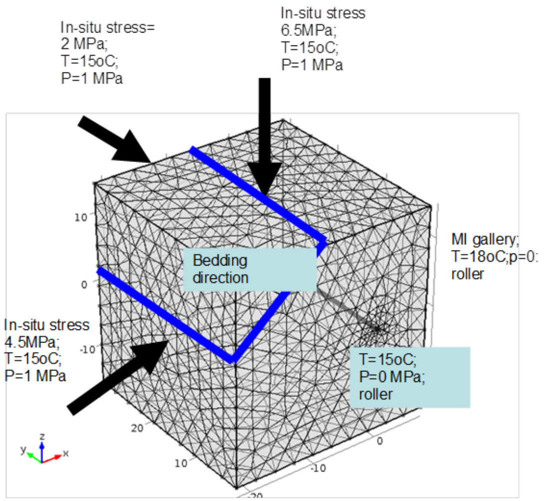
Integration of experimentation and modelling to verify the safety case

Conceptual and Mathematical Model for Coupled THMC Processes

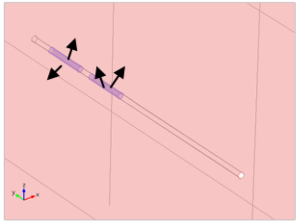


- Governing equations developed from conservation of mass, energy and momentum for a porous medium
- Adopt effective stress principle
- Adopt appropriate constitutive laws for stress-strain, mass and energy transport

Heater Experiment at Mont Terri Underground Laboratory



Entire model



Radial heat flux from heaters

Governing equations

$$\frac{\partial}{\partial x_i}\left(\kappa_{ij}\frac{\partial T}{\partial x_j}\right)+q=\rho C\frac{\partial T}{\partial t}$$

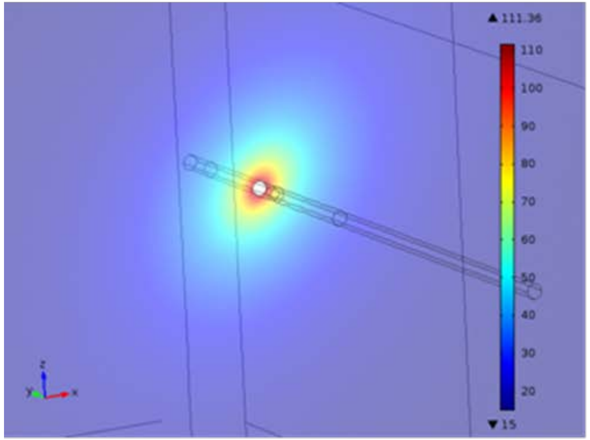
$$\frac{\partial}{\partial x_i}\left(\frac{\rho_w k_{ij}}{\mu}\left(\frac{\partial p}{\partial x_j}+\rho_w g\, j\right)\right)+\rho_w\left[\frac{-n}{K_w}+\frac{n-\alpha}{K_s}\right]\frac{\partial p}{\partial t}$$

$$+\rho_w\alpha\frac{\partial}{\partial t}\left(\frac{\partial u_k}{\partial x_k}\right)+\rho_w\left((1-\alpha)\beta-n\beta_w-(1-n)\beta_s\right)\frac{\partial T}{\partial t}=0$$

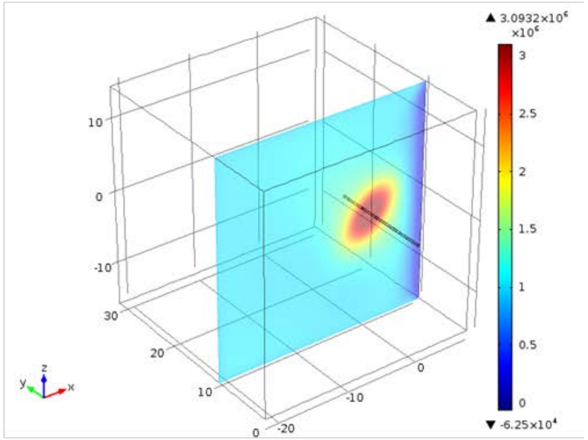
$$\frac{1}{2}C_{ijkl}\left(\frac{\partial^2 u_k}{\partial x_j\partial x_k}+\frac{\partial^2 u_l}{\partial x_i\partial x_l}\right)+\alpha\frac{\partial p}{\partial x_i}=0$$

Heater Experiment – Results (1)

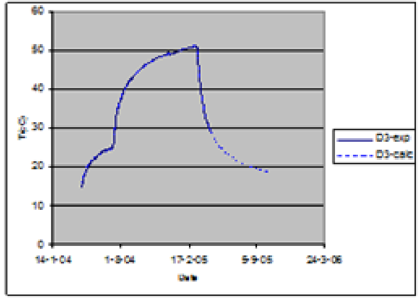
Temperature

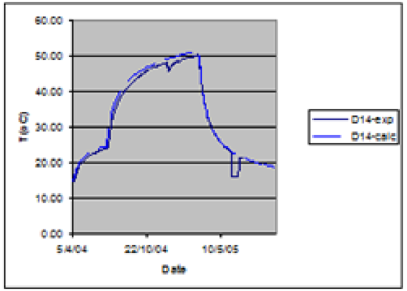


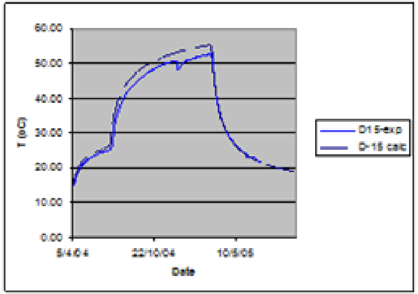
Pore pressure

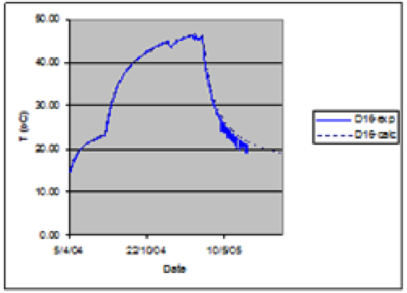


Heater Experiment – Results (2)

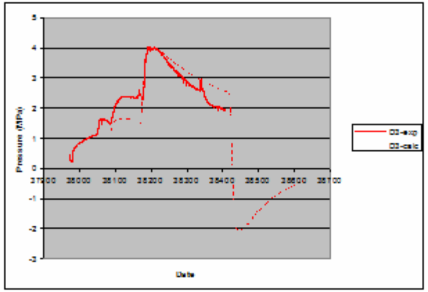


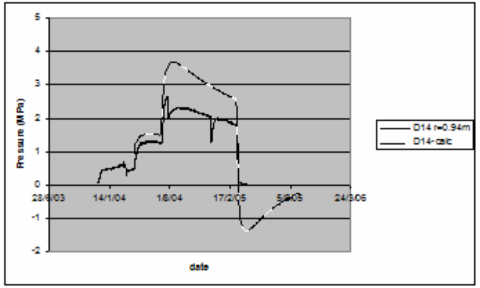


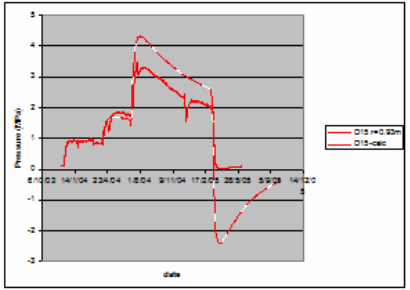


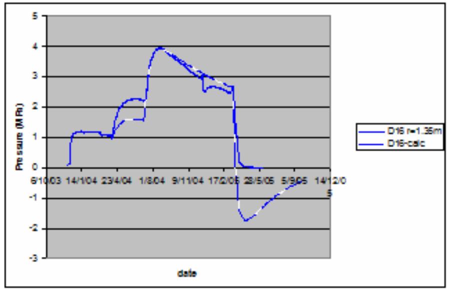


Temperature







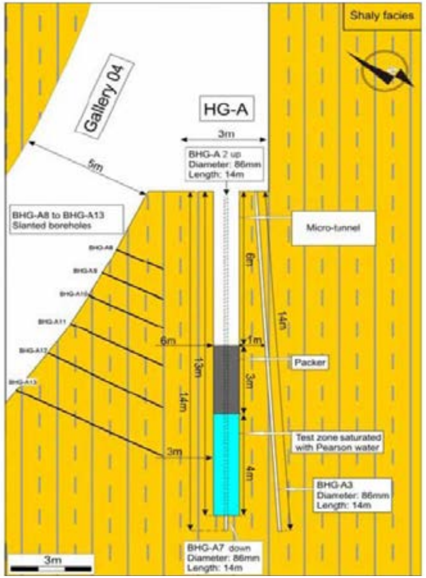


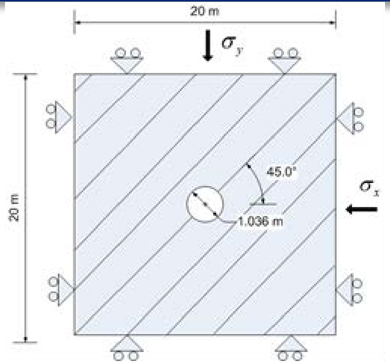
Pressure

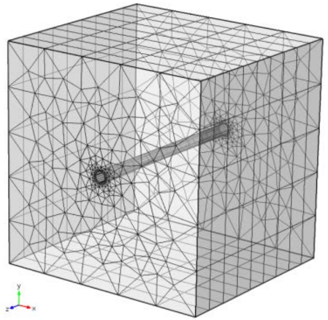
Heater Experiment: Main Findings

- The THM evolution of the rock mass around a waste repository needs to be understood in order to assess the performance of the rock as a barrier against potential radionuclide migration
- A mathematical model to evaluate that evolution was developed and validated with field data
- The field data shows the importance of inherent anisotropy in bedded sedimentary formations; the effects of anisotropy are well captured by the model

Water and Gas Injection Experiment at Mont Terri







$$\frac{\partial}{\partial x_i}\left[\rho_g k_{ij}\left(\frac{k_{rg}}{\mu_g}\left(\frac{\partial p_g}{\partial x_j}+\rho_g g_j\right)+H\frac{k_{rw}}{\mu_w}\left(\frac{\partial p_w}{\partial x_j}+\rho_w g_j\right)\right)\right]=\rho_g[n(H-1)\left(\frac{dS_w}{dp_c}\right)\frac{\partial p_c}{\partial t}+$$

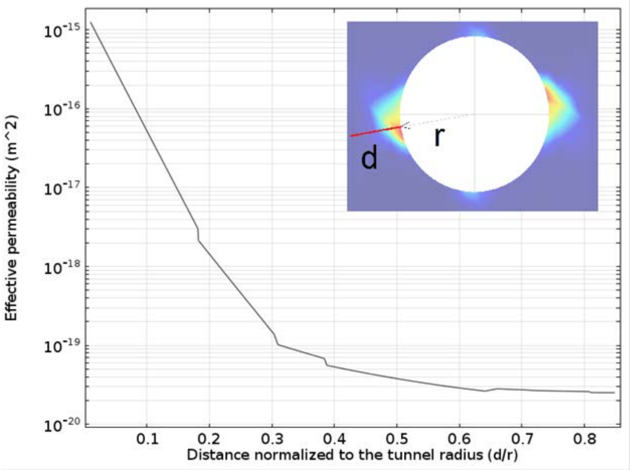
$$\frac{n(1-S_w+HS_w)}{K_g}\frac{\partial p_g}{\partial t}-(1-S_w+HS_w)\left(\frac{n+\alpha_B}{K_s}\right)\frac{\partial \bar{p}}{\partial t}+\alpha_B(1-S_w+HS_w)\frac{\partial^2 u_k}{\partial t\partial x_k}$$

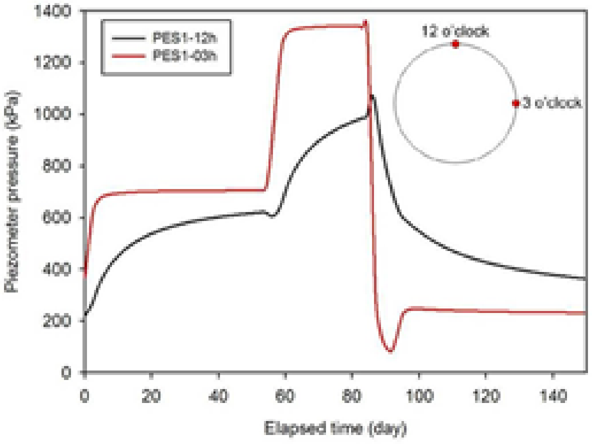
$$\frac{\partial}{\partial x_i}\left[\rho_w k_{ij}\frac{k_{rw}}{\mu_w}\left(\frac{\partial p_w}{\partial x_j}+\rho_w g_j\right)\right]=\rho_w\left[n\left(\frac{dS_w}{dp_c}\right)\frac{\partial p_c}{\partial t}+\frac{nS_w}{K_w}\frac{\partial p_w}{\partial t}-S_w\left(\frac{n+\alpha_B}{K_s}\right)\frac{\partial \bar{p}}{\partial t}+\alpha_B S_w\frac{\partial^2 u_k}{\partial t\partial x_k}\right]$$

$$\frac{1}{2}C_{ijkl}\left(\frac{\partial^2 u_k}{\partial x_j\partial x_k}+\frac{\partial^2 u_i}{\partial x_i\partial x_l}\right)+\alpha_B\frac{\partial \bar{p}}{\partial x_i}=0$$

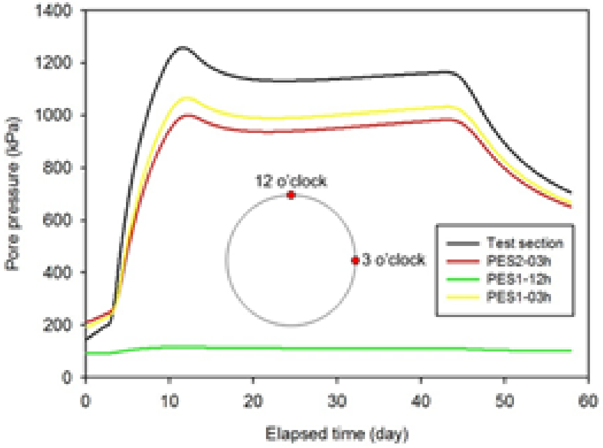
Rock is modelled as an anisotropic poro-elastoplastic, damage-susceptible material

Water and Gas Injection Modelling Results





a) Porewater pressure response to water injection



a) Gas pressure response to gas injection

Excavation damage zone

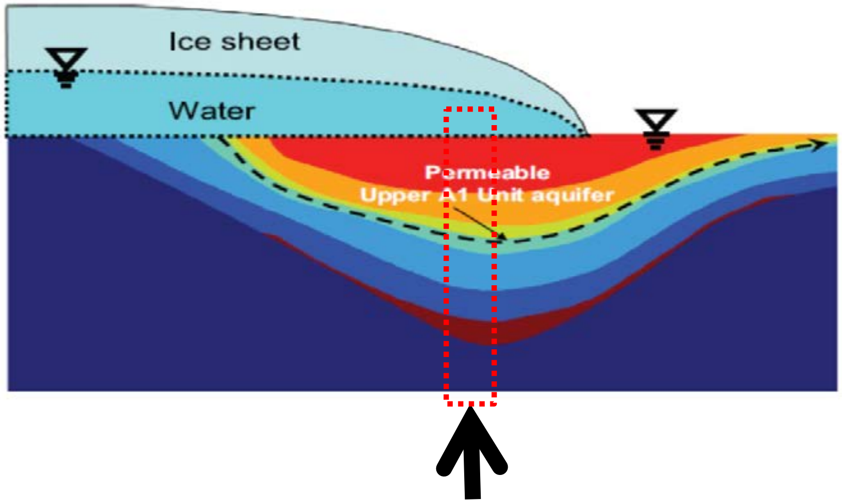
Migration of water and gas after injection

Water and Gas Injection Experiment – Main Findings

- A model for simultaneous water/gas transport in an anisotropic, poro-elastoplastic, damage-susceptible rock was developed, and was validated with a field injection experiment
- The model was able to predict the shape and extent of the excavation damage zone (EDZ)
- The model was able to predict that the EDZ constitutes a preferential pathway for water and gas transport

Glaciation on the Michigan Basin – Conceptualization

- Rock mass conceptualized as a poro-elastic medium
- Ice sheet imposes a surface load of 30–40 MPa, which leads to:
  - substantial increase in hydraulic gradients
  - redistribution of natural tracers by advection, dispersion and diffusion
- At deglaciation, underpressure results from the rapid withdrawal of ice load



Finite element model

Mathematical Model of Glaciation

➢ Governing equations

$$\nabla\left[\rho_f \frac{\kappa}{\mu}(\nabla p + \rho_f g \nabla D)\right] = n\gamma \frac{\partial C}{\partial t} + \rho_f \alpha' \frac{de_{ff}}{dt} + \rho_f S \frac{dp}{dt}$$

$$n\frac{\partial C}{\partial t} + \nabla(-nD_a \nabla C + \mathbf{u}C) = S_c$$

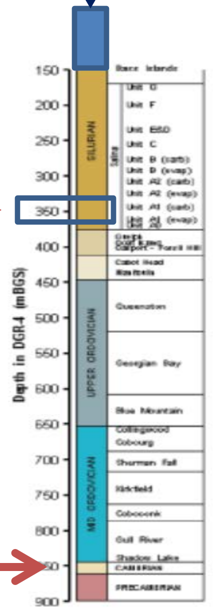
$$G\frac{\partial^2 u_i}{\partial x_j \partial y_j} + (G+\lambda)\frac{\partial^2 u_j}{\partial x_i \partial y_j} - \alpha\frac{\partial p}{\partial x_i} + F_i = 0$$

$$\rho_f = \rho_{f0} + \gamma C$$

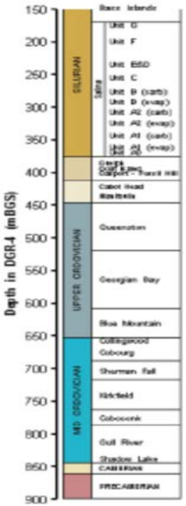
Surface loads from 9 glacial cycles in past 1 million years

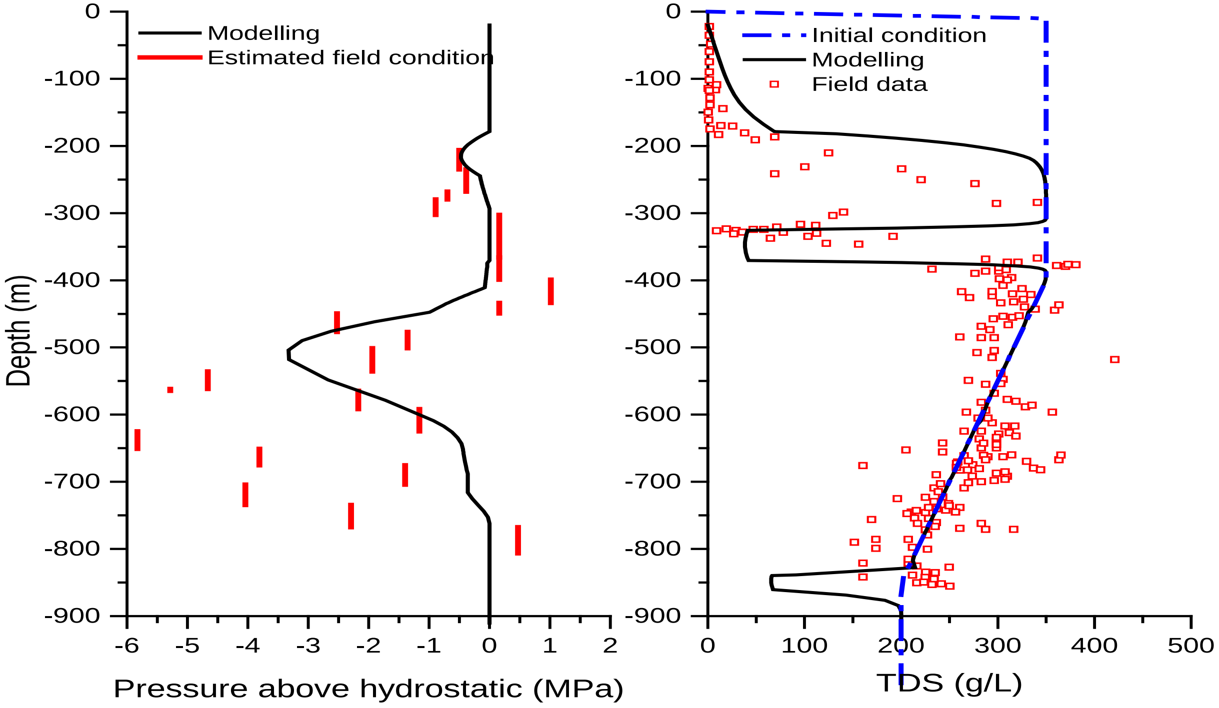
Free-draining C=0

Hydraulically open laterally to ground surface



Pressure and Total Dissolved Solids (TDS) Distribution After Nine Glacial Cycles





Main Findings From Glaciation Modelling

- Mathematical modelling and field data at a proposed low- and intermediate-level waste DGR site provide multiple lines of evidence that:
  - the deep groundwater system in the host and cap rock formations at the site is hundreds of millions of years old and virtually stagnant – transport of solutes is diffusion dominated
  - these rock formations and their groundwater have been unaffected by nine cycles of glaciation over the last million years
  - the Great Lakes are features resulting from Quaternary glaciation cycles – surface water bodies such as the Great Lakes have remained isolated from the deep groundwater

Concluding Remarks

- THMC processes in engineered and natural barriers need to be understood in order to assess their capability to contain radionuclides
- The CNSC's independent research on coupled THMC processes dates back to the early 1990s
- Research builds independent expertise and adds credibility to the CNSC, and public confidence in the CNSC's recommendations and decisions

Recent Publications

[1] Le D.A. and Nguyen T.S. 2014. Hydromechanical response of a bedded argillaceous rock formation to excavation and water injection, Canadian Geotechnical Journal, 52(1):1-17.

[2] Nasir O., Fall M., Nguyen T.S. and Evgin E. 2012. Modeling the thermo-hydro-mechanical-chemical response of sedimentary rocks of Ontario to past glaciations, Int. J. Rock Mech. and Min. Sci, 64:160-174.

[3] Nasir O., Nguyen T.S., Barnichon J.D. and Millard A. 2017 (in press). Simulation of the hydro-mechanical behaviour of bentonite seals for the containment of radioactive wastes, Canadian Geotechnical Journal.

[4] Nguyen T.S., Li Z., Barnichon J.D. and Garitte B. 2017. Modelling a heater experiment for radioactive waste disposal, Environmental Geotechnics , 4(2).

[5] Nguyen T.S. and Le D.A. 2014. Simultaneous gas and water flow in a bedded argillaceous rock, Canadian Geotechnical Journal, 52(1):18-32.

[6] Nguyen T.S. and Le D.A. 2015. Development of a constitutive model for a bedded argillaceous rock from triaxial and true triaxial tests, Canadian Geotechnical Journal, 52(8): 1072-1086.

Questions?

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