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DECOVALEX III BMT3/BENCHPAR WP4: The thermo-hydro-mechanical responses to a glacial cycle and their potential implications for deep geological disposal of nuclear fuel waste in a fractured crystalline rock mass

T. Chan[a,*], R. Christiansson[b], G.S. Boulton[c], L.O. Ericsson[d], J. Hartikainen[e], M.R. Jensen[f], D. Mas Ivars[g], F.W. Stanchell[a], P. Vistrand[d], T. Wallroth[d]

[a]Atomic Energy of Canada Limited, c/o 700 University Ave. 17th Floor, Toronto, Canada M5G 1X6
[b]Svensk Kärnbränslehantering AB, Sweden
[c]School of GeoSciences, University of Edinburgh, UK
[d]Chalmers University of Technology, Sweden
[e]Institute of Mathematics, Helsinki University of Technology, Finland
[f]Ontario Power Generation, Canada
[g]Royal Institute of Technology, Sweden

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Abstract

A number of studies related to past and on-going deep repository performance assessments have identified glaciation/deglaciation as major future events in the next few hundred thousand years capable of causing significant impact on the long term performance of the repository system. Benchmark Test 3 (BMT3) of the international DECOVALEX III project has been designed to provide an illustrative example that explores the mechanical and hydraulic response of a fractured crystalline rock mass to a period of glaciation. The primary purpose of this numerical study is to investigate whether transient events associated with a glacial cycle could significantly influence the performance of a deep geological repository in a crystalline Shield setting. A conceptual site-scale (tens of kilometres) hydro-mechanical (HM) model was assembled based primarily on site-specific litho-structural, hydrogeological and geomechanical data from the Whiteshell Research Area in the Canadian Shield, with simplification and generalization. Continental glaciological modelling of the Laurentide ice sheet through the last glacial cycle lasting approximately 100,000 years suggests that this site was glaciated at about 60 ka and between about 22.5 and 11 ka before present with maximum ice sheet thickness reaching 2500 m and maximum basal water pressure head reaching 2000 m. The ice-sheet/drainage model was scaled down to generate spatially and temporally variable hydraulic and mechanical glaciated surface boundary conditions for site-scale subsurface HM modelling and permafrost modelling. Under extreme periglacial conditions permafrost was able to develop down to the assumed 500-m repository horizon. Two- and three-dimensional coupled HM finite-element simulations indicate: during ice-sheet advance there is rapid rise in hydraulic head, high transient hydraulic gradients and high groundwater velocities 2–3 orders of magnitude higher than under nonglacial conditions; surface water recharges deeper than under nonglacial conditions; upon ice-sheet retreat, the gradients reverse; fracture zone network geometry, interconnectivity and hydraulic properties significantly influence flow domain response; residual elevated heads are preserved for 10,000 s in the low-diffusivity rock; and no hydraulic jacking or shear failure occurs at depth. It was found that transient coupled modelling is necessary to

*Corresponding author. Tel.: +1 416 592 5296; fax: +1 416 592 7336.
E-mail address: chant@aecl.ca (T. Chan).

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capture the essence of glacial effects on Performance Assessment. Model dimensionality also significantly affects simulated results.

Keywords: Glaciation; Permafrost; Coupled THM responses; Radioactive waste disposal; Performance assessment; Transient; Hydrogeology; Stress analysis; DECOVALEX III, 2D and 3D Numerical modelling

1. Introduction

This paper presents an overview of the contents, objectives, methods and major results of Benchmark Test 3 (BMT3) of the DECOVALEX III Project [1], which is also known as a Work Package 4 (WP4) of the BENCHPAR Project. This overview is based on the final report of BMT3 [2], team progress and/or final reports [3–7] and pertinent papers [8–10] in the book edited by Stephansson et al. [11]. Two companion papers [12,13] complement the contents of this paper. Further technical details of literature review, modelling approaches, governing equations, material models, results and discussions can be found in the final BMT3 reports and papers cited above.

1.1. Background

DECOVALEX[1] is an international co-operative project to support the development of mathematical models of coupled thermal (T), hydrological (H) and mechanical (M) processes in fractured geological media for potential deep geological nuclear fuel waste repositories [1]. The third phase, DECOVALEX III, was initiated in July 1999 and ended in December 2003. A main theme of DECOVALEX III was to examine state-of-science issues surrounding the application of coupled THM models to geoscientific problems related to deep geologic disposal.

Three Benchmark Test Cases (BMTs) were defined by the DECOVALEX participants to illustrate through numerical experiments the relevance (or not) of THM couplings to flow system evolution and mechanical stability in the context of long-term performance of nuclear waste repositories in complex rock structures. These were: BMT1—near-field resaturation, BMT2—homogenization of THM properties and BMT3—impact of glaciation process on far-field performance assessments. This paper pertains to Benchmark Test 3 (BMT3).

Benchmark Test 3 (BMT3) provides an illustrative example that explores the hydraulic and mechanical response of a fractured crystalline rock mass to glaciation. The primary purpose is to investigate through numerical simulation whether transient events associated with a glacial cycle could significantly affect the performance of a deep geological repository in a crystalline Shield setting.

In 2000, the DECOVALEX III was coordinated with the European Commission (EC) co-funded BENCHPAR project that is aimed at improving the thermo-hydro-mechanical (THM) coupled processes content of radioactive waste repository Performance Assessment (PA). BMT3 of DECOVALEX was coordinated with WP4 of BENCHPAR, which considers the far-field rock mass subject to glacial perturbations.

1.2. Overview and objectives of Benchmark Test 3 (BMT3)/work package 4 (WP4)

Evidence from continental deposits and oxygen-isotope ratios in marine sediments demonstrates that during the last million years, much of the northern part of the Northern Hemisphere has been subject to repeated glacial cycles, with a dominant period of approximately 100,000 years, with intervening and relatively brief interglacial periods. The glacial cycles have seen dramatic extensions of permafrost and of ice-sheets, associated with major eustatic fluctuations of relative sea levels. These events have changed the pattern of mechanical load and hydraulic boundary conditions on the Earth's crust; the patterns of groundwater recharge and discharge and of recharge chemistry, such that we expect hydromechanical impacts to have occurred in the subsurface. A number of studies related to past and on-going deep repository performance assessments have identified glaciation/deglaciation as major future events in the next few hundred thousand years capable of causing significant impact on the long-term performance of the repository system [14–20].

The BMT3/WP4 (hereafter referred to as BMT3 for brevity) was a generic numerical exercise constructed from geological and hydrogeological characteristics of a Northern Hemisphere site that is subject to a prescribed time sequence of climatically driven glaciation/deglaciation events. A generic spent-fuel repository was assumed to be located in a crystalline rock mass, which consists of low-permeability, low-porosity, sparsely fractured intact rock matrix (with $10^{-19}\,m^2$ or lower permeability), traversed by an interconnected three-dimensional network of fracture zones. These conditions are representative of those that would be encountered in a Shield setting.

[1]Acronym for DEvelopment of COupled (THM) models and their VALidation against EXperiments in nuclear waste isolation. See paper by Tsang et al. [1].