Thermal and hydraulic modelling of road tunnel joints

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  - Boundaries conditions for the joint model
  - Equations of the model and implementation in COMSOL
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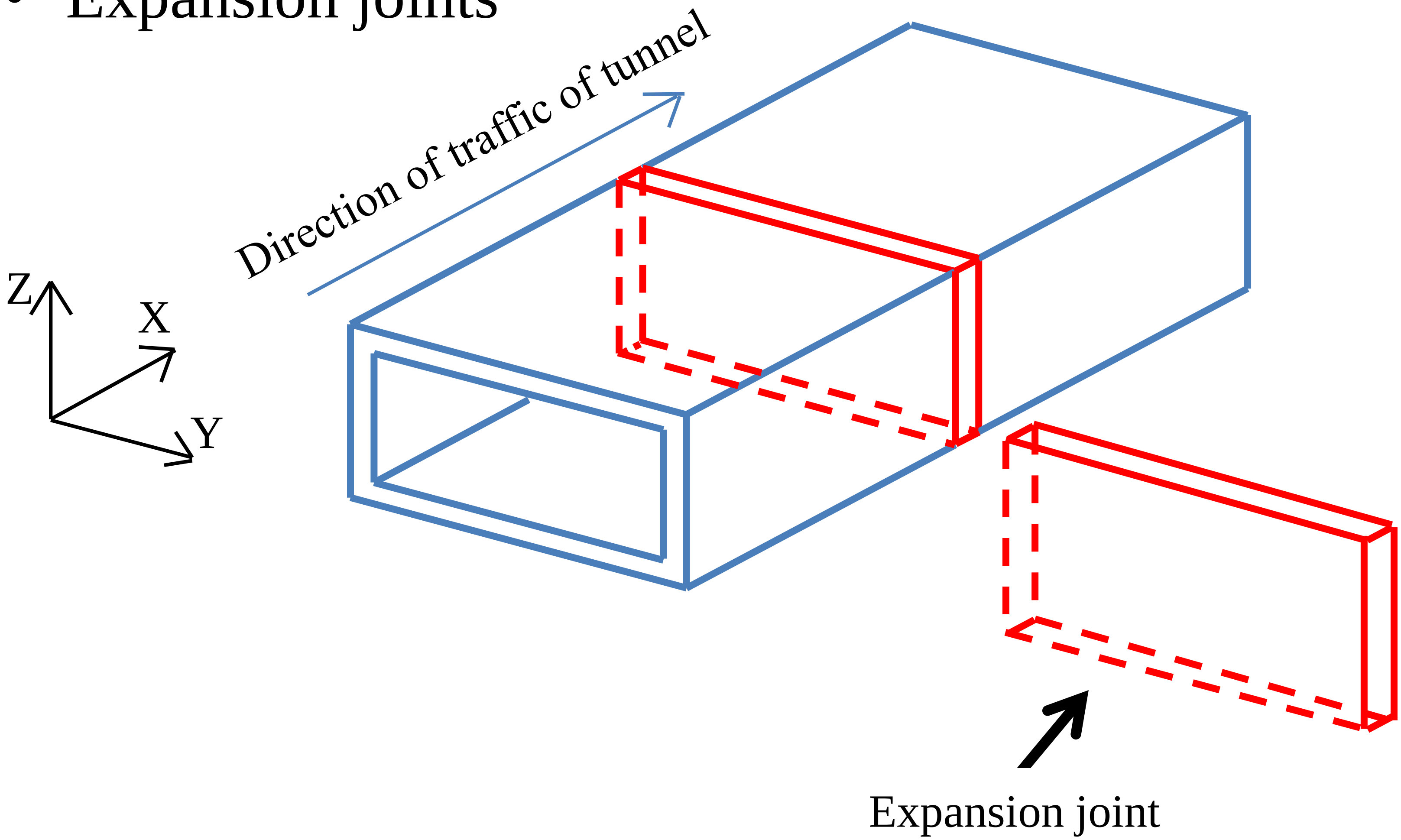
Introduction

- Expansion joints



Introduction

- For tunnels in cold regions, groundwater seepage can lead to the formation of ice.

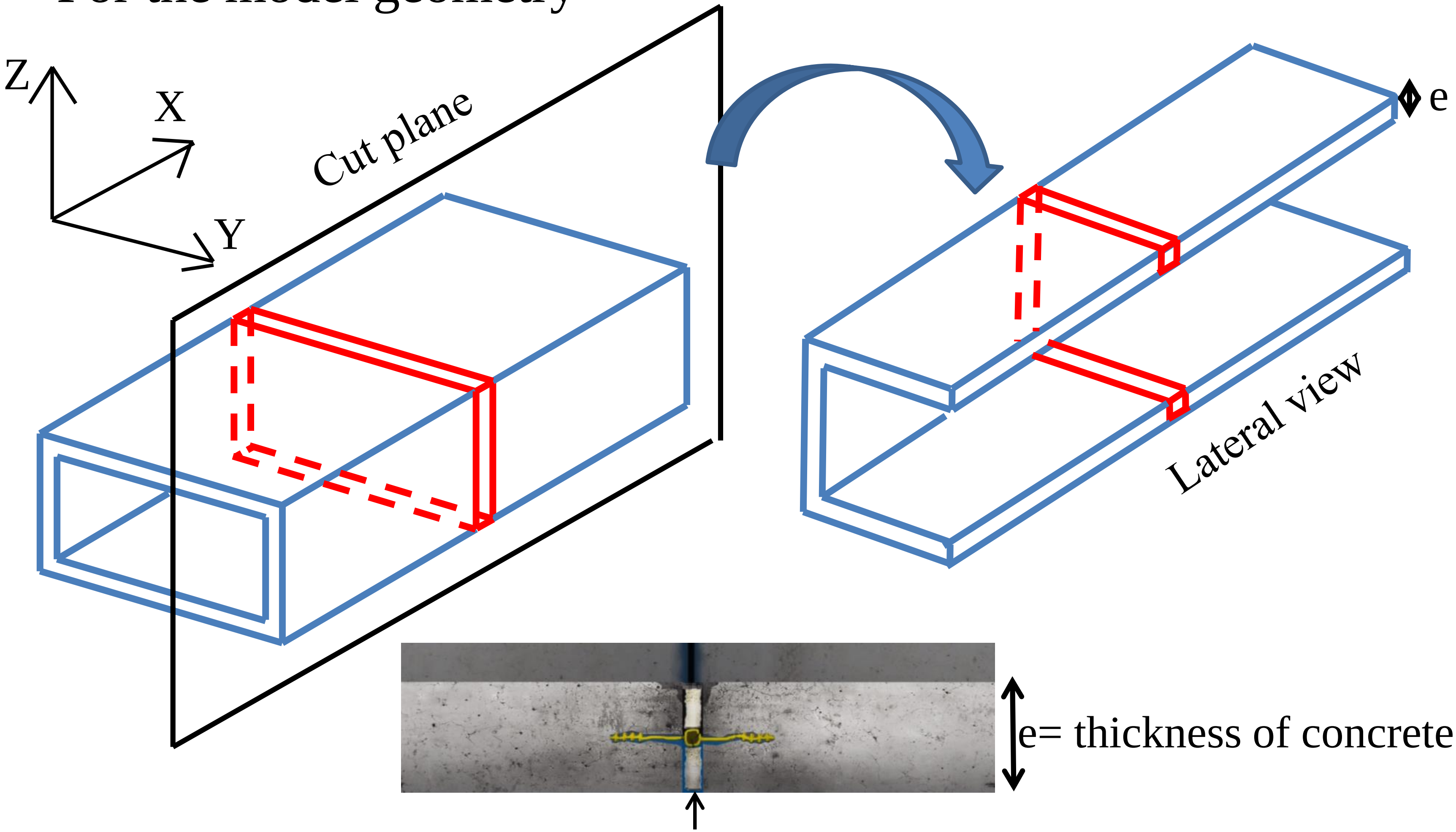
Pack of ice coming from a joint and spreading onto the walkway

Ice stalactites and ice patches on the ground

- To develop a numerical model at the joint scale to simulate the coupled phenomena that control seepage and the formation of ice, namely heat transfer, water flow and phases change.

Simplified model of expansion joints

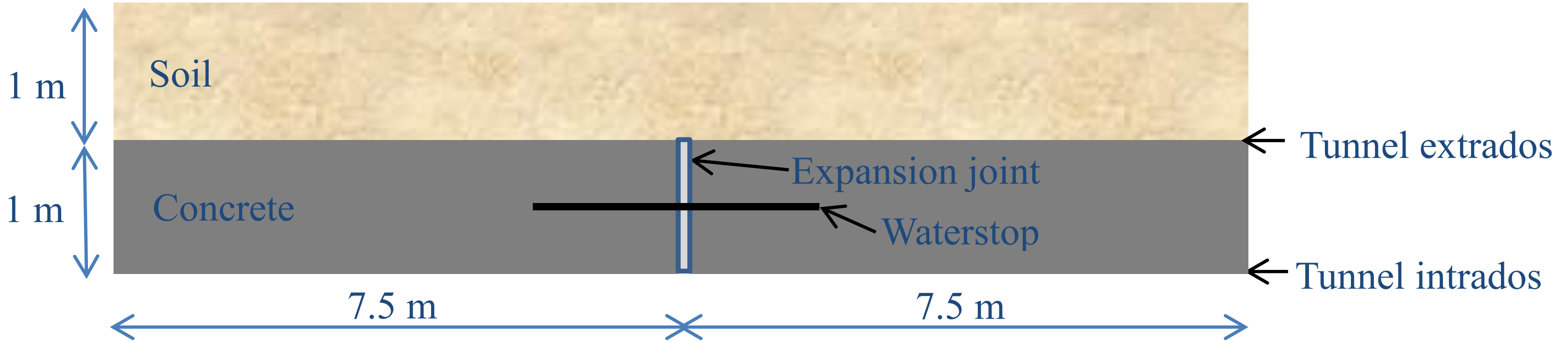
- For the model geometry



Expansion joint in expanded polystyrene + waterstop in the concrete

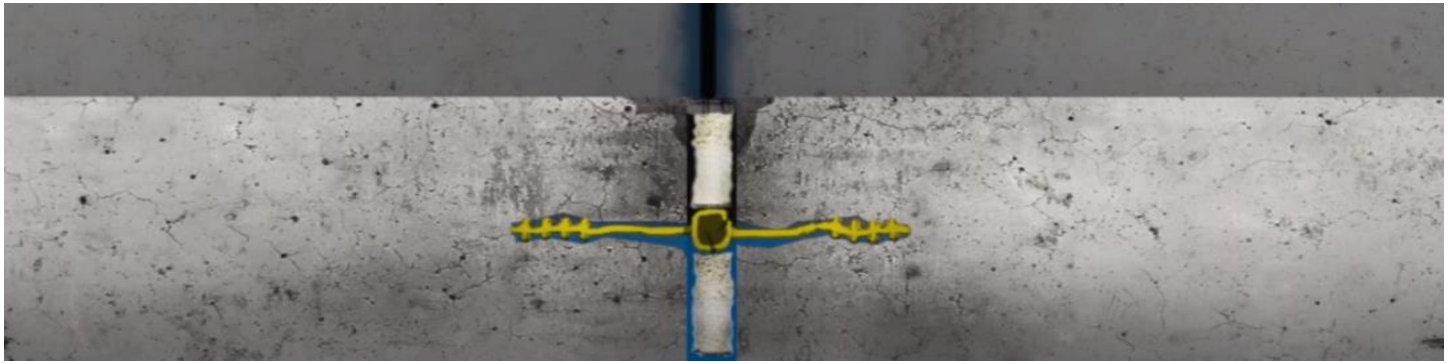
Simplified model of expansion joints

- For the numerical model



Simplified model of expansion joints for the numerical model

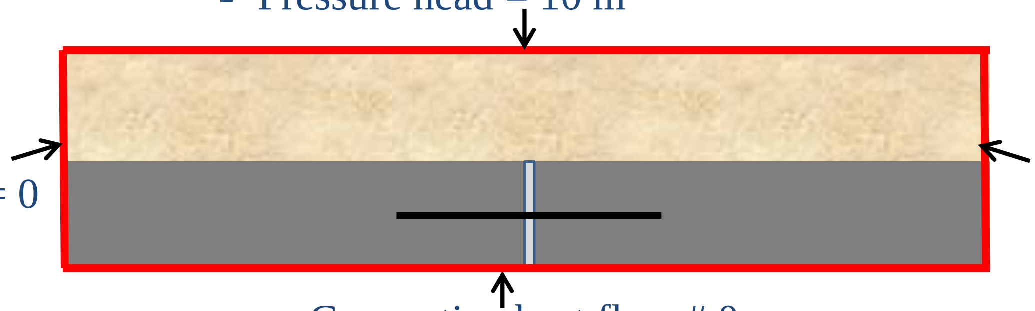
- This model corresponds to a cross section of the concrete tunnel lining at the key of the vault.



Boundaries conditions for the joint model

- Groundwater temperature (T= 10°C);
- Pressure head = 10 m

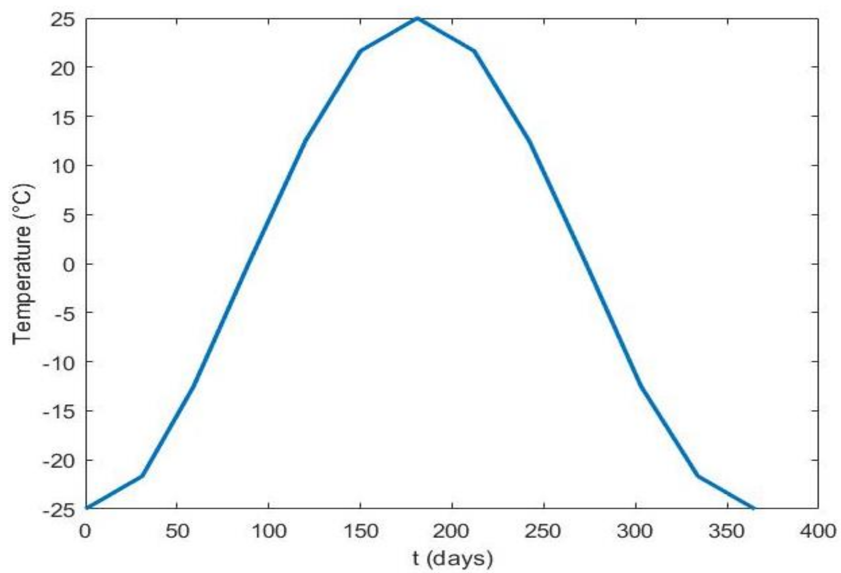
Flow = 0 ;
Temperature = 0



Flow = 0 ;
Temperature = 0

- Convective heat flow # 0;
- Pressure head = 0

Boundary conditions for the joint model



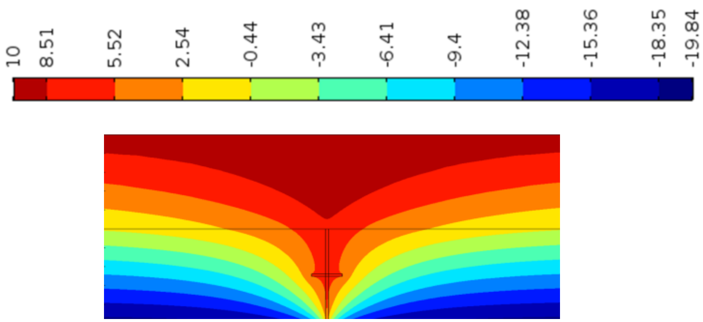
Air temperature as a function of time

Equations of the model and implementation in COMSOL

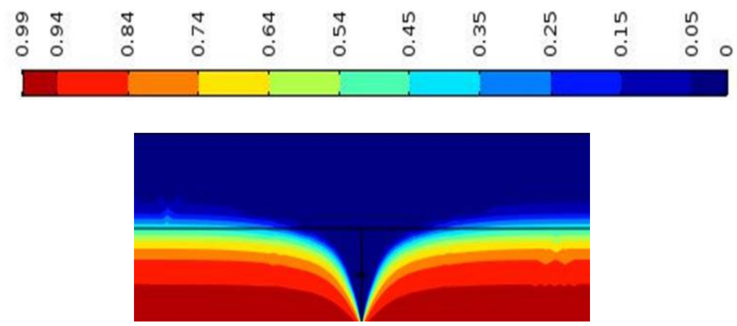
- Two equations govern this model
  - Heat conduction equation deduced from energy conservation in freezing porous media
  - Continuity equation
- Those equations are implemented in COMSOL in using the coefficient form PDEs interface

Results

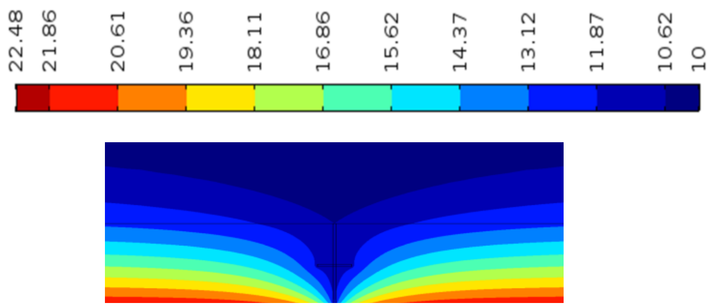
- Permeable joint



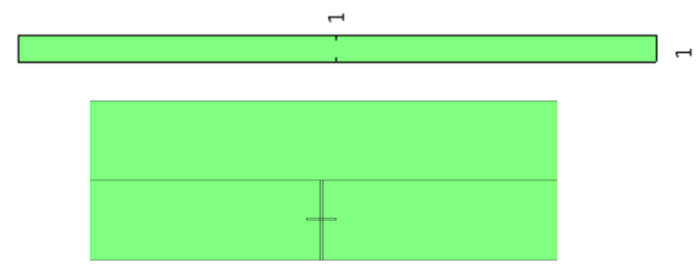
Isotherms in °C at t=31 days (January)



Ice saturation $(1 - w_u)$ at t= 31 days (January)



Isotherms in °C at t=181 days (July)

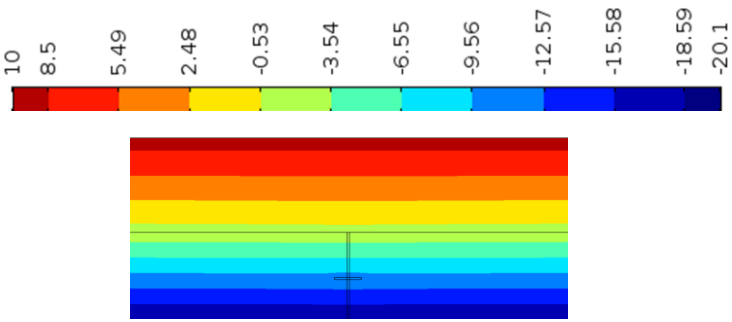


Water saturation (w_u) at t= 181 days (July)

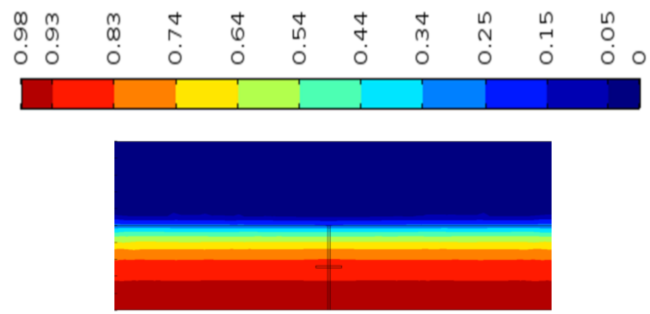
- The isotherms obtained in summer and winter have the shape of a drawdown cone with a water temperature inside the tunnel at the joint of 3 °C in winter and 10 °C in summer
- In winter, the ice saturation shows that the soil and the joint are saturated with water contrary to the concrete which is frozen (impermeable to water) during winter

Results

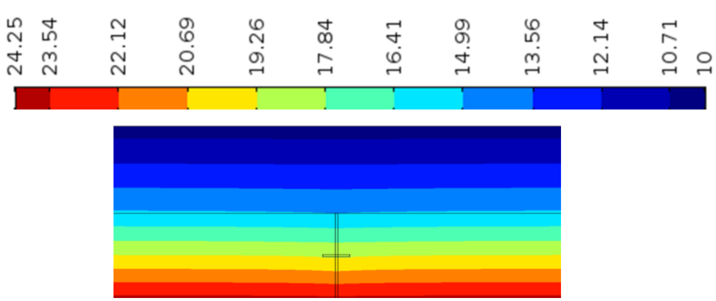
- Impermeable joint



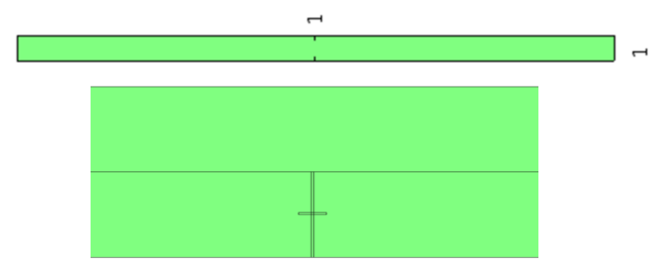
Isotherms in °C at t=31 days (January)



Ice saturation $(1 - w_u)$ at t=31 days (January)



Isotherms in °C at t=181 days (July)



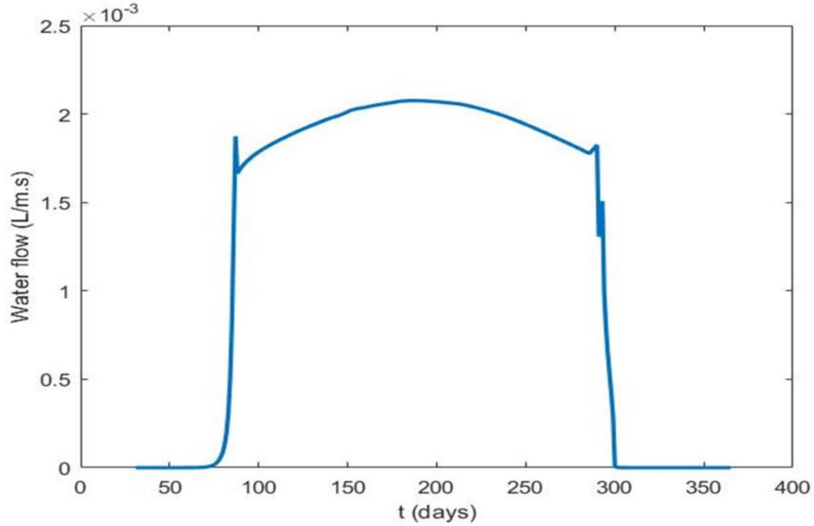
Water saturation (w_u) at t= 181 days (July)

- During winter, the isotherms are parallel to the tunnel axis with a temperature inside tunnel at the joint of -20 °C. In summer, this temperature is equal to 24 °C
- The ice saturation shows frozen materials (impermeable to water) during winter, whereas liquid water is present during summer

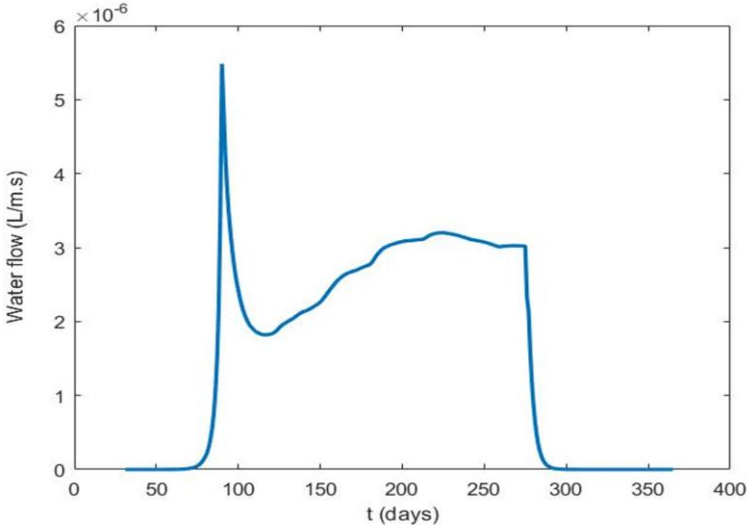
Results

- Water flow inside the tunnel through the expansion joints

$$Q = \left(\frac{k\ k_r(T)\ \rho_l\ g\ A}{\mu(T)}\right) \nabla H$$



Low-permeability joint

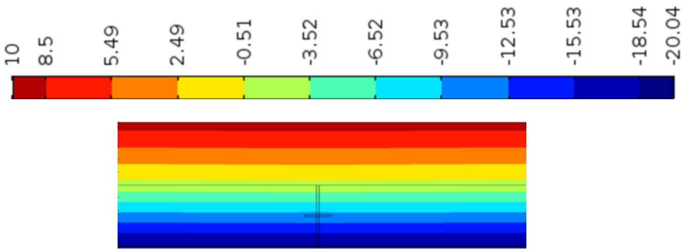


Impermeable joint

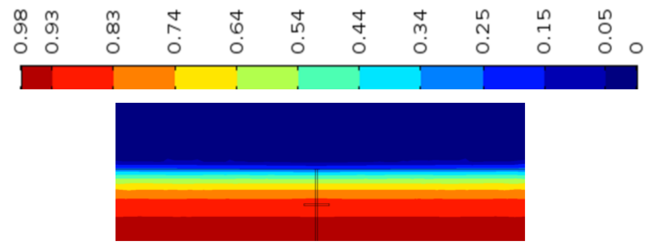
- For both joints (low-permeability joint and impermeable joint), the water flow in winter is equal to zero because of the presence of ice (impermeable to water) but in summer the flow rate increases.
- On the other hand, we observe two sudden changes corresponding to the ice to water phase change at t=89 days (April) and the opposite phase change (water to ice) at t=273 days (October) for both joints

Example of solution

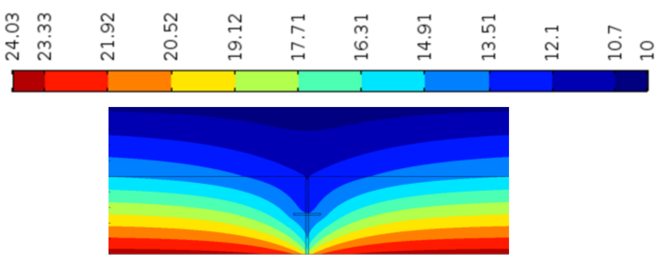
- The model has been used to validate different solutions meant to decrease water infiltration through permeable joints
  - A decrease in water pressure at the extrados applied through controlled drainage is used as an example herein



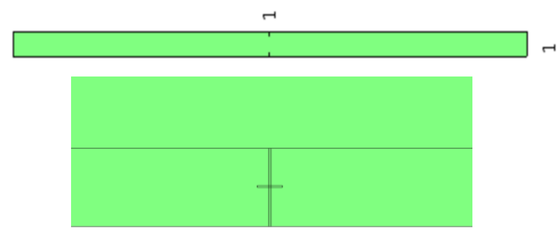
Isotherms in °C at t= 31 days (January)



Ice Saturation $(1 - w_u)$ at t= 31 days (January)



Isotherms in °C at t= 181 days (July)



Water Saturation (w_u) at t= 181 days (July)

  - In winter, the isotherms are parallel to the tunnel axis and the whole joint is frozen (impermeable to water)
  - In summer, the joint is not frozen and the water temperature has the shape of a drawdown cone with a value of 15 °C inside the tunnel at the joint

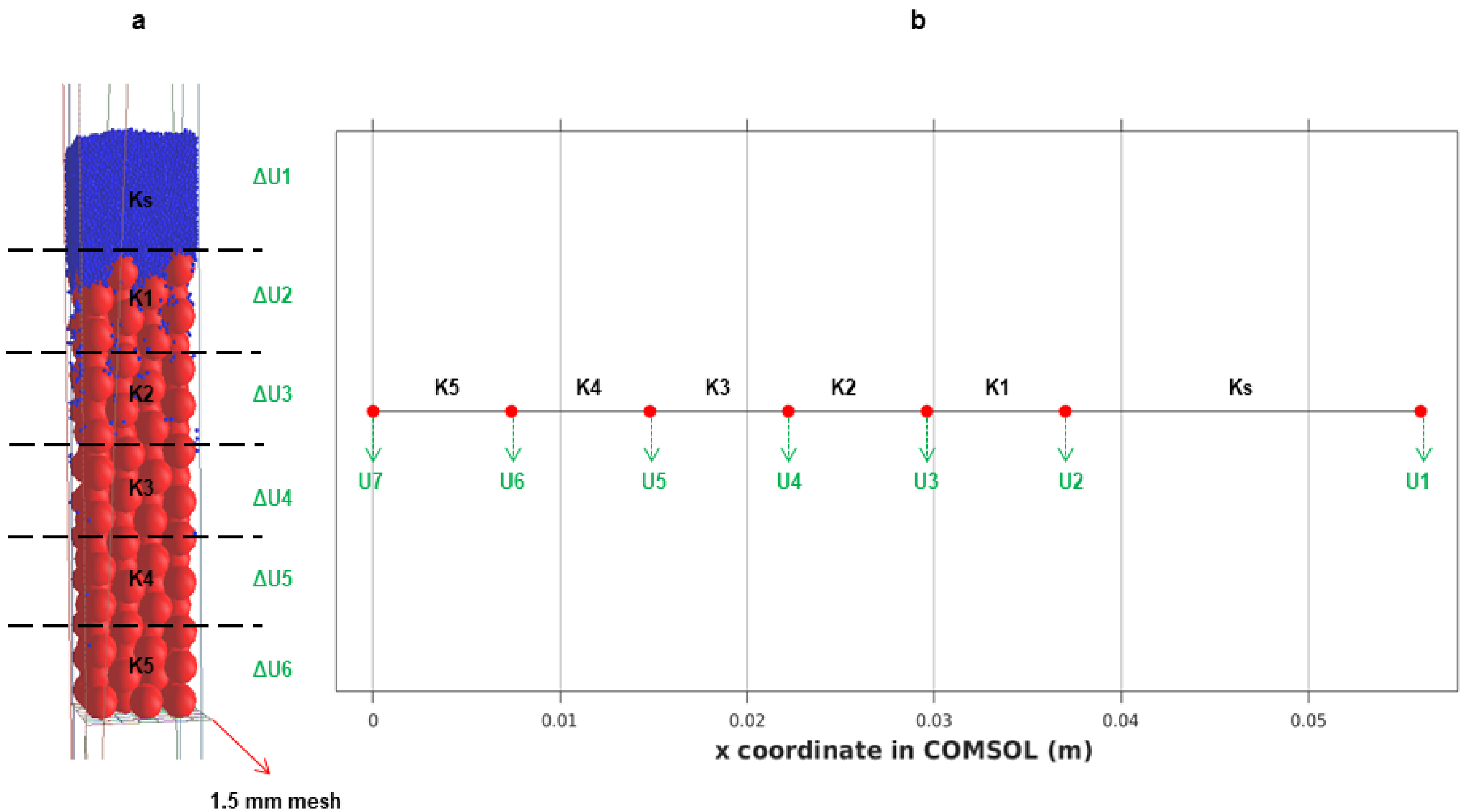
Conclusion

- Under proper boundary conditions, these equations allow the flow rate and the temperature and pressure fields around each type of joint (permeable, low-permeability, impermeable) to be evaluated for the summer and winter periods

- Our results show that the permeable joint is not frozen in winter (saturated with water) unlike the low-permeability and impermeable joints which are frozen (impermeable to water)

- The evaluation of the flow rate as a function of the permeability of the joint has allowed the time corresponding to the ice/water and water/ice phase change at the expansion joint to be determined
  - t= 89 days (April) and t= 273 days (October) for both types of joints (low-permeability and impermeable)

- The simulated solution approach has shown that the reduction of the pressure head allows the permeable joint to freeze in winter, similarly to the low-permeability and impermeable joints



Pirnia, P., Duhaime, F., Ethier, Y., Dubé, J.-S., 2018. ICY: an interface between COMSOL Multiphysics and YADE. *Computers & Geosciences*.

Thanks you for your attention

Properties	Symbols	Numerical values				Units
		Soil	Concrete	Joint	Waterstop	
Porosity	n	0.065	0.01	0.9	0.01	
Solid matrix density	ρ_s	2600	2300	11.5	7850	kg/m^3
Water density	ρ_l	1000				kg/m^3
Ice density	ρ_i	917				kg/m^3
Specific heat capacity of the solid matrix	c_s	851	880	1450	475	J/kg.K
Specific heat capacity of water	c_l	4180				J/kg.K
Specific heat capacity of ice	c_i	2100				J/kg.K
Thermal conductivity of the solid matrix	λ_s	2.9	1.8	0.05	44.5	W/m.K
Thermal conductivity of water	λ_l	0.59				W/m.K
Thermal conductivity of ice	λ_c	1.7				W/m.K
Intrinsic permeability	k	1.49×10^{-13}	1.84×10^{-19}	Variable	10^{-9}	m^2
Heat exchange coefficient (air)	h	20				$W/m^2.°C$