Numerical Modelling of Cryo-Hydrogeological Dynamics within Variable-Aperture Fractures

Mahsa Malmir, John Molson, René Therrien

Department of Geology and Geological Engineering, Université Laval, Québec City, QC, Canada.

mahsa.malmir.1@ulaval.ca, john.molson@ggl.ulaval.ca, rene.therrien@ggl.ulaval.ca

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Objectives and Conceptual Models

- Investigate freeze-thaw (FT) behavior in a lab-scale single fracture, containing a stochastic aperture distribution
- Assess potential relationships between the equivalent freezing functions (FFs) across various scenarios
- Study FT behavior in discretely fractured networks in permafrost regions
- Compare discrete fracture network (DFN) and equivalent porous medium (EPM) models

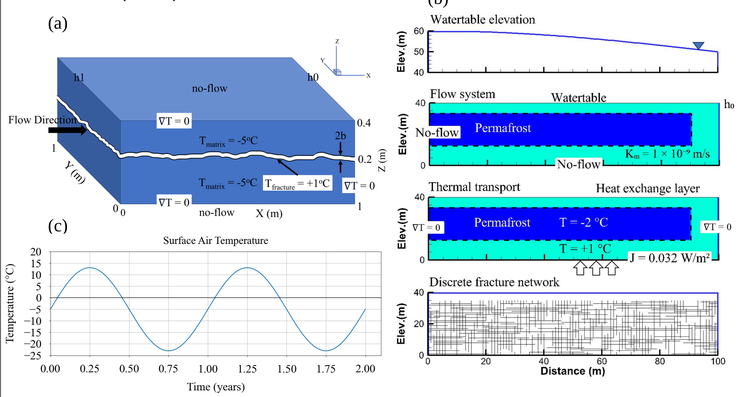


Figure 1. Conceptual models.
(a) Single fracture model, (b) Discrete fracture network
(c) Surface air temperature of large-scale DFN case

Scenarios

Table 1. Range of variables for selected scenarios

	Mean aperture	Variance	Hydraulic gradient	Temperature
LT-HG*	500 µm	0, 0.1, 0.2, 0.3	6%	3 °C
HT-LG**	500 µm	0, 0.1, 0.2, 0.3	3%	6 °C

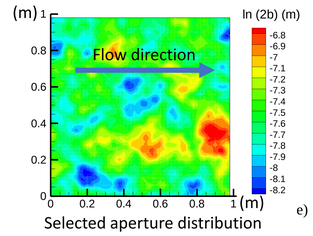
*LT-HG: Low temperature-high gradient

**HT-LG: High temperature-low gradient

Conditions and Processes

- Fully-saturated
- Density-dependent flow
- Advective-conductive heat transport
- Freeze-thaw/latent heat
- Relative permeability kr(T)

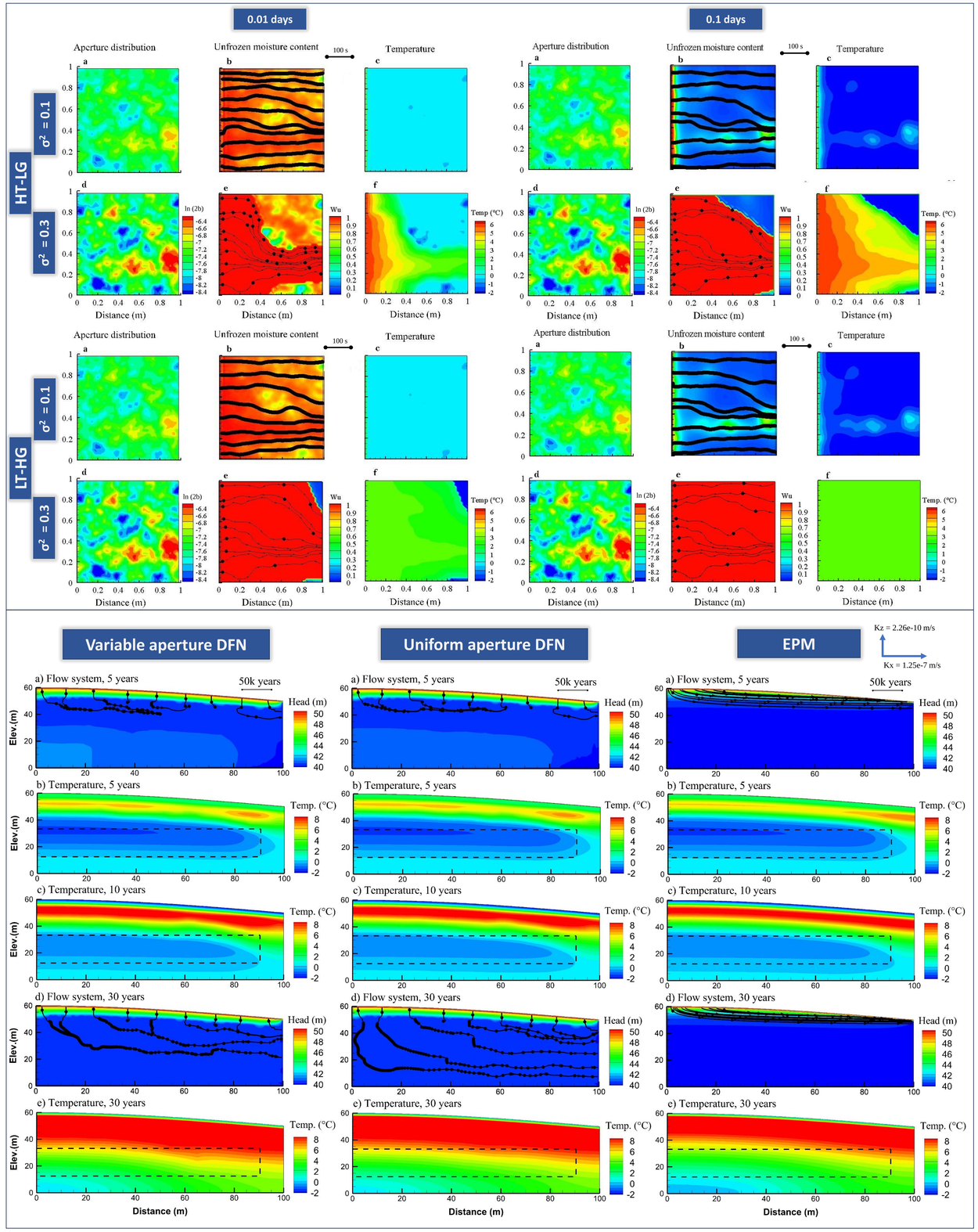
Fracture Aperture Distribution

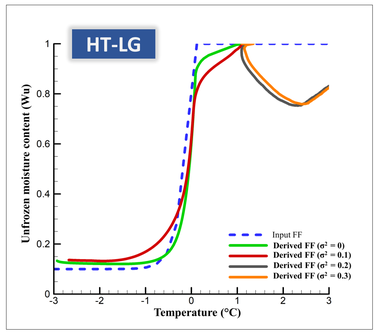


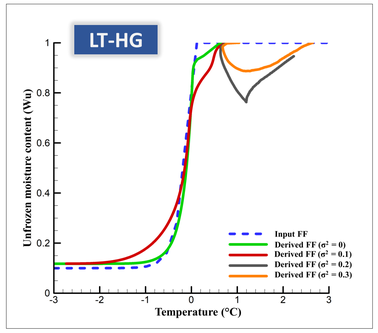
Models

1. HEATFLOW-SMOKER (Molson & Frind, 2024) (Coupled flow-heat transport)
2. Fgen92 (Robin et al., 1993) (Stochastic aperture field generation)

Results







Discussion and Conclusions

- Single fracture model:

- Fracture openness during FT dynamics depends on both the thermal state of the fracture and the hydraulic gradient.
- Under sufficient hydraulic gradients, variable apertures enable preferential flow, keeping the fracture open.
- Model-derived freezing functions remain similar to the input freezing functions.
- In a variable aperture fracture, for mean temperatures of T>0, the mean unfrozen moisture content can be Wu<1, reducing the effective K and flow rate relative to a uniform aperture fracture.

- Discrete fracture network model:

- High thermal conduction attenuates the effect of individual fractures, whereas discrete fracture networks significantly enhance fluid flow and, in turn, heat transport.
- Compared to the variable aperture DFN, the uniform-aperture DFN system exhibits a more dispersed flow system over time, due to the exclusion of low aperture fractures.
- Compared to the EPM, the DFN shows stronger flow channeling and higher permeability, which influences fluid velocity and thermal propagation.