Influences of permafrost on deep groundwater flow

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Presentation of numerical code: Ginette

- 2-D variably saturated flow (x,z) and interaction with a stream (Riviere et al. 2014)
- Coupled fluid flow-heat transfer taking account the freezing processes
- 2 validation tests :
  - Phase change : Stefan's solution
  - An experimental study of pore water pressure variations in sub-permafrost groundwater
- Numerical set-up:
  - Finite difference numerical scheme
  - Boundary conditions are specified on each face
  - Mass balance is calculated at each cell's center
  - Adaptative time step
  - Coupling methods: Picard's iterative scheme
  - Resolution: PCGS

Process formalism:

- Heat transport:

$$div[\lambda(grad(T))] - \rho_w C_w div(U T) = \rho C \frac{\delta T}{\delta t} - \rho_w \omega L_i \frac{\delta S_{ice}}{\delta T}\frac{\delta T}{\delta t}$$

  - Taking into account the latent heat effect
  - Thermal properties change as a function of temperature

$$\lambda = \left((1-\omega)\sqrt{\lambda_s} + \omega(1-S_{ice})\sqrt{\lambda_W} + \omega S_{ice}\sqrt{\lambda_{ice}}\right)^2$$

$$\rho C = (1-\omega)\rho_S C_s + \omega(1-S_{ice})\rho_W C_W + \omega S_{ice}\rho_{ice} C_{ice}$$

- Groundwater flow:

$$\frac{\delta}{\delta x}\left[\frac{\rho_w k_x k_x^r(T)}{\eta}\frac{\delta p}{\delta x}\right] + \frac{\delta}{\delta x}\left[\frac{\rho_w k_z k_z^r(T)}{\eta}\frac{\delta p}{\delta z} + \rho_w g\right] = \frac{S_k}{g}\frac{\delta p}{\delta t} + \Gamma$$

  - Freezing functions : Change of the relative permeability and ice saturation as a function of temperature (linear, Van Genuchten)

Process formalism:

- Heat transport:

$$div[\ \lambda\ (grad(T)] - \rho_w C_w div(\ U\ T) = \rho C \frac{\delta T}{\delta t} - \rho_w \omega L_i \frac{\delta S_{ice}}{\delta T}\frac{\delta T}{\delta t}$$

- Groundwater flow:

$$\frac{\delta}{\delta x}\left[\frac{\rho_w k_x\ \ k_x^r(T)}{\eta}\frac{\delta p}{\delta x}\right] + \frac{\delta}{\delta x}\left[\frac{\rho_w k_z k_z^r\ (T)}{\eta}\frac{\delta p}{\delta z} + \rho_w g\right] = \frac{S_k}{g}\frac{\delta p}{\delta t} + \Gamma$$

  - Confined cell: Sk = specified storage coefficient :

$$S_k = \rho_W \omega g \left(\beta_l - \beta_s + \frac{\alpha}{\omega}\right)$$

  - Cell containing the water table: Sk = storage coefficient:

$$S_k = \frac{\omega_d}{e_m}$$

Process formalism:

- Heat transport:

$$div[\ \lambda\ (grad(T)] - \rho_w C_w div(\ U\ \ T) = \rho C \frac{\delta T}{\delta t} - \rho_w \omega L_i \frac{\delta S_{ice}}{\delta T} \frac{\delta T}{\delta t}$$

- Groundwater flow:

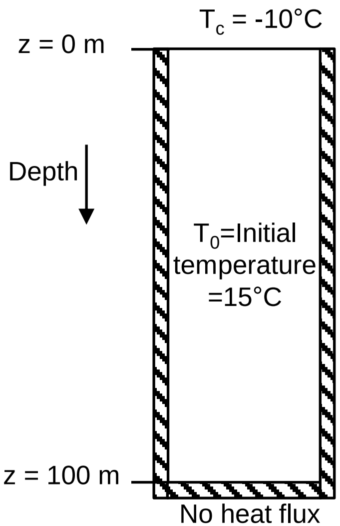
$$\frac{\delta}{\delta x}\left[\frac{\rho_w k_x\ \ k_x^r(T)}{\eta}\frac{\delta p}{\delta x}\right] + \frac{\delta}{\delta x}\left[\frac{\rho_w k_z k_z^r\ (T)}{\eta}\frac{\delta p}{\delta z} + \rho_w g\right] = \frac{S_k}{g}\frac{\delta p}{\delta t} + \Gamma$$

  - Pressure term related to the ice expansion:

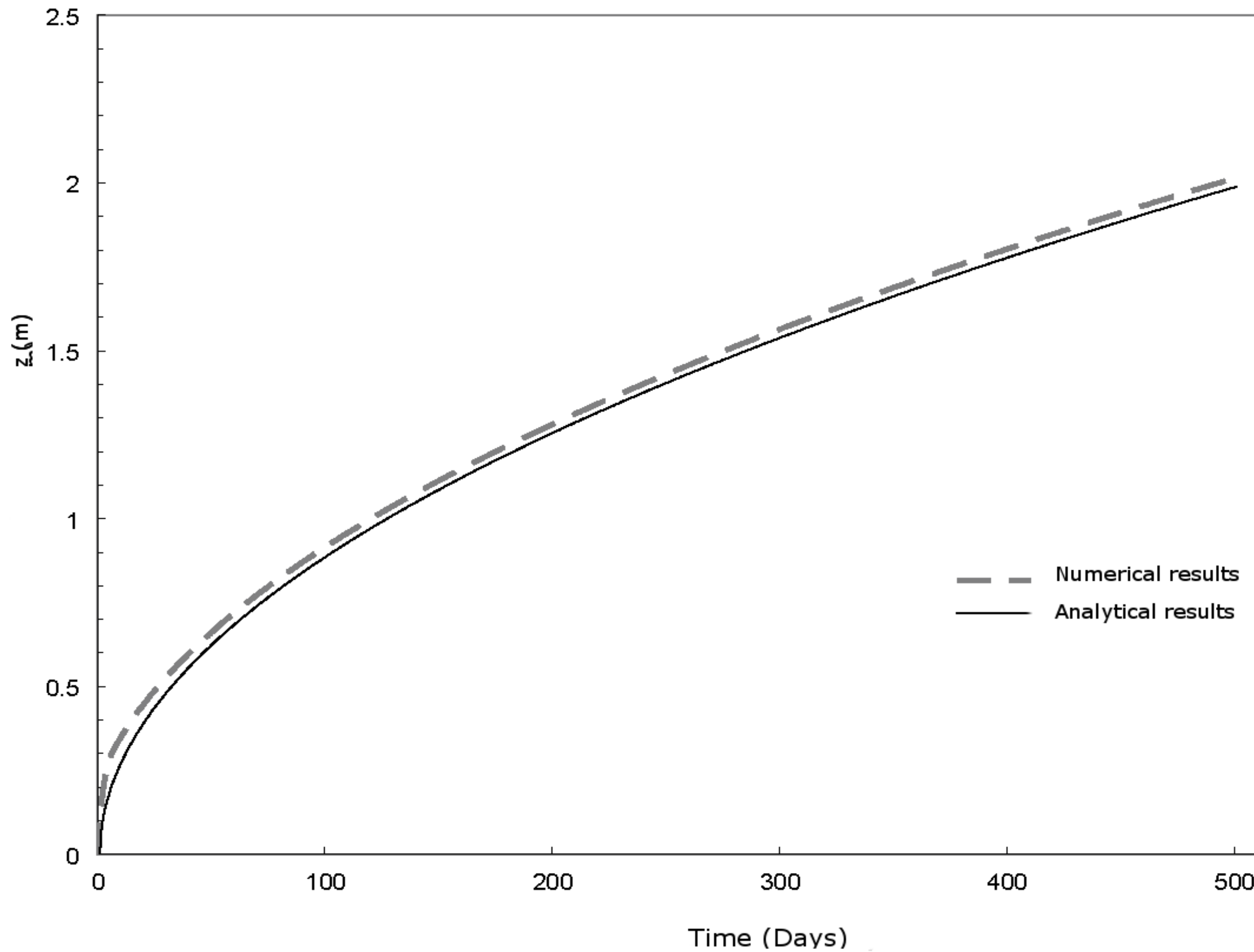
$$\Gamma = \omega(\ \rho_W - \rho_{ice}\ )\ \frac{\delta S_{ice}}{\delta t}$$

Stefan's solution

- $z_i = 2\lambda\sqrt{K_w t}$ with λ the solution of $\frac{-\lambda_f T_c}{erf\left(\lambda\sqrt{\frac{\alpha_u}{\alpha_f}}\right)} e^{-\lambda^2 \frac{\alpha_u}{\alpha_f}} - \frac{\lambda_w T_0}{erfc(\lambda)} e^{-\lambda^2} = \omega L \rho_w \alpha_u \sqrt{\pi}$

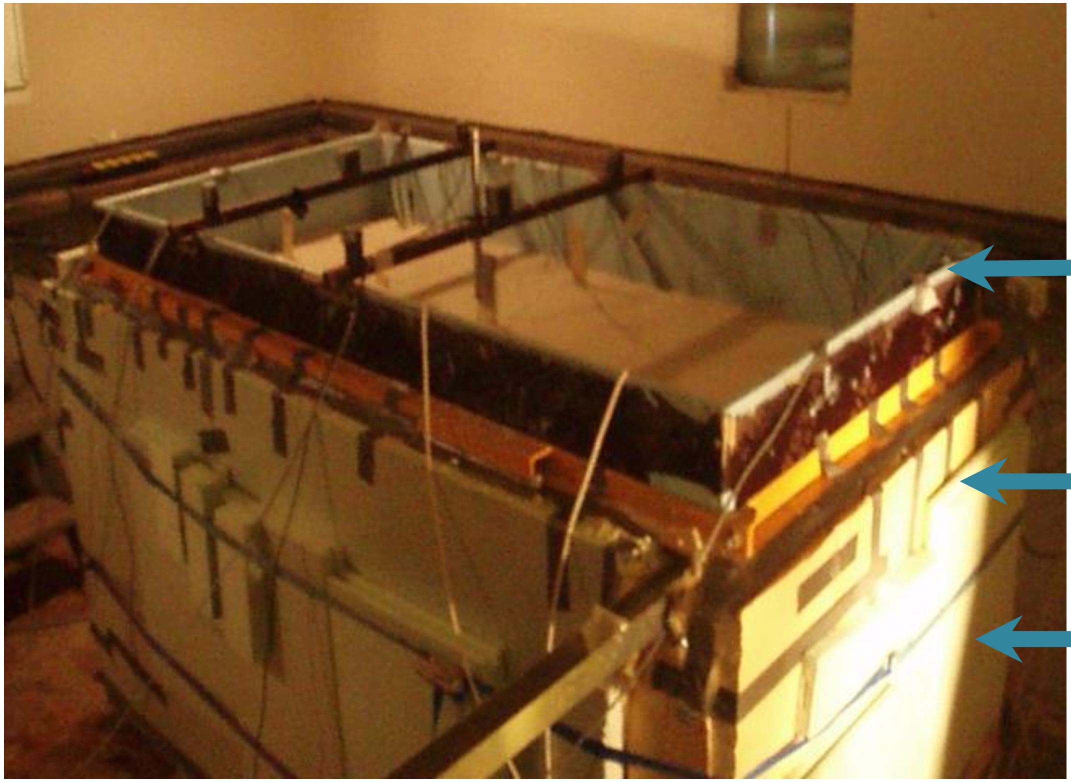


Parameters	values
ω	0.38
λ_s (W.m^{-1}.K^{-1})	2
C_s (J.kg^{-1}.K^{-1})	1030
ρ_s (kg.m^{-3})	1850
T_s (°C)	-0.4
T_l (°C)	0



Validation with an experimental model T→P : P ↑

- An experimental study of pore water pressure variations in sub-permafrost groundwater
- Set-up:



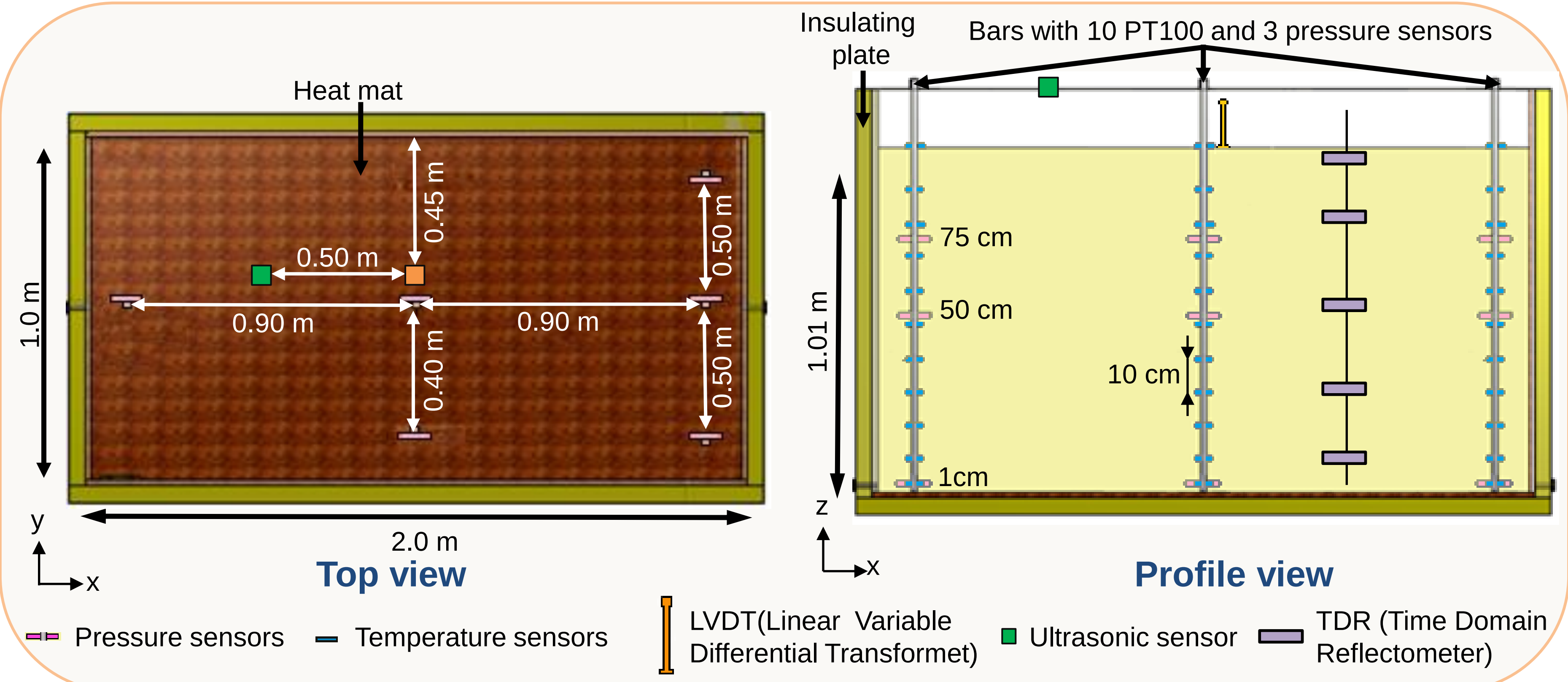
Fiberglass-coated wood plate

Metal buttress

Insulation : polystyrene plate

Validation with an experimental model T→P : P ↗

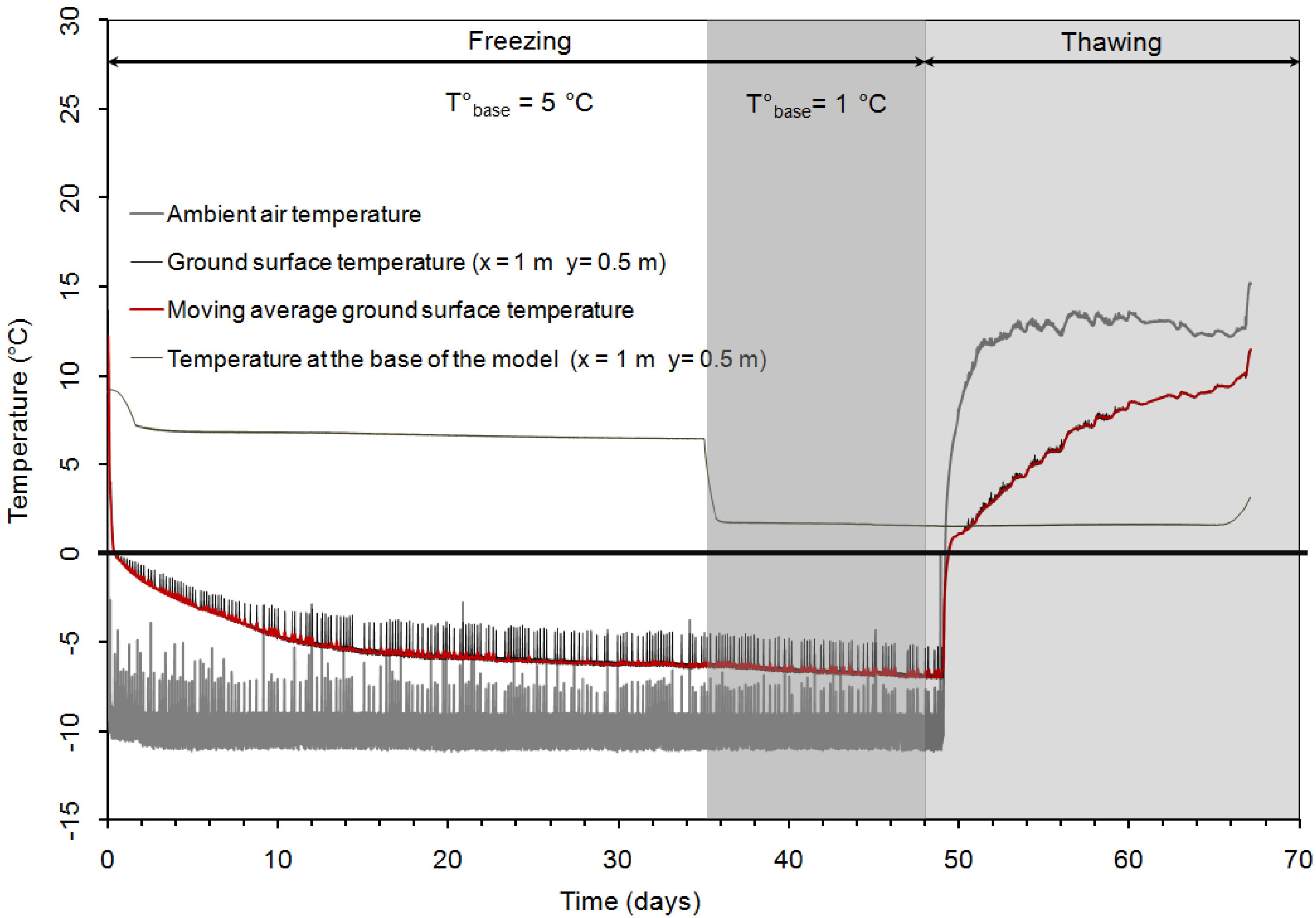
- An experimental study of pore water pressure variations in sub-permafrost groundwater
- Set-up:



- Measures : • Pressure fields, • Temperature profile, • Soil motion

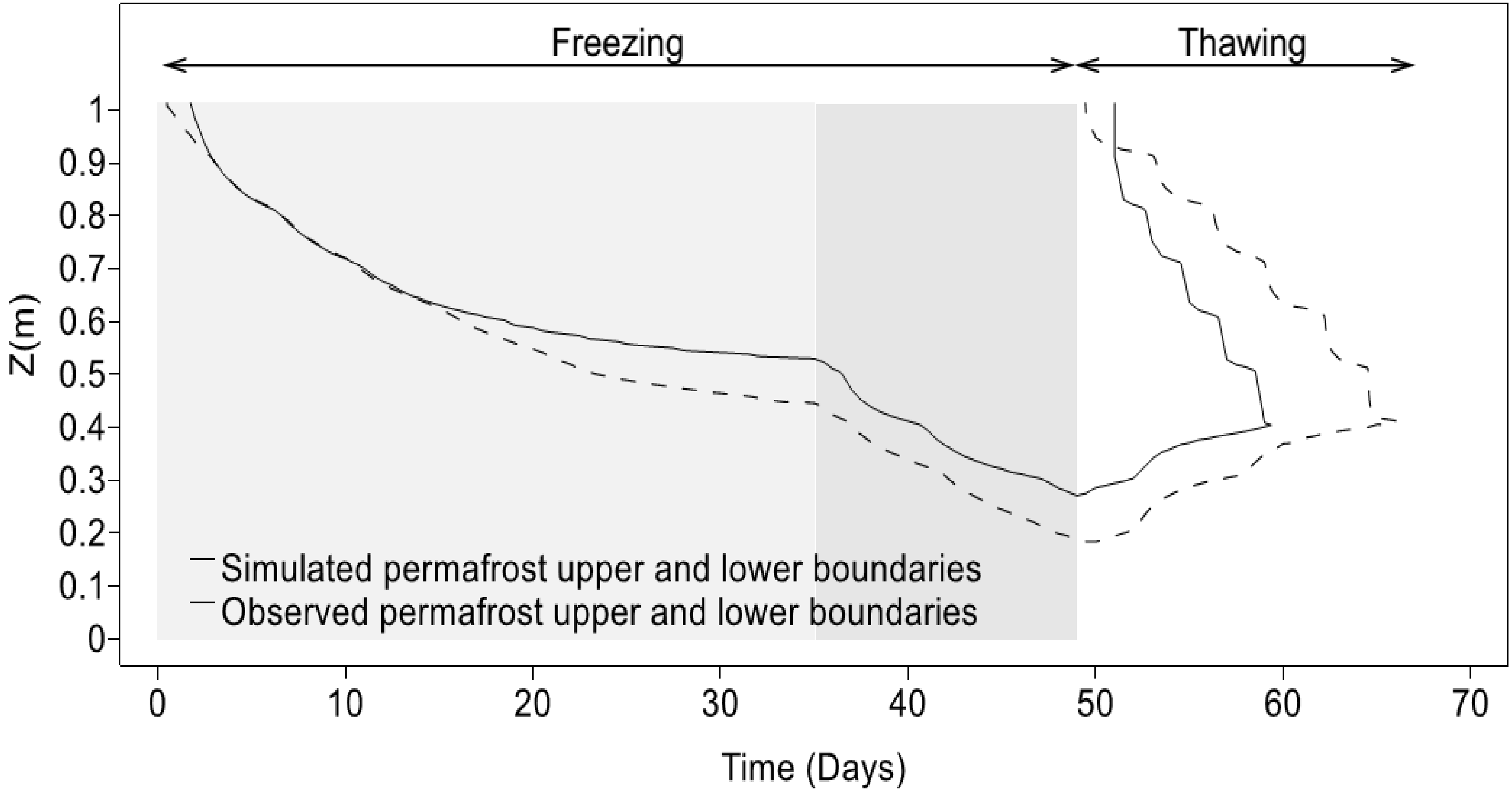
Validation with an experimental model T→P : P ↗

- **Boundary conditions**



Validation with an experimental model T→P : P ↑

- An experimental study of pore water pressure variations in sub-permafrost groundwater
- Freezing front evolution:



Validation with an experimental model T→P : P ↑

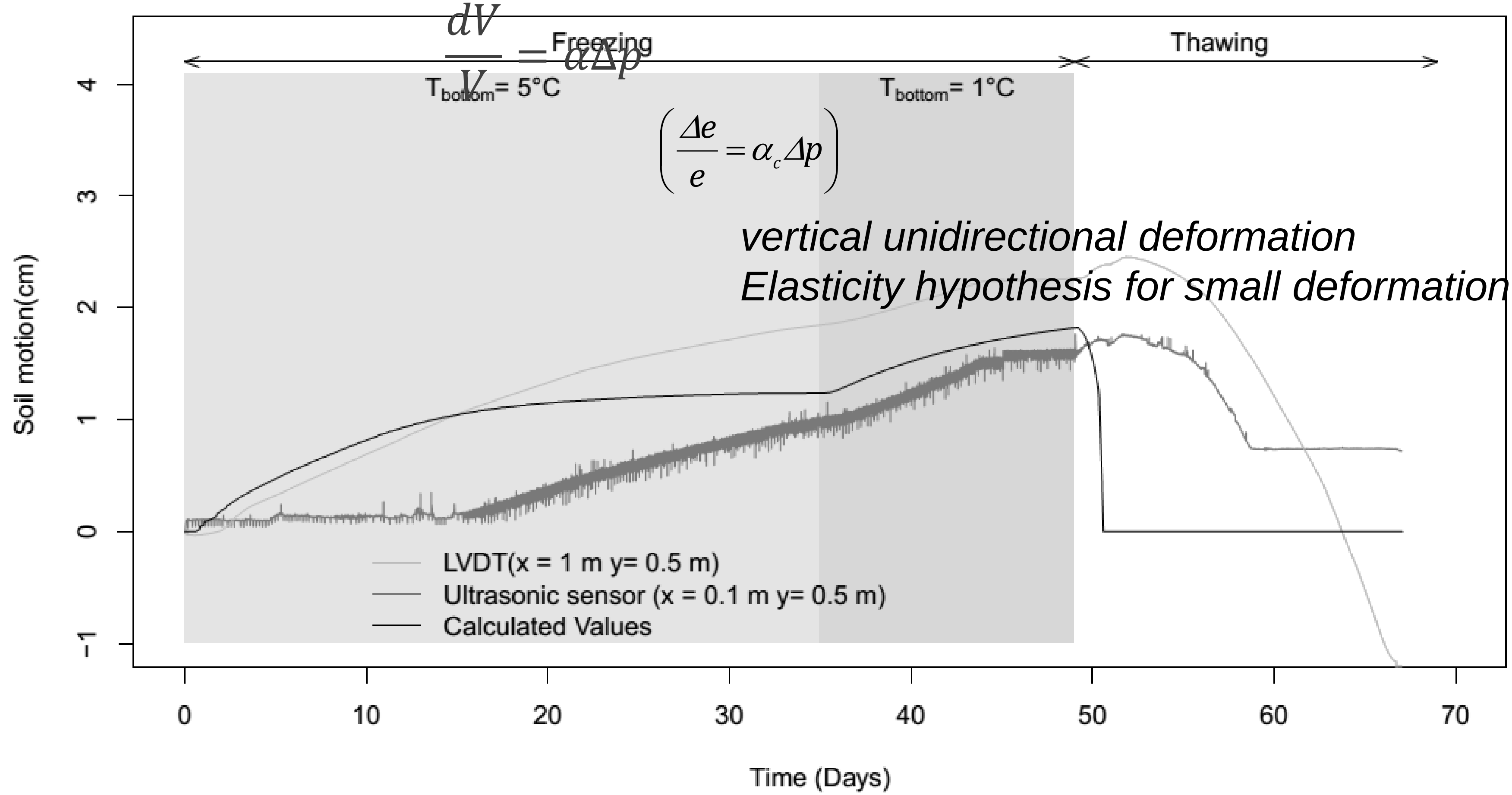
- An experimental study of pore water pressure variations in sub-permafrost groundwater
- Heave related to the ice expansion:

Soil Motion

$$\frac{dV}{V} = \alpha \Delta p$$

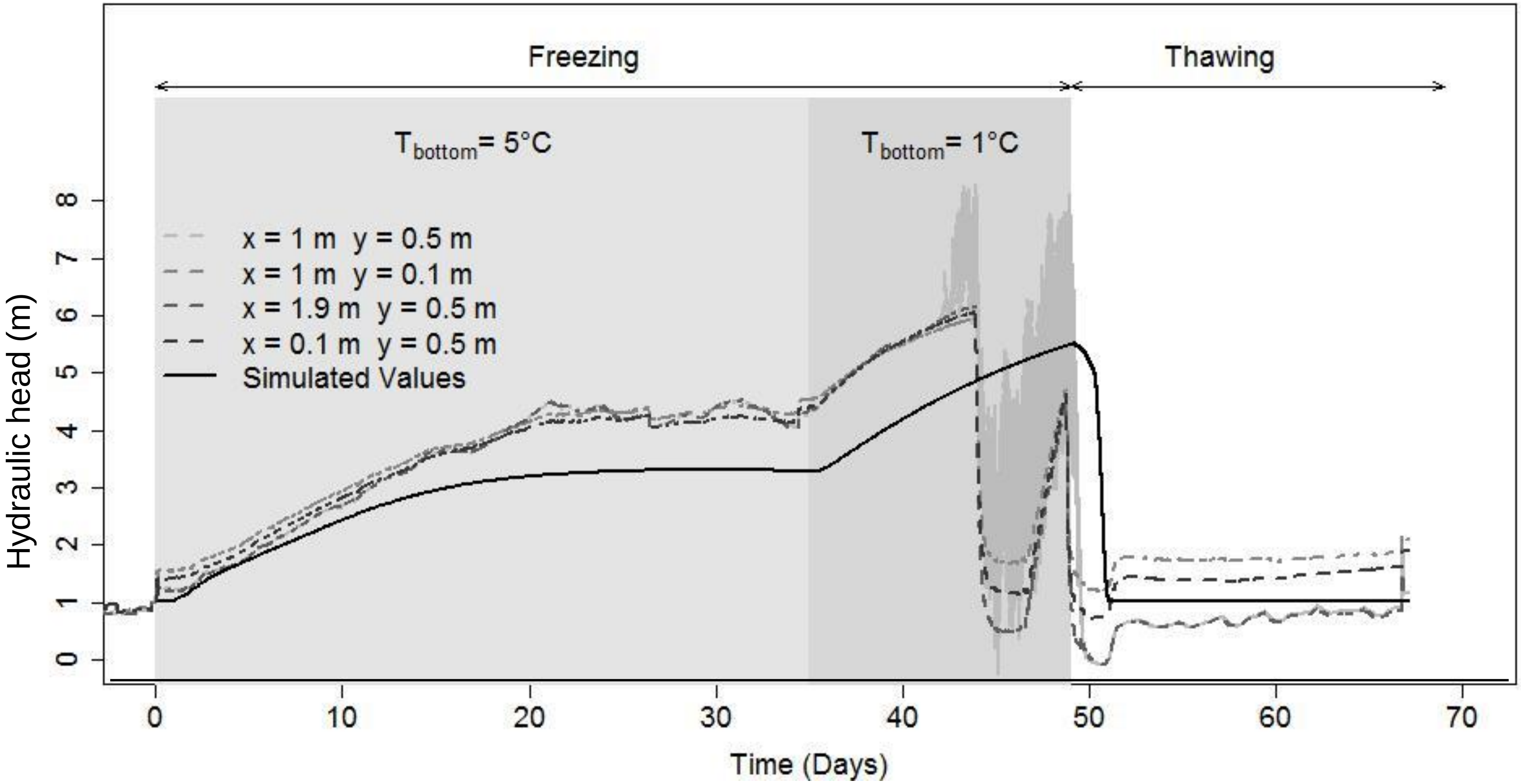
$$\left(\frac{\Delta e}{e} = \alpha_c \Delta p \right)$$

vertical unidirectional deformation
Elasticity hypothesis for small deformation



Validation with an experimental model T→P : P↗

- An experimental study of pore water pressure variations in sub-permafrost groundwater
- Pore water pressure evolution:



Conclusions

- Volumetric ice expansion 9%
  - ≈ 51 %: Frost heave ≈ 1.75 cm
  - ≈ 49 %: Over-pressure in the sub-permafrost aquifer ≈ 6 m

➡ Correct simulation of the observed overpressure in the experiment by the numerical code during the freezing period.

➡ Outlook on the future work :

- Improvement of thermo-mechanical coupling
- Cryosuction process

Thanks for your attention