Multiphysics coupling induced by artificial ground freezing in a granular material

Francesca Casini, Antonio Gens, Giulia Viggiani, Sebastia Olivella

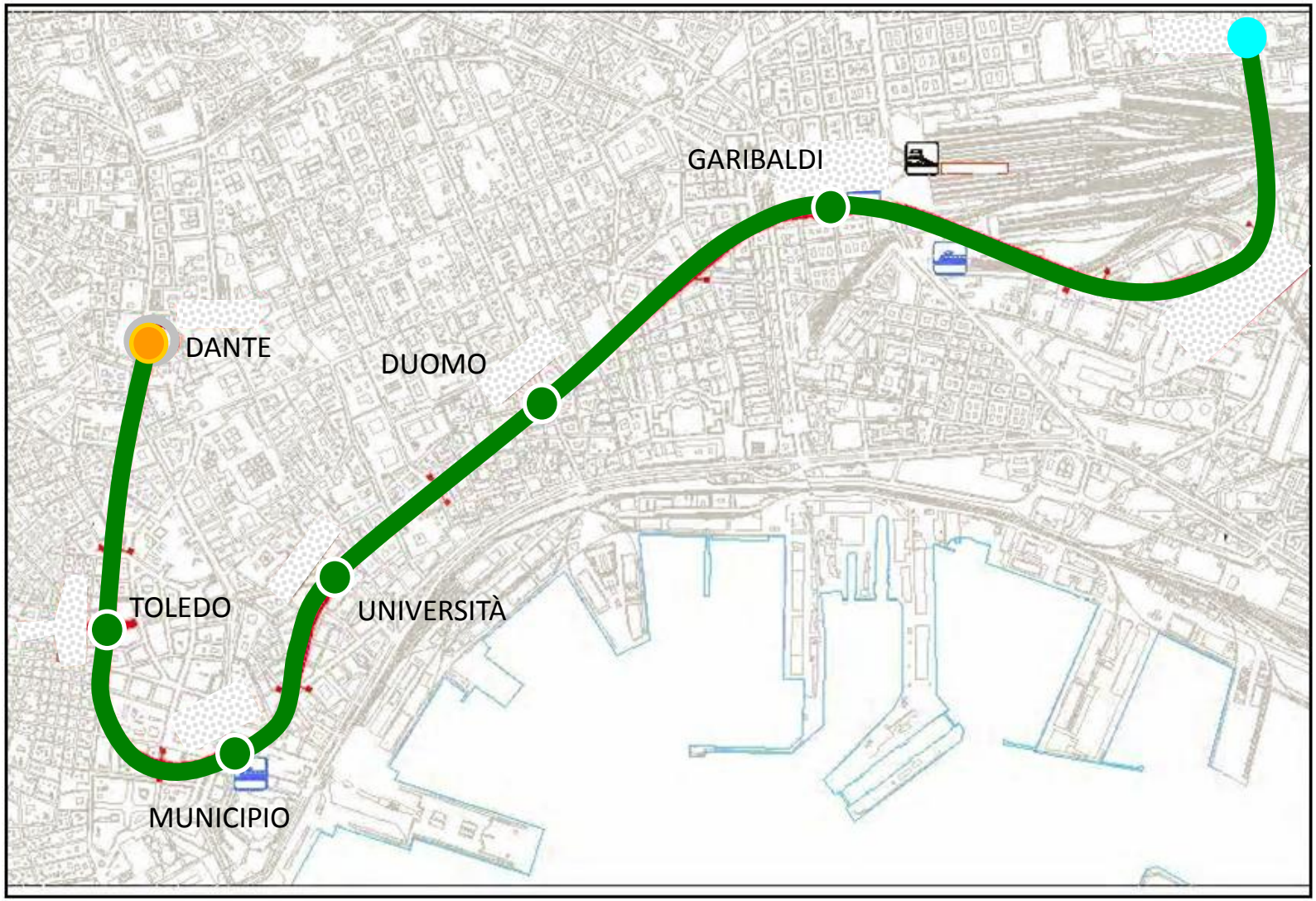
UNIVERSITA' DEGLI STUDI DI ROMA TorVergata

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Departament d'Enginyeria del Terreny, Cartogràfica i Geofísica

- Enrique Romero (UPC – Barcelona)
- Ronny Pelaez (UPC – Barcelona)

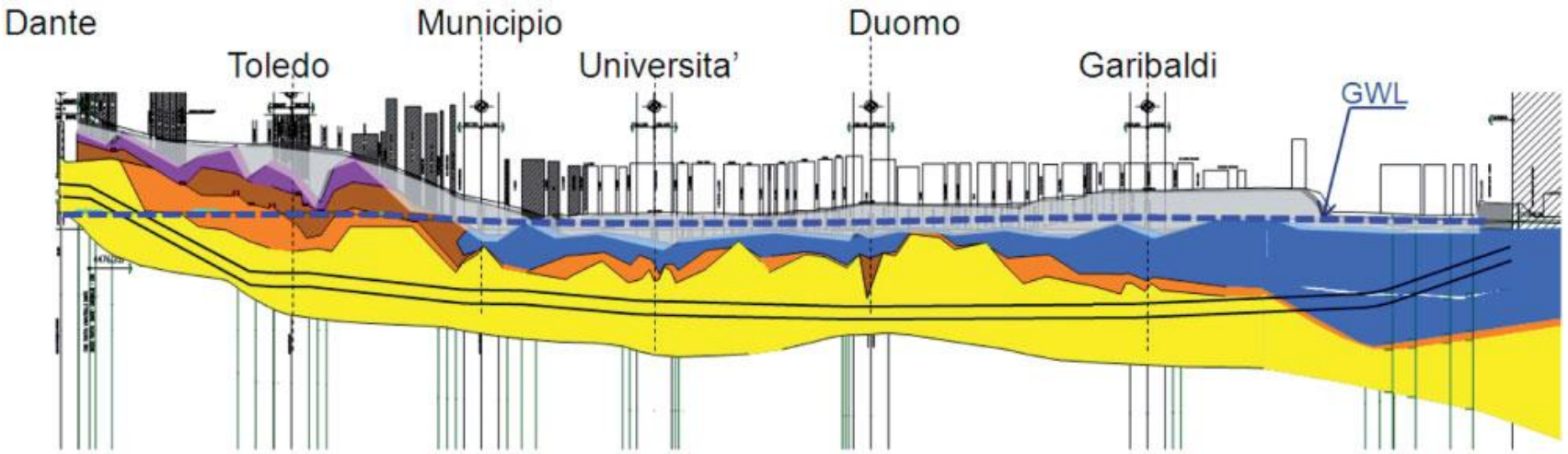
- Alessandro Mandolini (UNISUN-Napoli)
- Studio Cavuoto (Napoli)
- Tecno-In SpA (Napoli)

LINE 1 - TRATTA BASSA



Viggiani et al. (2009)

Geotechnical interest: line 1 of Napoli Underground



made ground
Neapolitan pyroclastic pile
altered pozzolane
marine and palustrine deposits
pozzolane
neapolitan yellow tuff

III Phlegrean Phase
II Phlegrean Phase

cohesionless granular deposits

Viggiani et al. (2009)

LINE 1 – TRATTA BASSA

station tunnels

- fractured soft rock (yellow tuff)
- below the water table

inclined access tunnels

- granular soil (pozzolana)
- below the water table

construction techniques

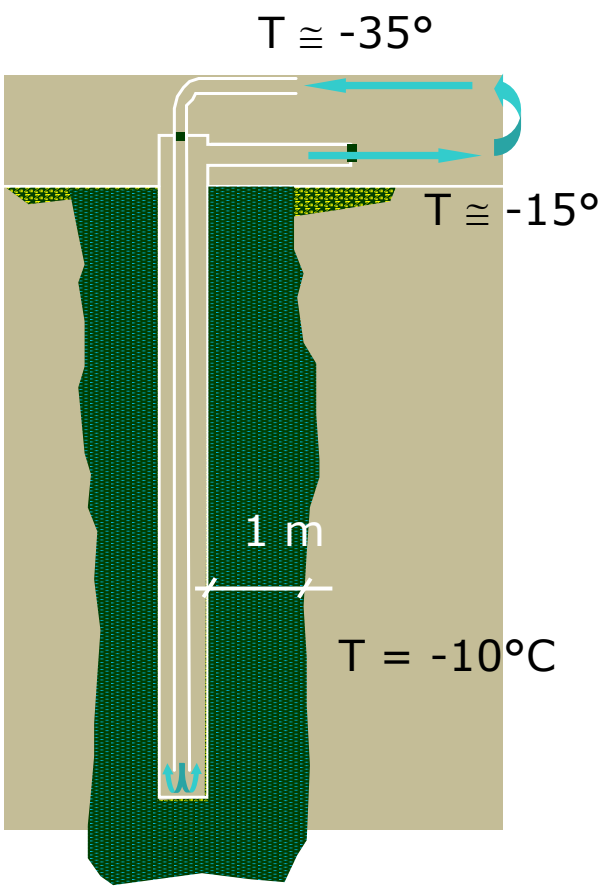
- Artificial Ground Freezing

- static
  (inclined tunnels only)
- water tightness
  (inclined and station tunnels)

Geotechnical interest

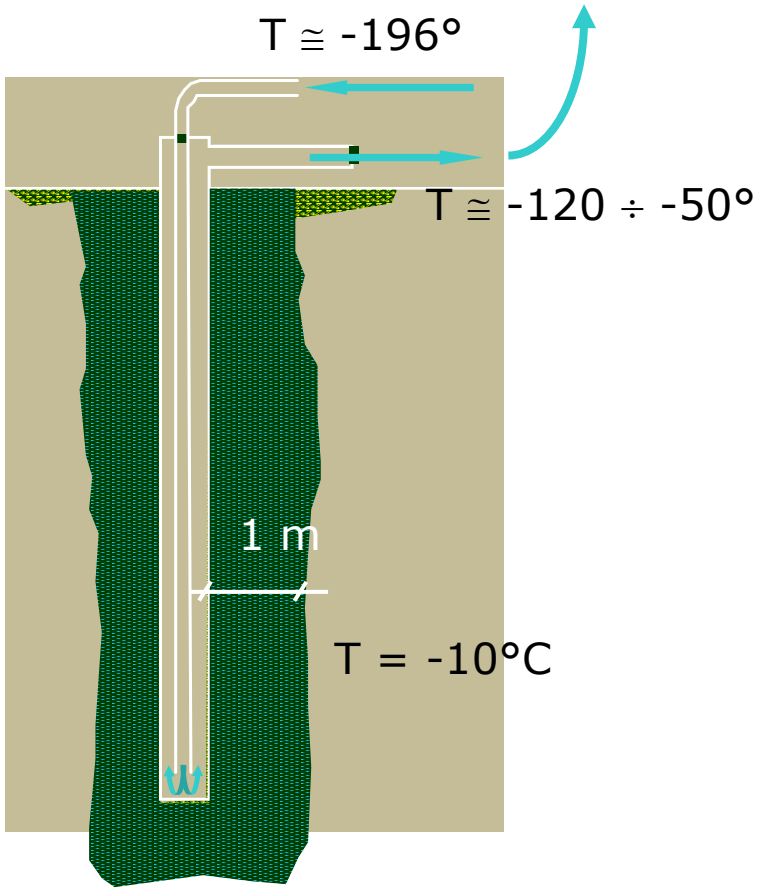
ARTIFICIAL GROUND FREEZING

brine



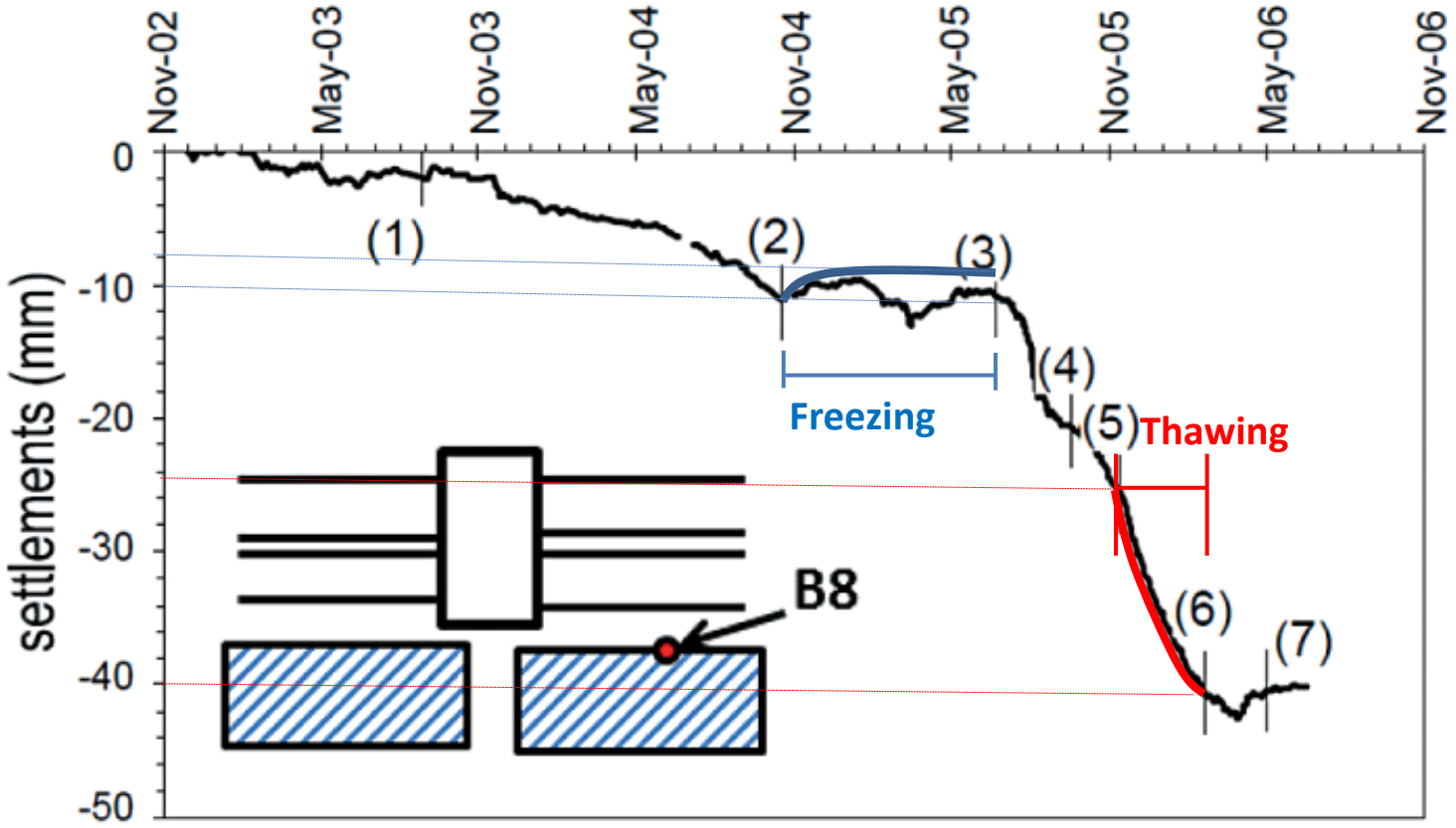
average rate 50-100 kWh/m^3
For soil with 30% water content

nitrogen



average rate 1000-1300 lt/m^3
For soil with 30% water content

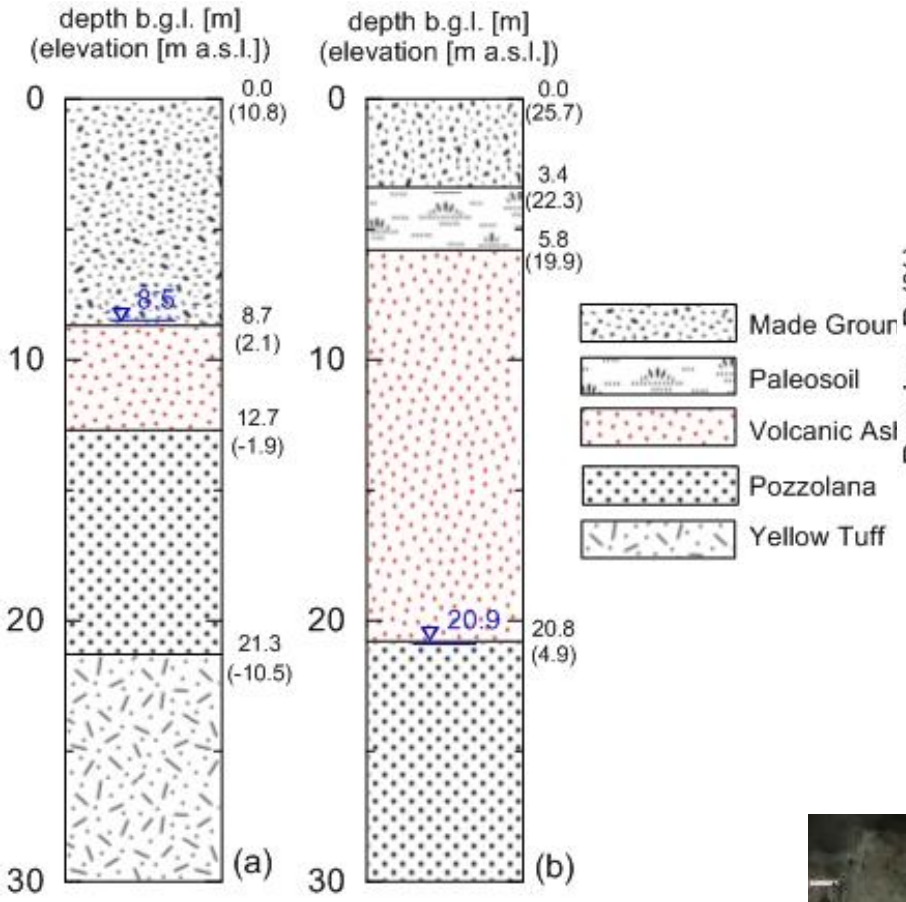
Analysis of displacement during freezing and thawing



Settlements of reference point B8. **(1)** to **(2)**: installation of anchors; **(2)** to **(3)**: ground freezing; **(4)**: excavation of platform tunnel; **(5)**: permanent lining; **(5)** a **(6)**: thawing; **(7)**: underpinning.

Russo et al. (2012)

Typical soil profiles



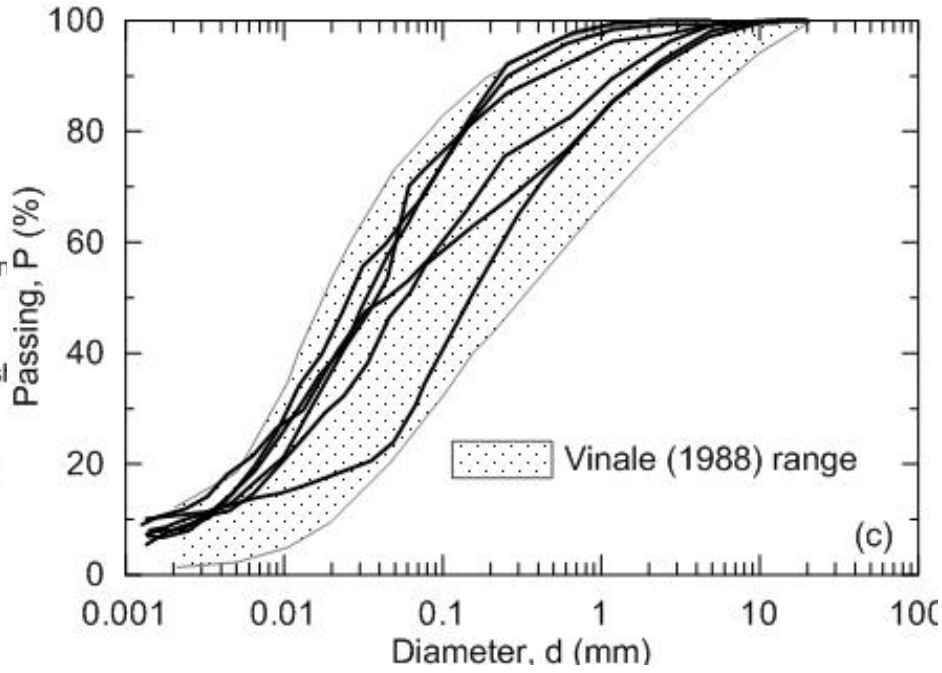
Piazza Municipio

Toledo

Casini et al 2014

Permeability $k=10^{-5}$-10^{-6} m/s

In situ void ratio e=0.9-1.4



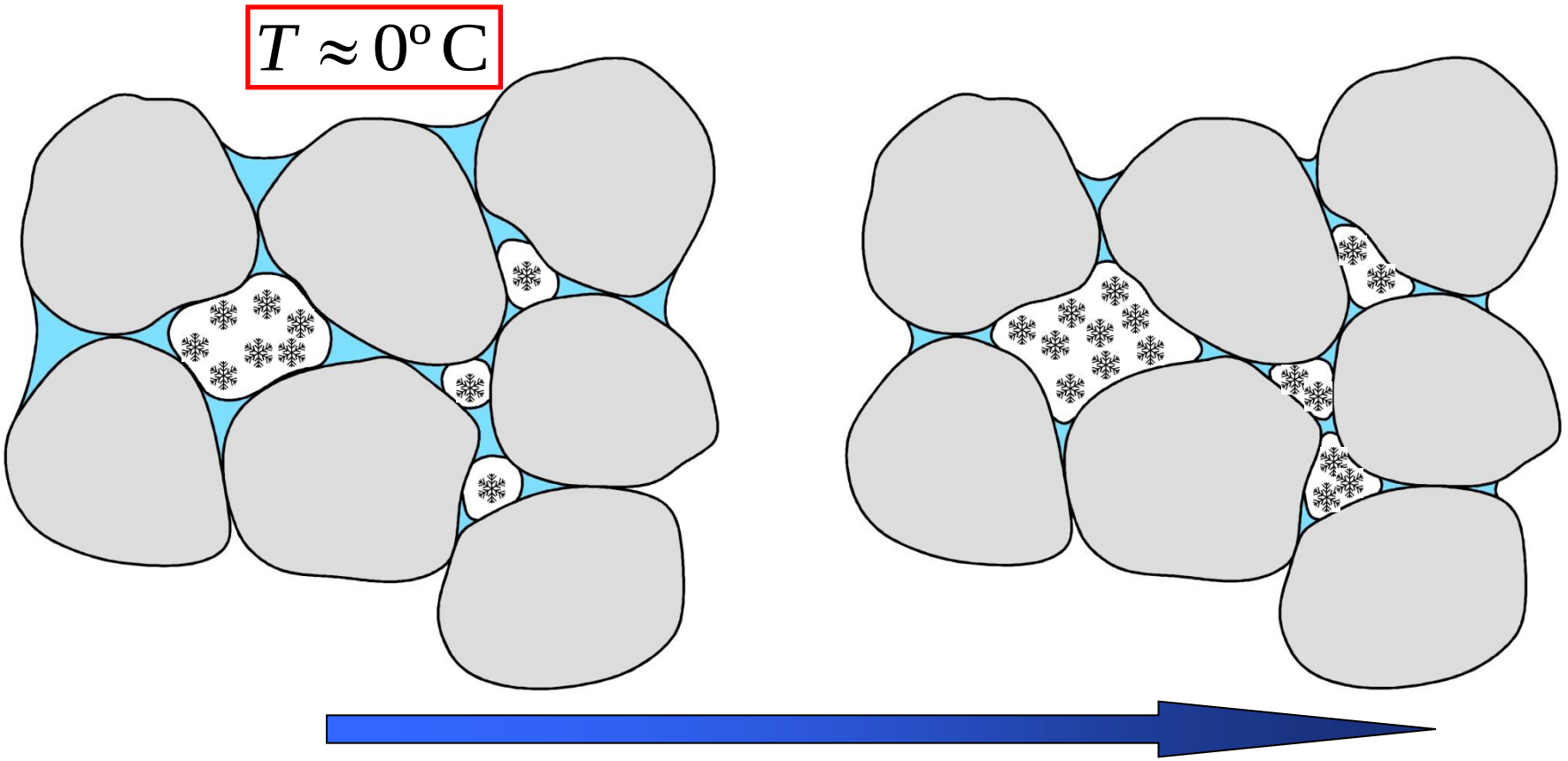
Pozzolana

Pelaez et al 2014

Yellow Tuff

Thermal effects: low temperature

Development of soil freezing



- Interface between liquid and ice
- Suction develops in the liquid water

after Gens (2010)

Thermal effects: low temperature

- Assuming thermodynamical equilibrium in the freezing soil
  - Equal chemical potential in the two phases (unequal pressures)

$$-(s_l - s_i)dT + v_l dp_l - v_i dp_i = 0 \quad v_l = \frac{M}{\rho_l} \quad v_i = \frac{M}{\rho_i}$$

$$\boxed{p_i - \frac{\rho_i}{\rho_l} p_l = -\frac{L}{T_f}(T - T_f)}$$

$L = (s_l - s_i)T$ Latent heat: 333.7 kJ/kg

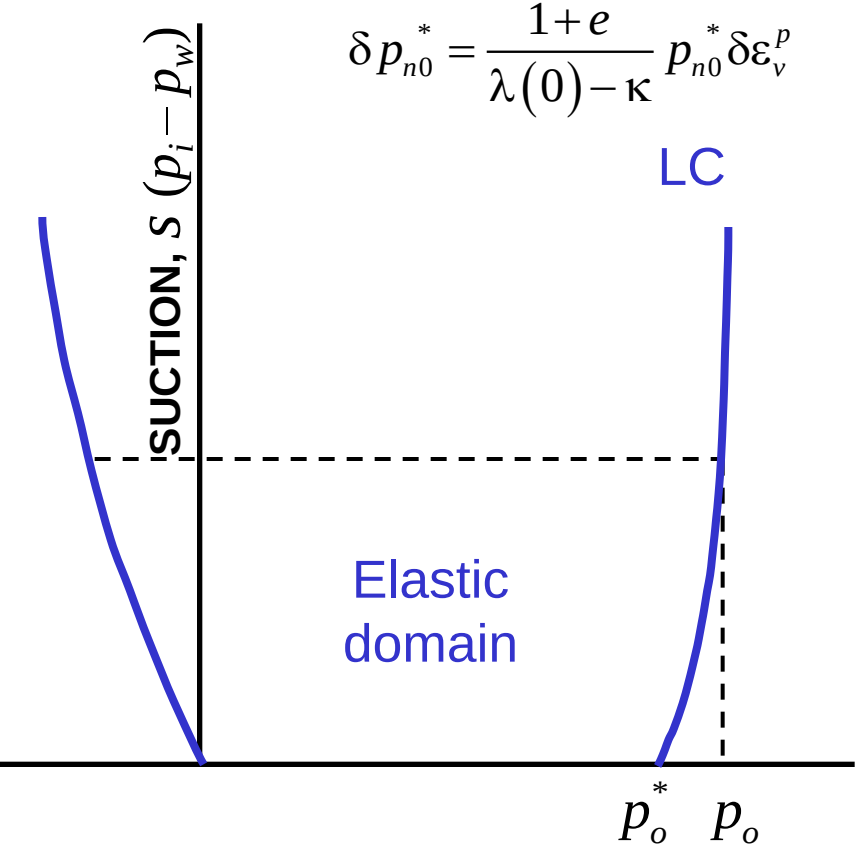
Clasius-Clapeyron-Poynting equation

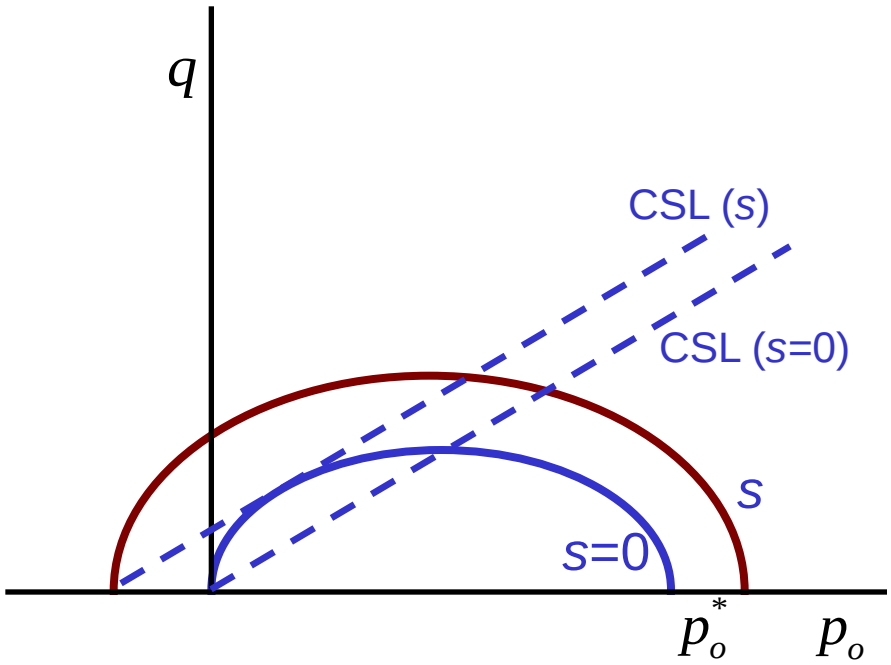
Thermal effects: low temperature

- Mechanical model : adaptation of BBM

$$F = \left\{ p_n - \left(\frac{p_{n0} - ks}{2} \right) \right\}^2 + \frac{q^2}{M^2} - \left(\frac{p_{n0} + ks)}{2} \right)^2 \qquad p_{n0} = \left(\frac{p_{n0}^*}{p^c} \right)^{\frac{\lambda(0)-\kappa}{\lambda-\kappa}}$$

$$\delta p_{n0}^* = \frac{1+e}{\lambda(0)-\kappa} p_{n0}^* \delta\varepsilon_v^p \qquad \lambda = \lambda(0)\{(1-r)\exp(-\beta s) + r\}$$

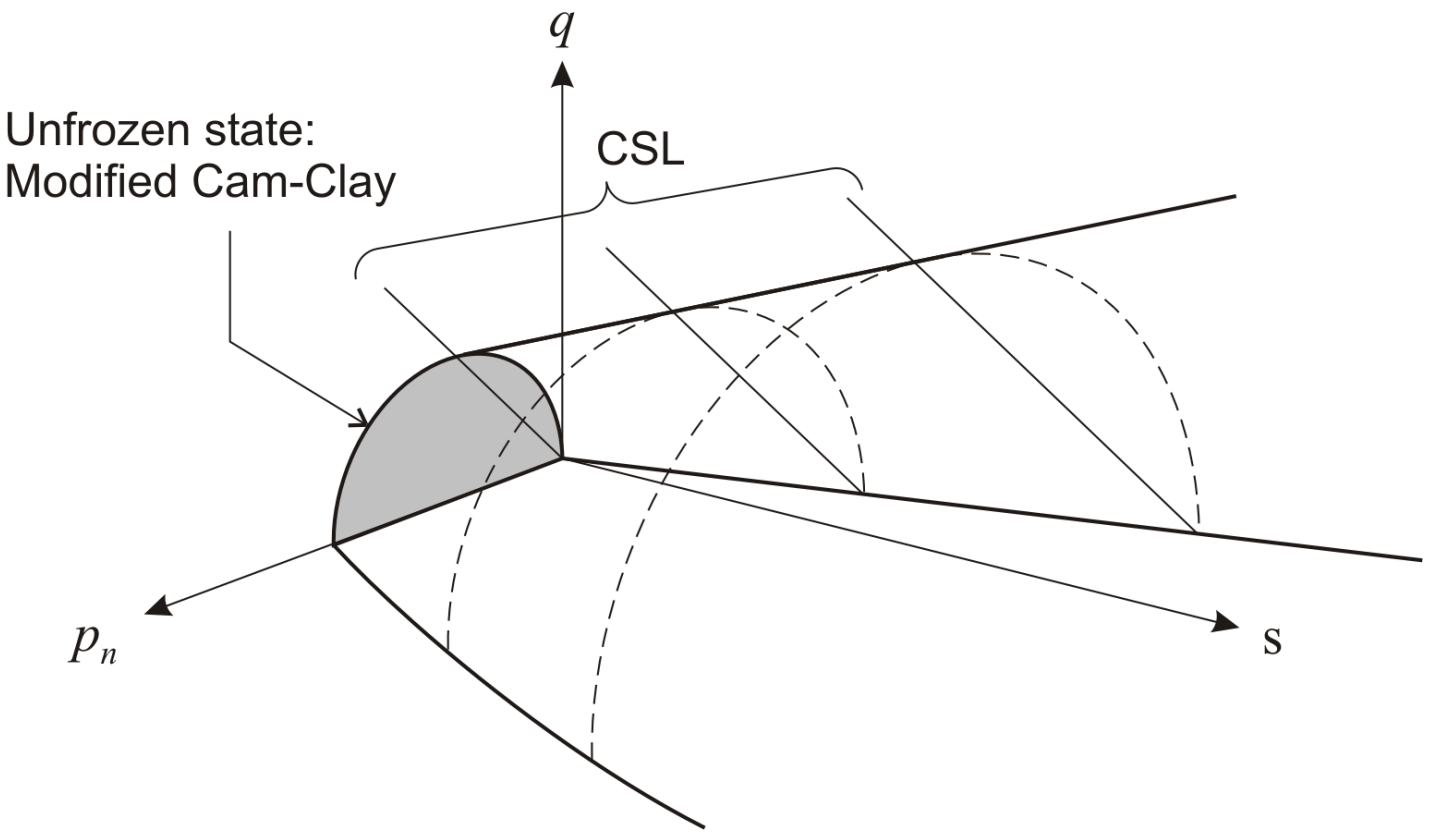




after Nishimura *et al* 2009

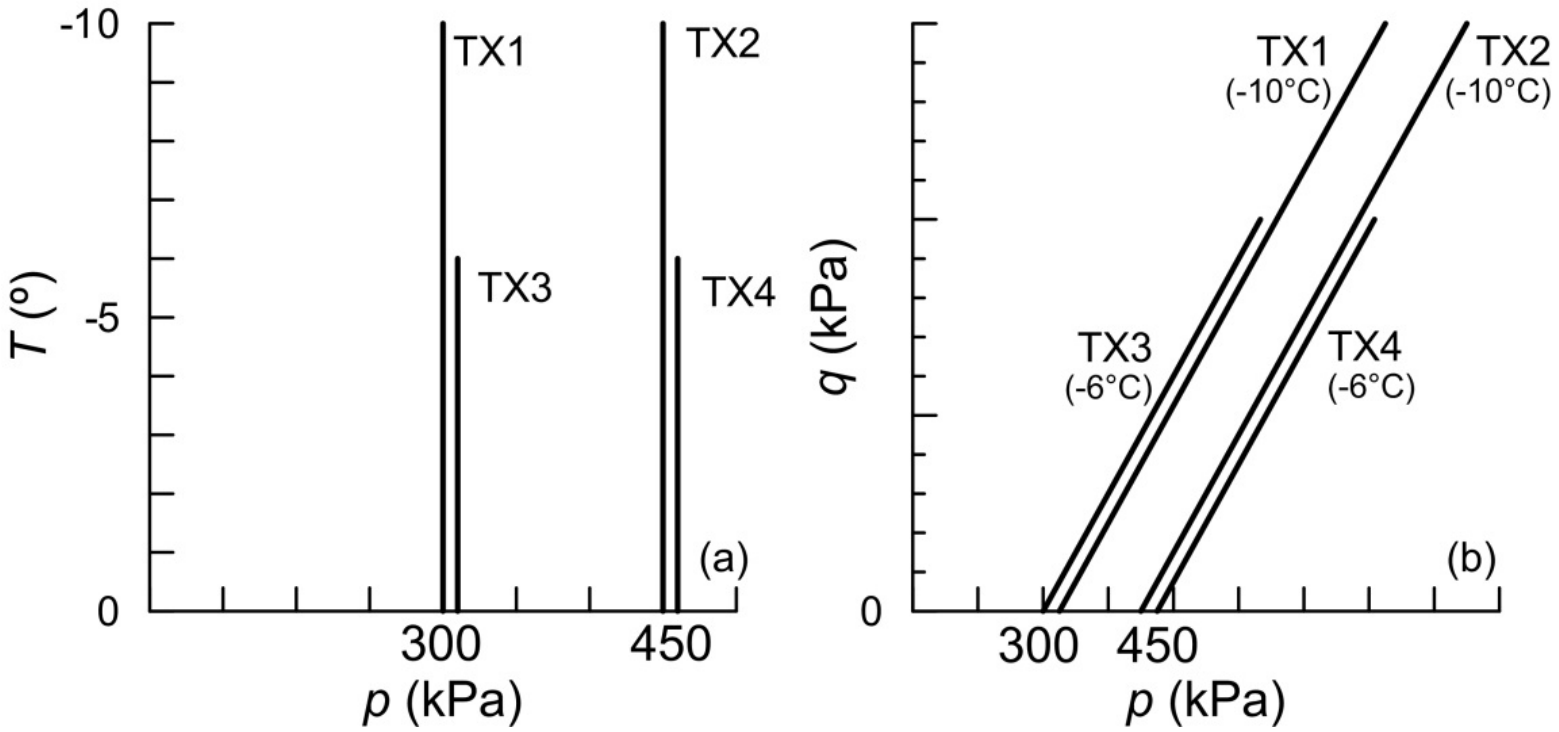
Thermal effects: low temperature

- Elastoplastic model

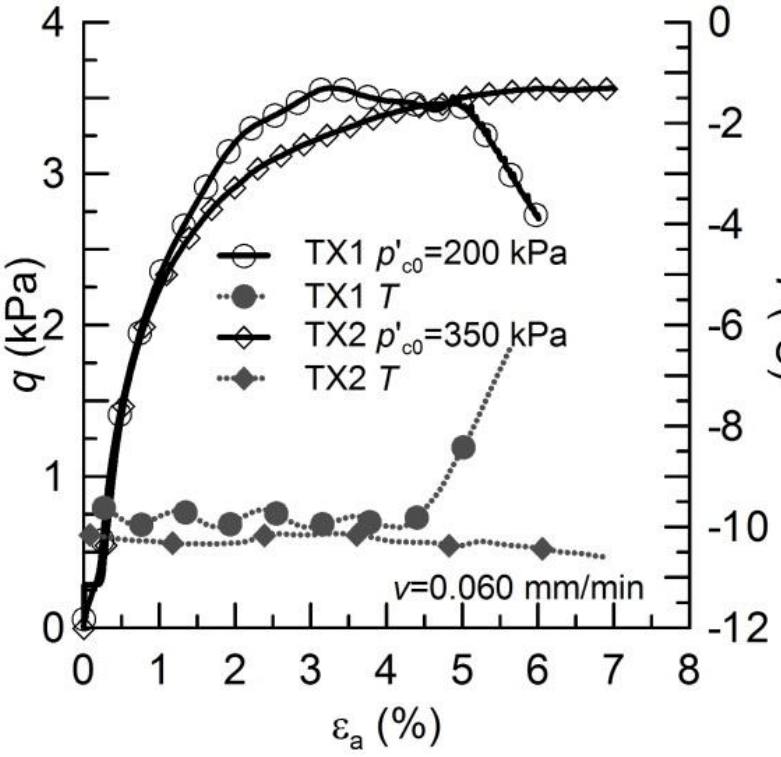


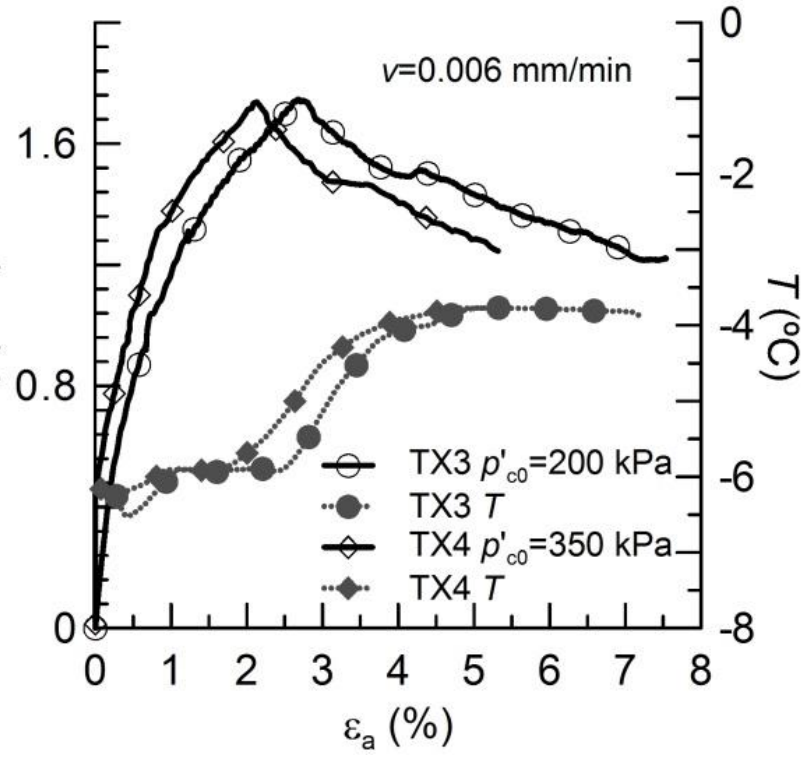
after Nishimura *et al* 2009

Laboratory results: Pozzolana

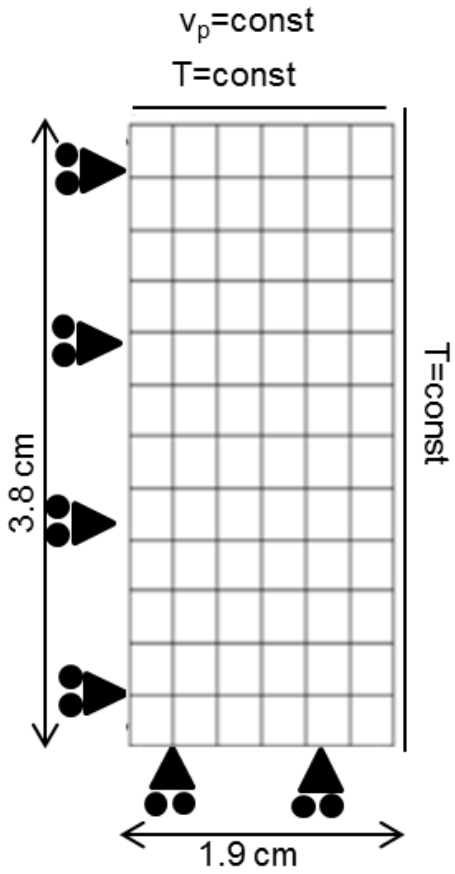


Laboratory results: Pozzolana

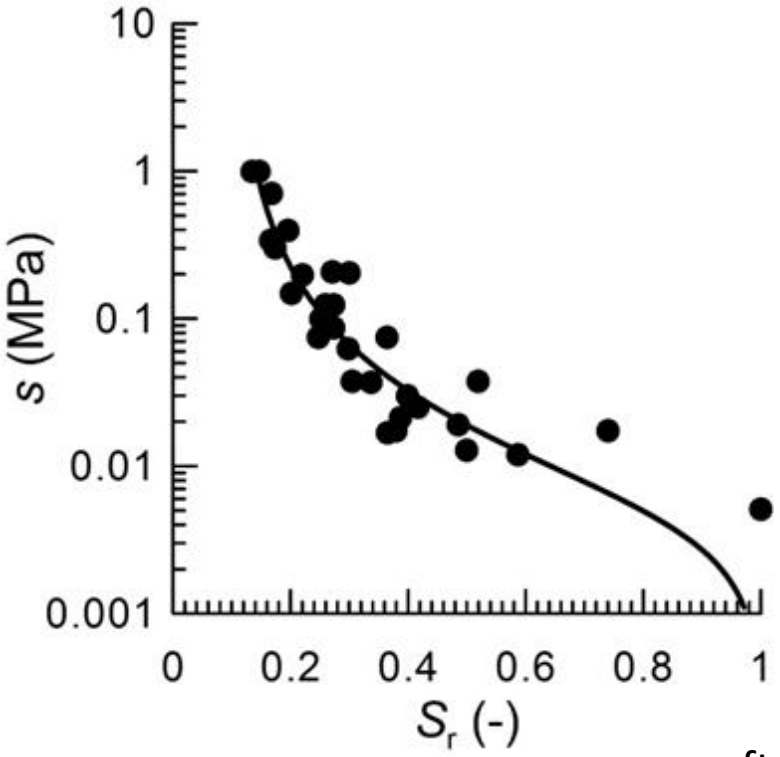




Modelling: geometry, mesh and boundary condition



Modelling: calibration



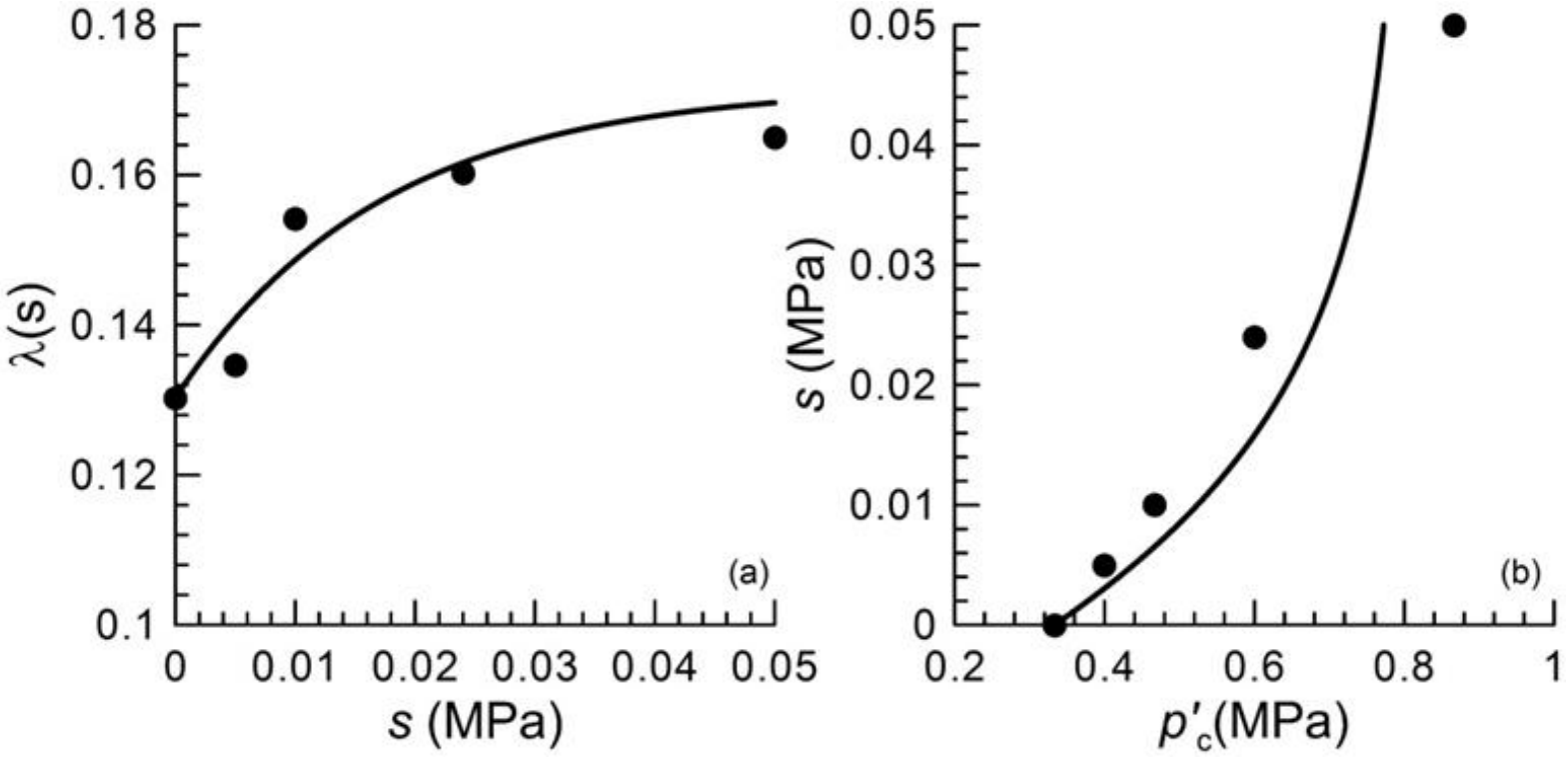
after Nicotera (1998)

Parameters for Freezing Retention Model FRM

P_a (kPa)	m	K_{sat} (m/s)	P (kPa)
5	0.366	10^{-6}	10

$$P = P_a \cdot \sigma_{li} / \sigma_{la}$$

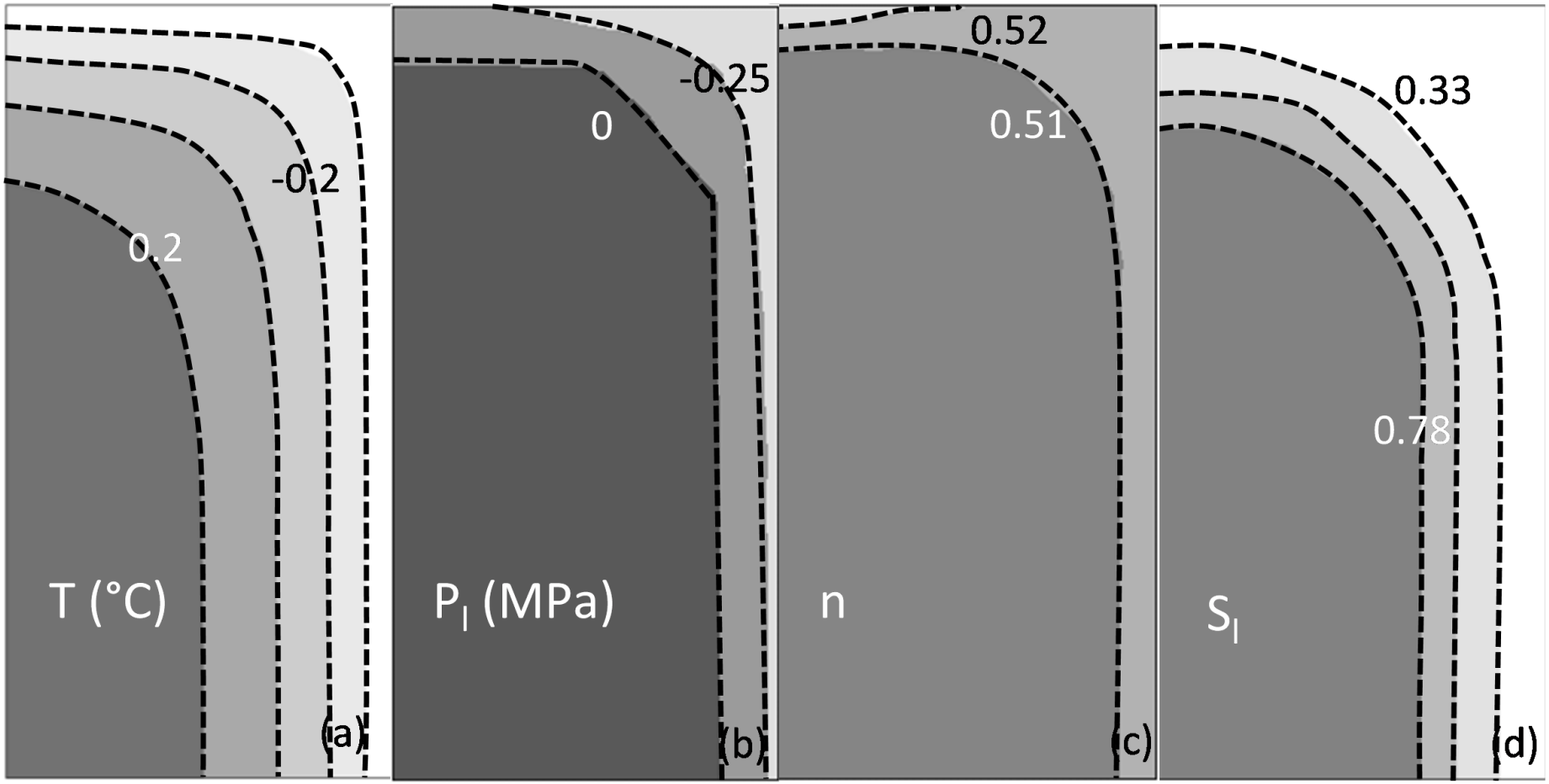
Modelling: calibration



Parameters for Barcelona Freezing Model BFM

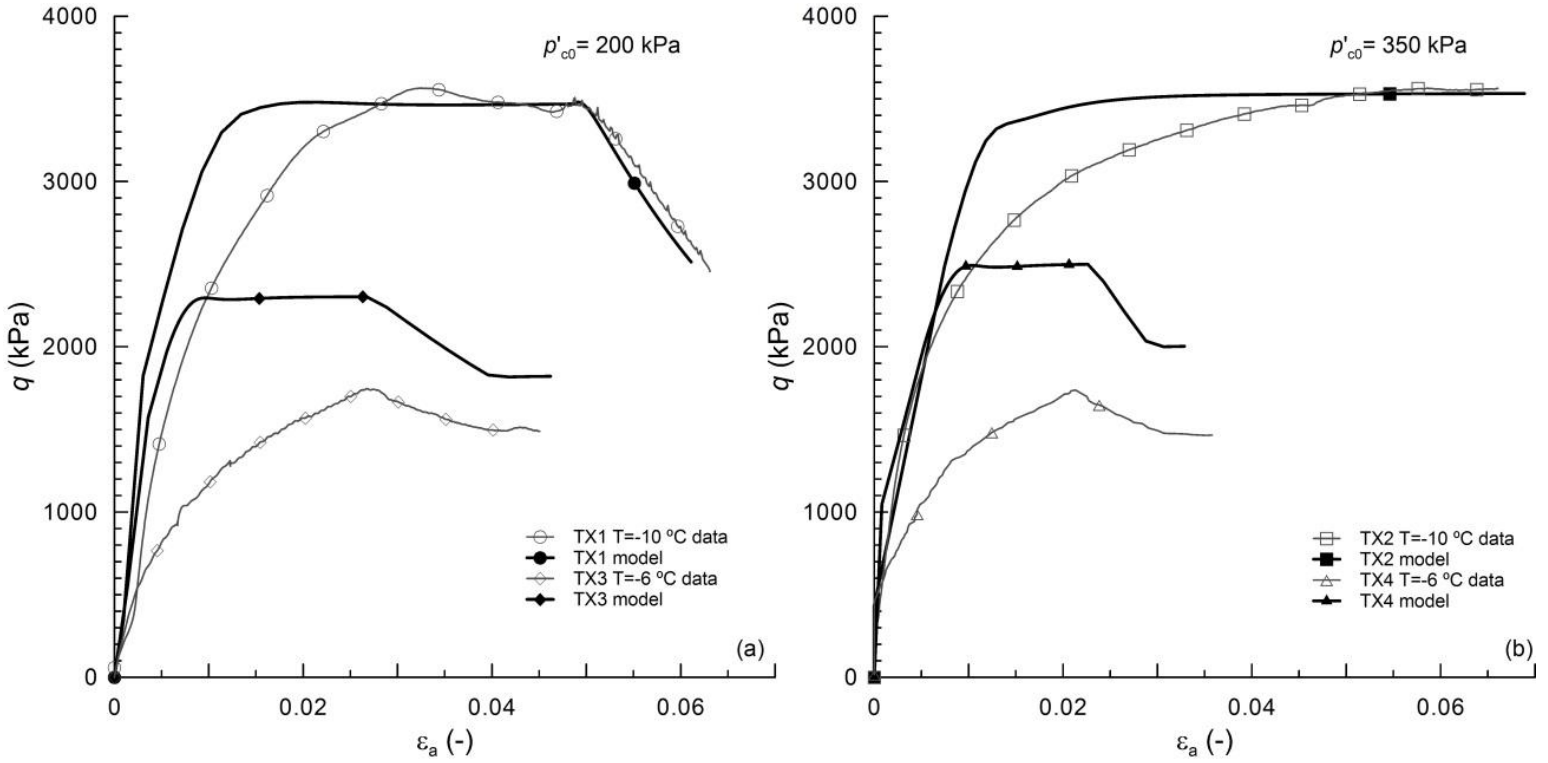
N	δ	κ	$\lambda(0)$	r	β	p^c (MPa)	k	M	G (MPa)
3	0	0.02	0.13	1.3	58	10	1.2	1.3	40

Numerical simulation: freezing stage

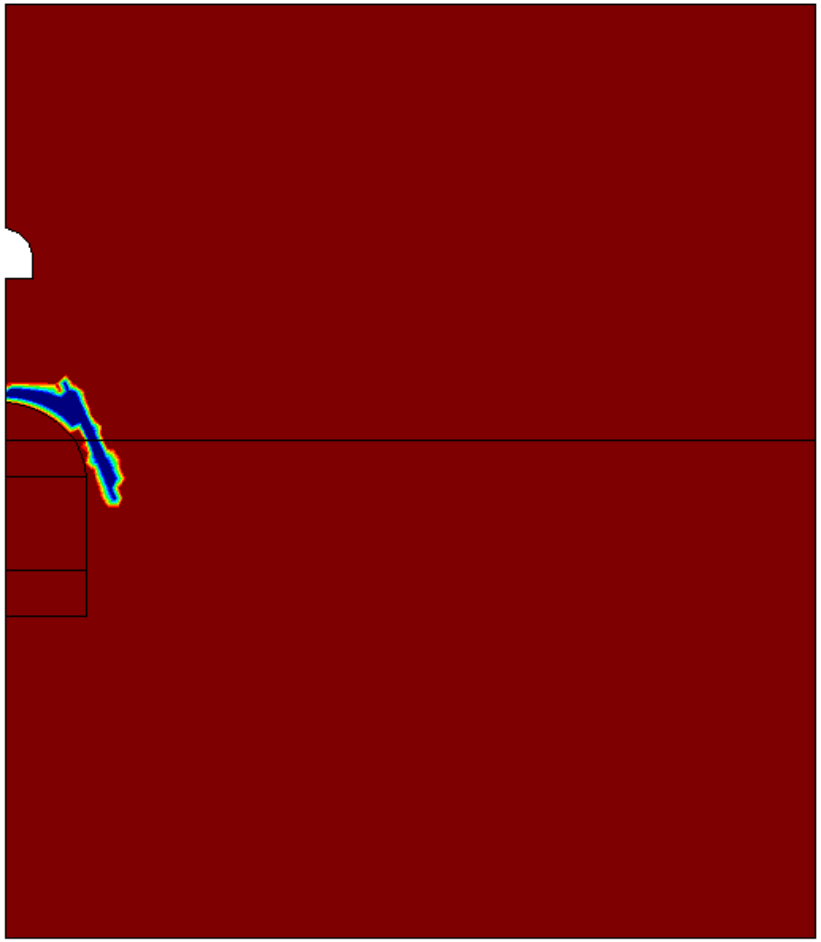


Numerical simulation: axial loading phase

Comparison experimental results vs model prediction

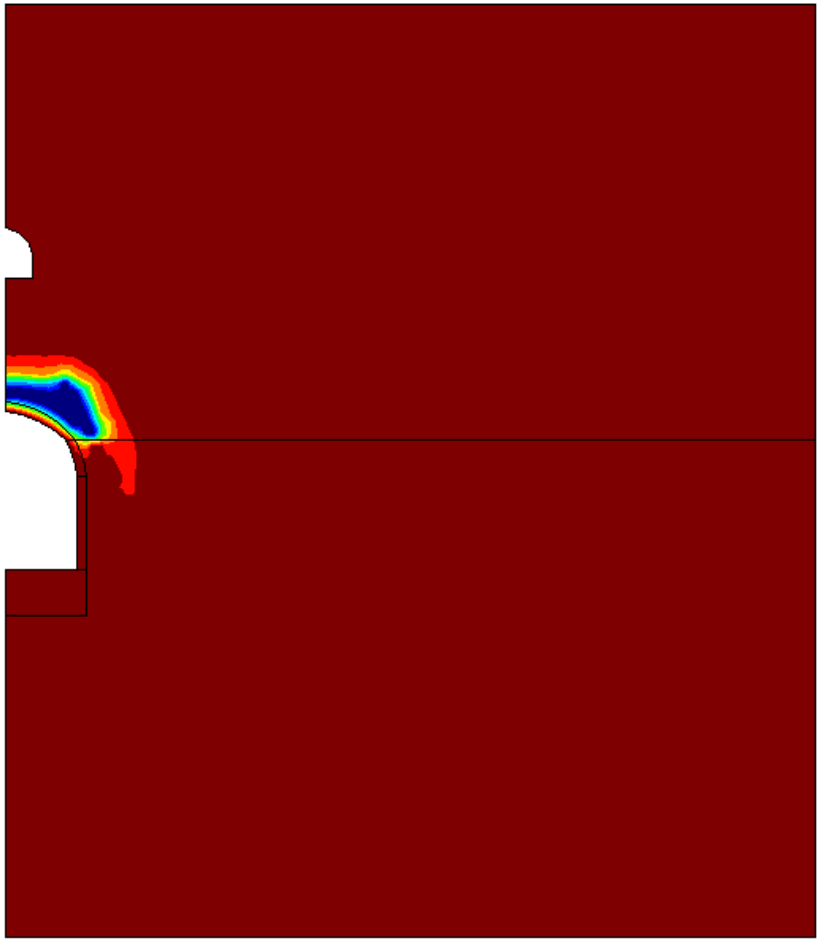


Toledo station: temperature prediction

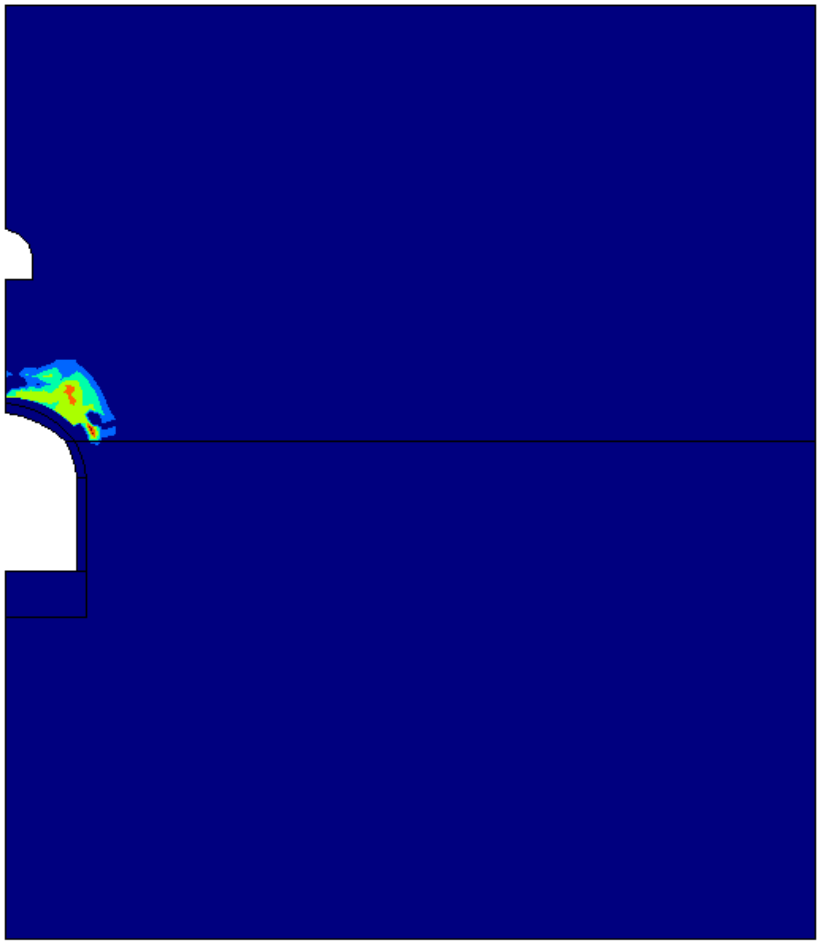


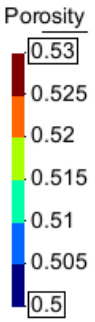
step 10
Contour Fill of Temperature.

Toledo station: temperature prediction



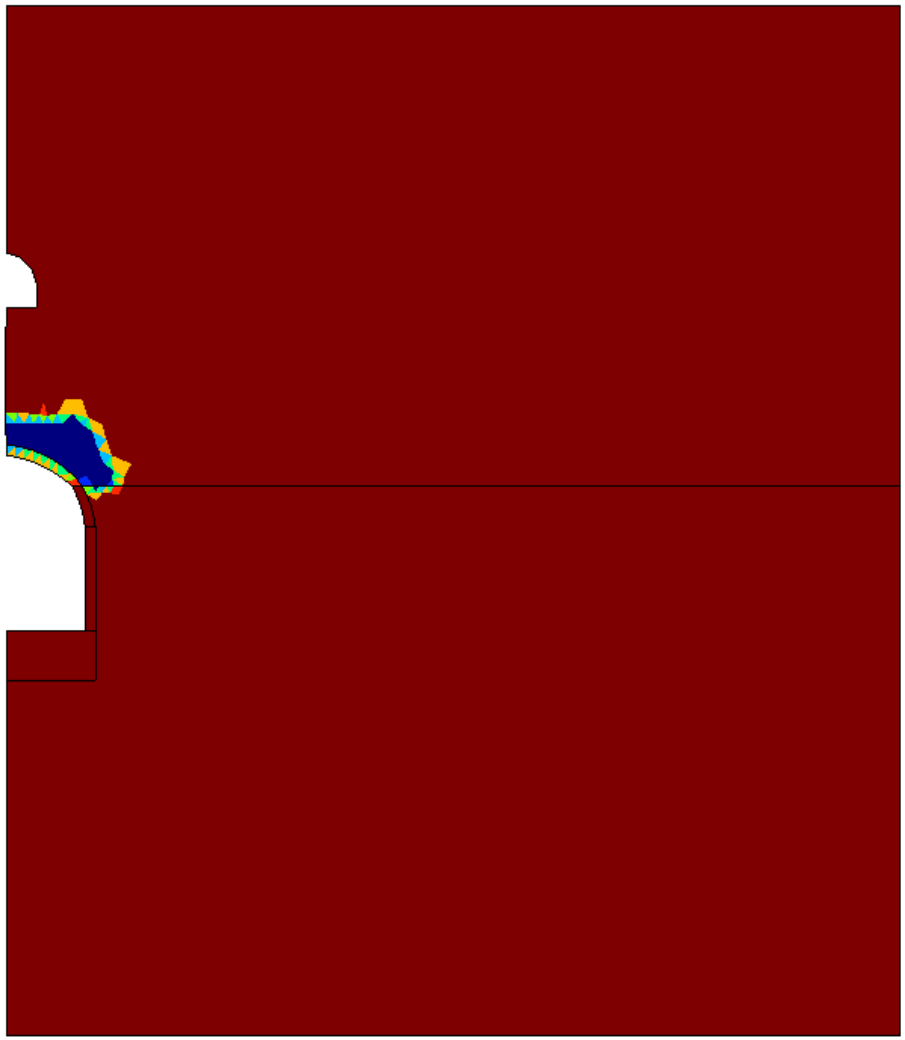
Toledo station: porosity prediction





step 230
Smooth Contour Fill (Mean) of Porosity.

Toledo station: degree of saturation liquid water



Conclusion

- ✓ AGF has been extensively during construction of line 1 in Naples
- ✓ The settlement induced by thawing are 3-4 times greater than swelling in freezing
- ✓ A constitutive law has been developed that accounts for a number of behaviour features of frozen ground
- ✓ Comparison with field test data confirms that formulation and constitutive model can simulate satisfactorily the patterns of temperature, water migration and ice accumulation in case of AGF .
- ✓ Further work, currently under way, includes the comparison of the displacement during freezing and thawing during construction of Toledo station.
- ✓ From the point of view of constitutive modelling modifications to the present formulation are being examined to include the viscous behaviour of the ice phase, mechanical degradation on cycles of freezing and thawing, and the adoption of the Bishop stress as a constitutive variable.

francesca.casini@uniroma2.it

http://www.icevirtuallibrary.com/content/article/10.1680/envgeo.14.00004