Validation of Cryohydrogeological codes: the InterFrost project

Christophe Grenier[1], Hauke Anbergen[2], Victor Bense[3], Quentin Chanzy[1&4], Ethan Coon[5,6], Nathaniel Collier[6], François Costard[7], Michel Ferry[8], Andrew Frampton[9], Jennifer Frederick[10], Julio Gonçalvès[11], Johann Holmén[12], Anne Jost[13], Samuel Kokh[14], Barret Kurylyk[15], Jeffrey McKenzie[16], John Molson[17], Emmanuel Mouche[1], Laurent Orgogozo[18], Romain Pannetier[9], Eric Pohl[1], Agnès Rivière[19], Nicolas Roux[1&7], Wolfram Rühaak[20], Johanna Scheidegger[21], Jan-Olof Selroos[22], René Therrien[17], Patrik Vidstrand[22], Clifford Voss[23]

[1]LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France, christophe.grenier@lsce.ipsl.fr
[2]Dipl.-Ing. Peter Neumann Baugrunduntersuchung GmbH & Co. KG, Eckernförde, Germany
[3]Department of Environmental Sciences. Wageningen University, Netherlands
[4]ENS Cachan, Département Génie Mécanique, Université Paris-Saclay, Cachan, France
[5]Los Alamos National Laboratories, Los Alamos, USA
[6]ORNL Climate Change Science Institute, Oak Ridge, TN, USA
[7]GEOPS/IPSL, Geosciences Paris Sud, Université Paris-Saclay, Orsay, France
[8]MFRDC, Orvault, France
[9]Department of Physical Geography, Stockholm University, Stockholm, Sweden
[10]Sandia National Laboratories, Albuquerque, NM, USA
[11]Aix-Marseille University, CNRS, IRD, CEREGE, Aix-en-Provence, France
[12]Golder Associates, Stockholm, Sweden
[13]Sorbonne Universités, UPMC Univ. Paris 6, CNRS, EPHE, Metis, Paris, France
[14]Maison de la Simulation USR 3441, Digiteo, CEA Saclay, Gif-sur-Yvette, France
[15]Centre for Water Resources Studies and Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS, Canada
[16]Department of Earth and Planetary Sciences, McGill University, Montreal, PQ, Canada
[17]Département de géologie et de génie géologique, Université Laval, Québec, Canada
[18]GET, UMR 5563 CNRS-IRD-UPS, Université Toulouse, Toulouse, France
[19]PSL Research University, MINES ParisTech, Centre de Géosciences, Fontainebleau, France
[20]Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
[21]British Geological Survey. Nottingham, UK
[22]Swedish Nuclear Fuel and Waste Management Company, Solna, Sweden
[23]United States Geological Survey, Menlo Park, CA, USA

Abstract

Recent field and modelling studies indicate that a fully-coupled, multi-dimensional, thermo-hydraulic (TH) approach is required to accurately model the evolution of permafrost-impacted landscapes and groundwater systems. However, the relatively new and complex numerical codes being developed for coupled non-linear freeze-thaw systems require verification. This issue was first addressed within the InterFrost IPA Action Group, by means of an intercomparison of thirteen numerical codes for two-dimensional TH test cases (TH2 & TH3). The main results demonstrate that these codes provide robust results for the test cases considered. The second, ongoing phase of the InterFrost project is devoted to the simulation of a cold-room experiment based on Test Case TH2 (Frozen Inclusion). The experimental setup and monitoring results at the base of the common validation exercise are presented.

Keywords: numerical simulation; code benchmarking; thermo-hydrological coupling; permafrost; sharp interface

Introduction

Climate change has been most pronounced in high latitude regions and high altitude areas. The improvement of our understanding of the interplay between climate, hydrology and permafrost provides motivation for the development of a spatially distributed, multidimensional, fully-coupled TH approach for heat and water processes in permafrost areas. A new class of such cryohydrological codes emerged during the last decade fulfilling this intention (Walvoord & Kurylyk, 2016; Kurylyk *et al.*, 2014). However, the numerical solution of such coupled TH systems with non-linear equations and a sharp interface (freeze-thaw boundary) is challenging. Associated codes thus require some level of evaluation.

The InterFrost project (IPA Action Group) provides an open forum for such an evaluation. Validation is organized in three steps, each addressing one of the following questions: How well is the reference set of equations solved by existing codes? How realistic is the set of equations solved for fluid flow and heat transfer? How well can existing codes accommodate real world complexity?

The first step is a purely numerical issue, addressed by means of an inter-comparison of 13 codes on 2D benchmark cases with the main results presented below.

The second step is the simulation of an experiment under controlled conditions in the cold room (present status presented below). The third issue will require carefully selected field-case monitoring data.

Advancing with a group of modelers is a necessary requirement for code inter-comparison and code validation with real-world data. Promoting such a group process within the cryohydrogeological community is a major incentive of the InterFrost IPA Action Group.

Inter-comparison (TH2 & TH3 Test Cases)

Two complementary 2D test cases were developed as benchmarks for the intercomparison. Both incorporate the full complexity of TH coupling (see InterFrost web site wiki.lsce.ipsl.fr/interfrost). Evaluation of the numerical codes against these benchmarks is based on the intercomparison of simulation results through a set of performance metrics (PMs). Figure 1 presents a sketch of Test Case TH2 (initially frozen inclusion within an unfrozen domain) with 13 code simulation results for PM1 (minimum domain temperature).

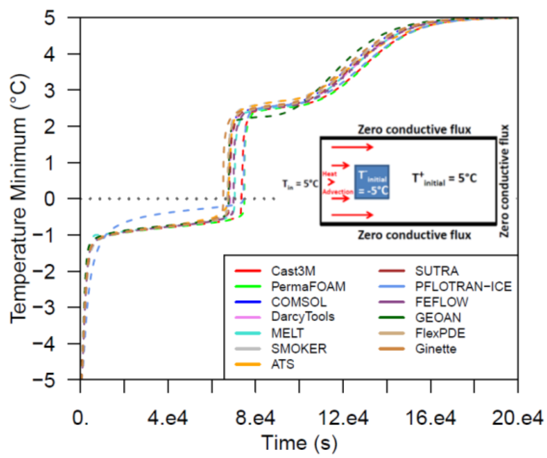

Figure 1. Result of the inter-comparison of 13 codes on TH2-PM1 (evolution of temperature minimum)

These results reflect the participant group conclusions drawn from the full inter-comparison body and are based on a critical number of participants with codes presenting a wide diversity of numerical approaches. A group of these 13 models, implementing the same equation sets and identical characteristic curves, behaved similarly for all test cases, all PMs, and over a large range of head gradients. This suggests that the codes are all solving the governing equations equally well. Discrepancies found in the intercomparison results were traced back to differences in the governing equations or simulation set-up issues. These are promising outcomes for coupled TH simulation. Interested readers may refer to the InterFrost web site, Rühaak *et al.*, (2015) and Grenier *et al.*, (in review).

Validation from experimental cases

In a need to exercise the codes' capabilities for real-world systems, Test Case TH2 was adapted for experimental conditions in the GEOPS Laboratory. The setup consists of a plexiglass box with a filter at the bottom allowing flow through. It is filled with saturated sand in which a frozen and saturated sand inclusion is placed. The box is installed in a cold room with controlled temperature conditions. Monitored parameters are: the temperature in several locations (inclusion center and down-gradient, in the air, the water and on the external wall), and water flow rates. Figure 2 provides a sketch of the setup as well as the temperature monitoring results (10_11_2017 experiment).

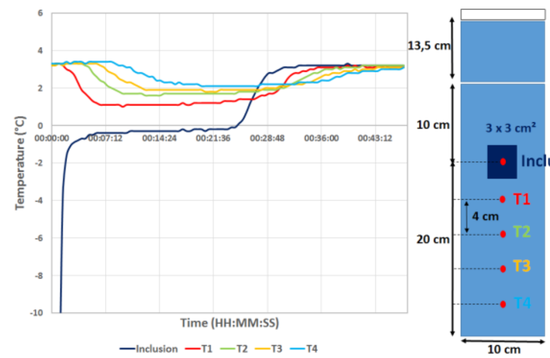

Figure 2. Experimental conditions and monitoring results

Preparatory simulations conducted with the Cast3M code indicate that conditions formerly simulated for the TH2 case may need to include additional complexity to account for actual setup conditions (e.g. the inclusion installation phase) while some calibration will be required to reproduce the observed variables. Complementary measurements (e.g. colored initial inclusion tracing the evolution of thawing water) would provide further constraints. Preliminary simulation results will be presented during EUCOP2018.

Acknowledgments

The InterFrost Action Group gratefully acknowledges the support of IPA and Labex-IPSL.

References

Grenier, C. et al., in review. Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators. *ADWR*

Kurylyk, B.L. et al. 2014. Climate change impacts on groundwater and soil temperature in cold and temperate regions: Implications, mathematical theory, and emerging simulation tools. Earth-Sci. Rev 138: 313-334, 2014.

Rühaak W. et al. Benchmarking Numerical Freeze/Thaw Models. *Energy Procedia* 76 (2015) 301 – 310

Walvoord, M.A., Kurylyk, B.L., 2016. Hydrologic impacts of thawing permafrost – A review. *Vadose Zone J* Vol. 15, Iss. 6, 2016