Hydro-Mechanical Response of Sedimentary Rocks of Southern Ontario to Past Glaciations

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Abstract: The last glacial cycle in the Northern Hemisphere started approximately 120,000 year ago. During that cycle, Southern Ontario was buried under a continental ice cap, with a maximum thickness of up to 3km. The ice cap retreated approximately 10,000 year ago. However, field data from deep boreholes in sedimentary rocks of Southern Ontario still bear the signatures of the past glaciation period. In this paper, the coupled hydro-mechanical (HM) response of sedimentary rocks of the Southern Ontario due to the past glacial cycle has been investigated. Particular emphasis has been placed on the evolution of pore water pressures. Modeling results, including pore-water pressure distribution have been compared with the available field data for validation. The results of this research can provide valuable information that will contribute to a better understanding of the impacts of future glaciations on the performance of a deep geological repository in sedimentary rocks.

Keywords: Past glaciation, HM coupled processes, Deep geological repositories, Sedimentary rocks.

1. Introduction

Glacial cycles are characterized by strong climatic variations with short but intensely cold periods followed by continental ice sheets, which are responsible for a significant change in the topography and groundwater regime [1]. Glaciations are considered as the main natural processes that can cause a significant impact on Deep Geological Repositories (DGR) systems [2]. Glaciations induce modifications to the thermal, mechanical, hydraulic and chemical conditions at the earth's crust, potentially causing Thermo-Hydro-Mechanical-Chemical (THMC) changes at depths where a DGR could be located. The stability of the DGR system can be influenced by glaciations in different ways such as the mechanical effect due to ice loading-unloading with significant mechanical responses [3-4], or as hydraulic effect by changing water pressure due to loading and melting of ice. Modeling the future evolution of a repository site, with emphasis on how this evolution affects repository safety functions, is a key component of repository performance and safety assessment [5]. The THMC processes are coupled, and can be analyzed by using numerical modeling.

Internationally, two main cooperative projects dealt with coupled THMC processes: first the DECOVALEX (abbreviation for the international co-operative project for the Development of Coupled models and their Validation against Experiments in nuclear waste isolation) with the Bench mark Test 3 (BMT3) to study the impact of glaciation process on far-field performance assessment; this project is applied on the crystallized rocks in the Canadian shield. The second project is BENCHPAR, sponsored by the European Commission (EC) [1,2]. In the above two projects, glaciation effects have been assessed for Scandinavian and Canadian granitic rock formations. In the present work, the impact of glaciations will be assessed for sedimentary rocks in southern Ontario.

The main objective of the present study is to build a conceptual model for the area of southern Ontario to perform coupled HM modeling which can provide valuable information for the Safety Assessment (SA) of DGR in similar rock formations.

In the first section of the paper, we will provide a description of the characteristics of the study area. In the second section, we will show the development of the relevant partial differential equations related to the HM coupled processes. In the third section, the modeling approach is explained for the site specific conditions using COMSOL Multiphysics. The fourth section presents some selected simulation results of the effect of past glaciations on the main processes.

Finally, the conclusions and recommendations are presented.

2. Characteristics of the study area

In this work, the developed model is applied on the sedimentary rocks of southern Ontario, particularly, part of the Michigan basin with Ordovician rock formations (with yellow color) at the level of a potential DGR system as shown in Figure 1. These geological formations were formed 450 millions years ago, during the Paleozoic era. The study area is located Northeast of the basin.

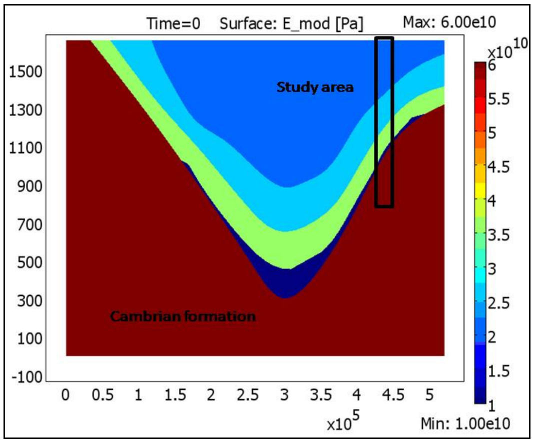

Figure 1. Cross section through Michigan basin showing rock formation and modulus of elasticity variation and location of the study area.

Hydraulic and mechanical properties, specifically, hydraulic conductivity and elastic modulus of the rock formations within the model as shown in Figures 2 and 3 are collected from the literatures [6, 7] and used as input for the mathematical model. These numbers represent the average value of the above properties.

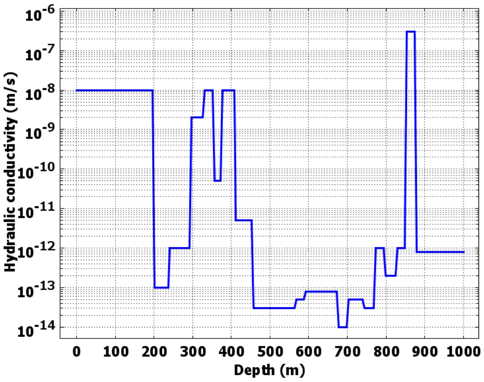

Figure 2. Variation of hydraulic conductivity with depth.

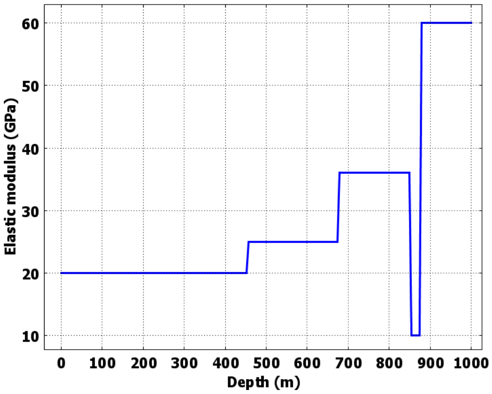

Figure 3. Variation of elastic modulus with depth used in the model.

3. Model development

3.0 Introductions

The COMSOL Multiphysics code is used to model the physical processes of the impact of past glaciations on the evolution of hydraulic system of sedimentary rocks of southern Ontario by using coupled flow and deformation in porous media using two COMSOL modules. The first module is the Earth Science module for the transient groundwater flow process and the second module is the Structural Mechanics module for the mechanical process with the plane strain model. Equations included in COMSOL have been modified to be compatible with the PDE derived in this work.

3.1 Model conceptualization

The main concept of DGR systems is the isolation of radioactive waste using multiple barriers (waste forms, container, buffer, backfill and host rock). The host rock is usually considered as the main barrier. Deep water can mix with shallow water if the hydraulic gradient and pore water pressure is significantly changed, and can potentially affect future radionuclides migration. Such perturbations are investigated here using a one dimensional poroelastic model subjected to glacial ice loading –unloading. The model is developed with the following assumptions:

1- One dimensional geological representation of the rock formation in southern Ontario.

2- Ice loading of the last two glaciation-deglaciation cycles is generated by Boulton's climate change model [8] as shown in Figure 4. That load is applied as a pressure at the top boundary of the model.

3- The effect of temperature is not included in this phase of the study.

4- The partial differential equations (PDE) is developed to include the HM processes in porous media based on the conservation of mass and balance equation.

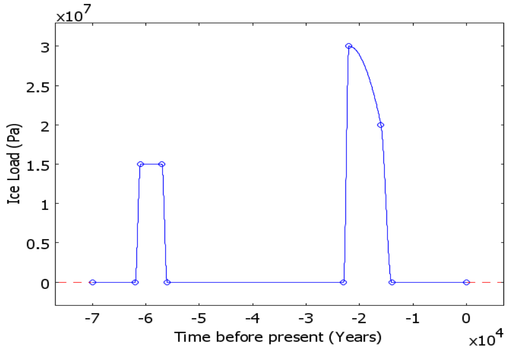

Figure 4. Ice loading (derived from Boulton's climate change model).

Ice loading shown in Figure 4, represents the variation of ice thickness for the last 70000 year at approximately (50.5° N; 96° W) near the western edge of the Canadian Shield in eastern Manitoba [8].

In order to take into account the actual ice load with respect to the study area, a steady-state ice sheet on a horizontal bed is assumed with a parabolic ice sheet that can be represented by the following equation [9]:

$$h = 3.4(L-x)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

3.2 Finite element discretization

A finite element mesh is generated by dividing the subdomains into elements using Lagrange-Quadratic triangular elements. The mesh is shown in Figure 5. The top boundary is subject to ice load as shown in Figure 4. At the top boundary, full drainage is assumed, thereby resulting in a constant zero water pressure.

Figure 5 shows all the rock formations based on information obtained from the geological data collected from the literature [10, 11], including the Ordovician formation located approximately at 600-900 m below ground surface.

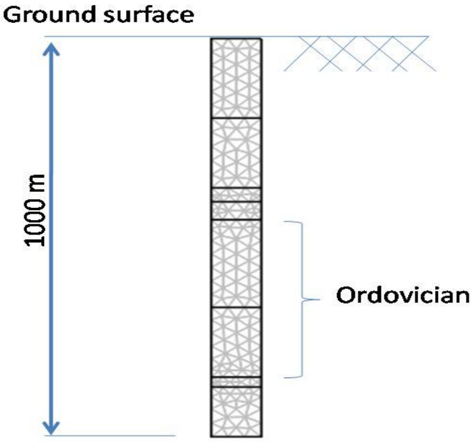

Figure 5. One dimensional model (unit in meters).

3.3 Mathematical formulations

The governing partial differential equations are derived from the consideration of conservation of mass and momentum. The following equations 2 and 3 express the conservation of mass for both fluid and solid, respectively, which can be written as [11]:

$$\nabla\cdot(\rho_f U_f)+\frac{\partial}{\partial t}(\rho_f n)+\rho_f q=0 \quad \ldots\ldots\ldots\ldots (2)$$

$$\nabla\cdot(\rho_s U_s)+\frac{\partial}{\partial t}(\rho_s(1-n))+\rho q=0 \quad \ldots\ldots\ldots\ldots (3)$$

When : ρ is density, U is fictitious velocities, t is time, n is porosity, q mass source, s is solid and f is fluid.

In the above equations, the mean velocities for fluid and solid can be defined as:

$u = \frac{U}{n}$, and $u_s = \frac{U_s}{(1-n)}$

Darcy's law can be expressed in terms of the mean velocities as:

$$(u - u_s) = -\frac{\kappa}{\eta}(\nabla p + \rho_f g \nabla D) \text{.................. (4)}$$

Where: κ is permeability, η is dynamic viscosity, p is pressure, D is the direction of gravitational acceleration (g).

Combining equation 2 and 3, and using Darcy's law we obtain [11]:

$$\nabla \cdot \left[\rho_f \frac{\kappa}{\eta}(\nabla p + \rho_f g \nabla D) \right] = n \frac{\partial \rho_f}{\partial t} + \frac{\rho_f}{1-n} \frac{\partial n}{\partial t} - \frac{\rho n}{\rho s} \frac{d\rho_S}{dt} \text{...(5)}$$

Which can be written as:

$$\nabla \cdot \left[\rho_f \frac{\kappa}{\eta}(\nabla p + \rho_f g \nabla D) \right] = (n\gamma)\frac{\partial C}{\partial t} + \rho_f \alpha' \frac{de_{ff}}{dt} + \rho_f \left(\frac{\alpha'}{K_s} - \frac{n}{K_S} + \frac{n}{K_f} \right) \frac{dp}{dt} \text{...(6)}$$
$$+ \rho_f \left(n\beta_S - \alpha'\beta + (\beta - \beta_S) - n\beta_f \right) \frac{dT}{dt}$$

Where $\alpha' = \frac{(\alpha - n)}{(1-n)}$, $\alpha = 1 - \frac{K_D}{K_S}$

Equation 6 includes the concentration (C) of dissolved solids in the pore fluid and the local average temperature (T) of the porous medium. The density of the pore fluid is assumed to vary with dissolved solid concentration according to the following equation:

$$\rho_f = \rho_{fo} + \gamma C \text{..................................(7)}$$

Where ρ_{fo} is the initial fluid density, and γ is a concentration –density coefficient.

Solute transport is modeled by single species transport representing the total dissolved solid in the porous media by advection-dispersion. The governing equation [14] for saturated porous media and entirely fluid or solid systems is:

$$\theta_s \frac{\partial c}{\partial t} + \nabla . \left[-\theta_s D_L \nabla c + \mathrm{u}c \right] = S_c \text{...........(8)}$$

Where: θs is porosity; D_L is the hydrodynamic dispersion tensor; u is vector of pore fluid velocities; Sc is solute source.

Assuming linearly elastic rocks, the mechanical part is included by taking the equation of conservation of momentum, coupled with the water pressure using Terzaghi's effective stress principle [15]:

$$G \frac{\partial^2 u_i}{\partial x_j \partial y_j} + (G + \lambda) \frac{\partial^2 u_j}{\partial x_i \partial y_j} - \alpha \frac{\partial p}{\partial x_i} - \beta K_D \frac{\partial T}{\partial x_i} + F_i = 0$$
$$\text{.. (9)}$$

Where: u is the displacement, G is shear modulus, λ Lamé's first parameter, α is Biot coefficient, K_D bulk modulus, T temperature, and β is thermal expansion coefficient.

3.4 Finite element solutions

In this work, continuum mechanics is used as the conceptual basis for the analysis of coupled processes by employing differential equations of global conservation principles. Some of these mathematical equations have specific applications to the materials under investigation, and are called constitutive equations, while those capturing the fundamental physical laws, are conservation of mass, momentum, and energy [for example see 16-18]. As we have to deal with sedimentary rock, which represents a porous media, we have to consider a multi-phase system consisting of solid (rock matrix), fluid (water) phases with a fully saturated conditions at all times. The governing partial differential equations for HM coupled processes in porous media are presented in section 3.3.

3.5 Verification and validation

For the purpose of model verification, the results obtained from the developed model are compared with the analytical solution for one dimensional consolidation equations by Terzaghi [19]:

$$u'(z,t)=\Delta\sigma_v\sum_{m=0}\frac{2}{M}\sin\left(M\frac{z}{H}\right)\exp\left(-M^2T_v\right)\cdots(8)$$

$M=\pi(2m+1)/2$, and $T_v=\frac{c_v t}{H^2}$

Where: u' is pore water pressure, $\Delta\sigma_v$ is change in vertical stress, z is depth, H is drainage path length and c_v is coefficient of consolidation.

Table 1 shows the material properties and initial conditions for the verification model, while Figure 6 shows the hydraulic and mechanical boundary conditions.

Table 1: Material properties for the validation model

Parameters	Value
Hydraulic conductivity (m/s)	2E-8
Initial water pressure (Pa)	0
Modulus of elasticity (Pa)	4E7
Poisson ratio	0.3

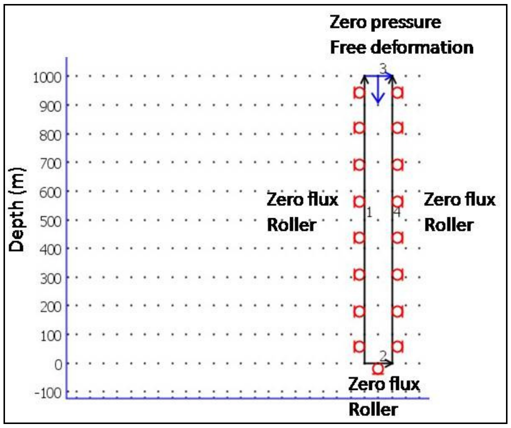

Figure 6. Boundary conditions for the validation 1D model.

The results obtained by using the developed COMSOL HM model show a very good agreement with the analytical solution proposed by Terzaghi as shown in Figure 7.

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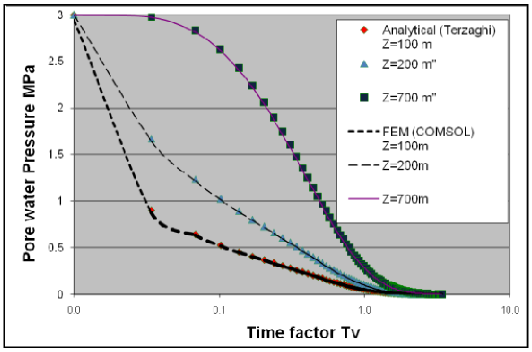

Figure 7. Comparison between COMSOL and Terzaghi's analytical solution.

In addition to the analytical solution, the developed COMSOL HM model is compared with field pore water pressure profile [20] as shown in Figure 8. Despite some differences in COMSOL results and field data at a greater depth, good agreement is achieved for the range of 0 to 700 m depth which includes the location of a potential DGR. Differences in results may be due to some assumption adopted in this work, such as linear elastic model, homogenous and isotropic material in addition to uncertainties in geological and glacial data.

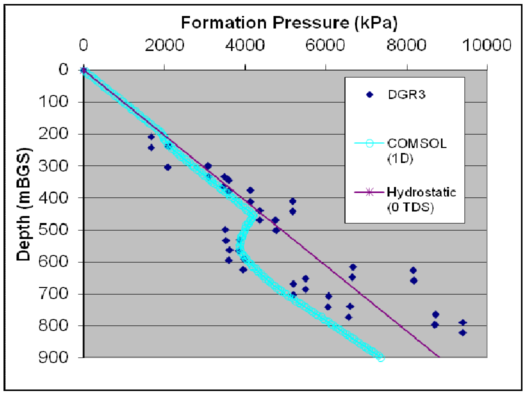

Figure 8. Comparison of experimental field measurements and results of water pressure profile at the present time.

4. Simulation of the Hydro-Mechanical model

The developed model is used to simulate the impact of the past two glacial cycles on the hydraulic and mechanical response of sedimentary rocks southern Ontario as shown in the 1D model in Figure 5. For the initial conditions, linear hydrostatic pore water pressure with depth is assumed as an initial pressure for the time 80000 years before present (this time is chosen based on the ice loading history). The same boundary conditions used for the validation model (see Figure 6) are assumed for the study area. The ice loading shown in Figure 4 is applied to the ground surface.

In this paper, some selected results are presented, particularly the time evolution of surface displacement and water pressure profile. Figure 9 shows the surface displacement under the impact of the past two glaciation cycles.

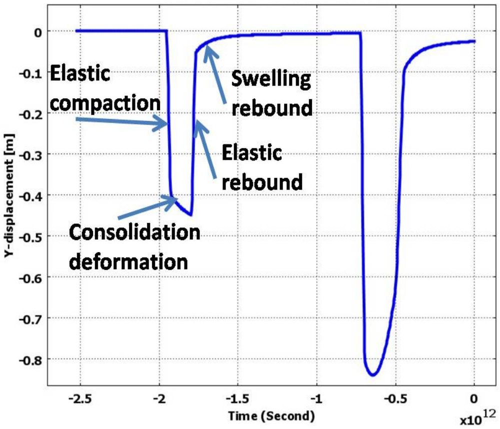

Figure 9. Results of surface displacement under the impact of past two glaciation cycles.

Two main cycles of loading-unloading can be detected; each one is mainly characterized by four parts of deformation: elastic deformation (compaction and rebound with straight lines) and consolidation deformation (curved lines). Consistent with field measurements, the model shows that surface rebound is still a process that still continues to the present time.

The variation of water pressure with time at a depth of 700 m is presented in Figure 10. Two jumps are noticed related to each glaciation cycle, with a significant abrupt drop in water pressure after ice unloading. That abrupt drop is induced by the elastic rebound. It takes a significant amount of time for that pressure drop induced by unloading to recover. The model predicts that the pressure at 700 m depth is lower than the hydrostatic pressure. This prediction is consistent with field measurements from boreholes at the site. Variation in pore water pressure and hydraulic gradient can be used for the safety assessment of DGR system under the impact of future glaciations.

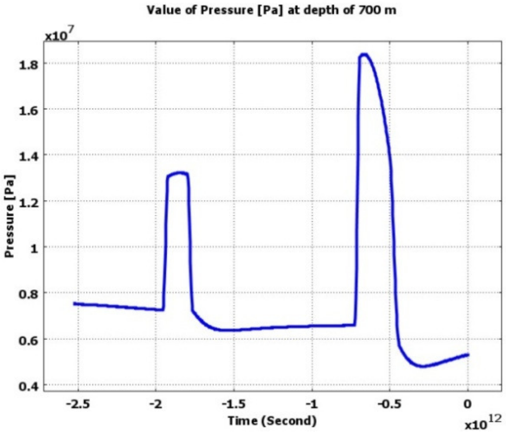

Figure 10. Results of water pressure at depth of 700 m under the impact of past two glaciation cycles.

5. Conclusions

In this paper, the COMSOL Multiphysics code is used to simulate Hydro-Mechanical processes associated with past glaciation cycles in sedimentary rocks in southern Ontario. The main HM coupled equation is derived from the conservation of mass and momentum, coupled with Darcy's law for pore water flow, Terzaghi's effective stress principle, and Hooke's law of linear elasticity for the solid skeleton. The initial hydraulic conditions for 80000 year before present is assumed as hydrostatic, and ice loading on the surface is generated based on the Boulton's model. Based on the results obtained from this study, the following conclusions can be drawn. First, the past glaciation, particularly the second cycle (22000 apb) had great impact on the pore water pressure gradient and distribution which persists to the present time. Second, the pore water pressure profile obtained by the 1D model shows a good agreement with the experimental measurements. However, more work is still needed to be done for the development of the model, particularly including the thermal and chemical effects, and threedimensional effects. Data uncertainties also need to be included using the suitable statistical methods.

6. Acknowledgement and Disclaimer

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