21st Gerald A. Leonards Lecture

11 April 2025, Purdue University, Lafayette Indiana

PURDUE UNIVERSITY®

ENGINEERING FROZEN GROUND

UNDERSTANDING THE BEHAVIOUR OF SOIL ON FREEZING AND THAWING

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UNIVERSITY OF CAMBRIDGE

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Line 1 of Napoli underground

project layout
ground conditions
design issues
use of Artificial Ground Freezing (AGF)

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Line 1 of Napoli underground

early applications (Garibaldi)

observed phenomena
heat propagation analyses
method optimisation & control of construction

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Line 1 of Napoli underground

early applications (Garibaldi & Municipio)

fully coupled THM modelling

- predictive capabilities
- TX data
- thaw behaviour

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Line 1 of Napoli underground

early applications (Garibaldi & Municipio)

fully coupled THM modelling

not just AGF

- permafrost degradation
- frost heave apparatus
- what next?

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LINE 1 project overview

13 km (9)
completed 1998

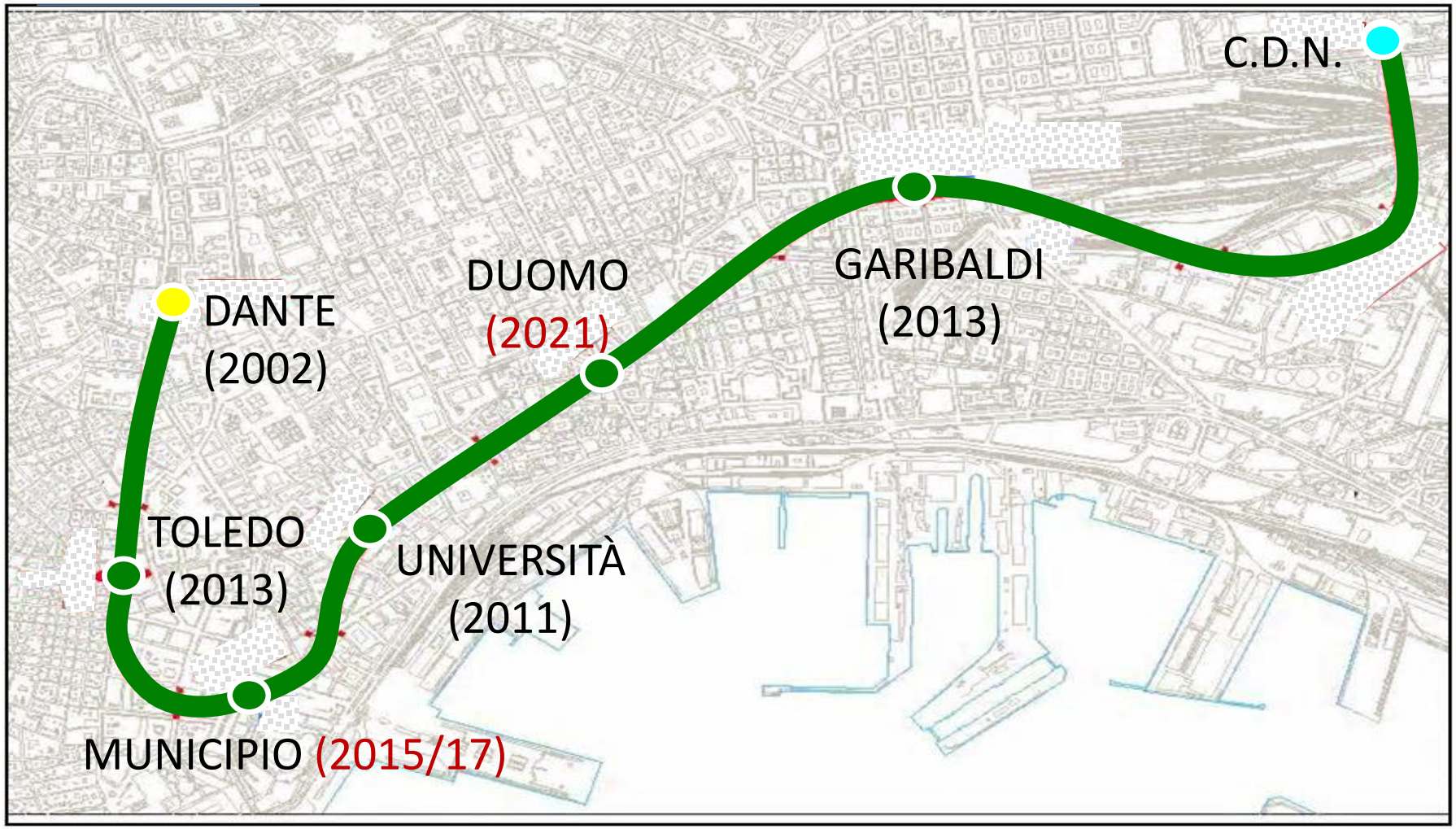
8 km (5)
completed 2002

6 km (5)
completed 2013

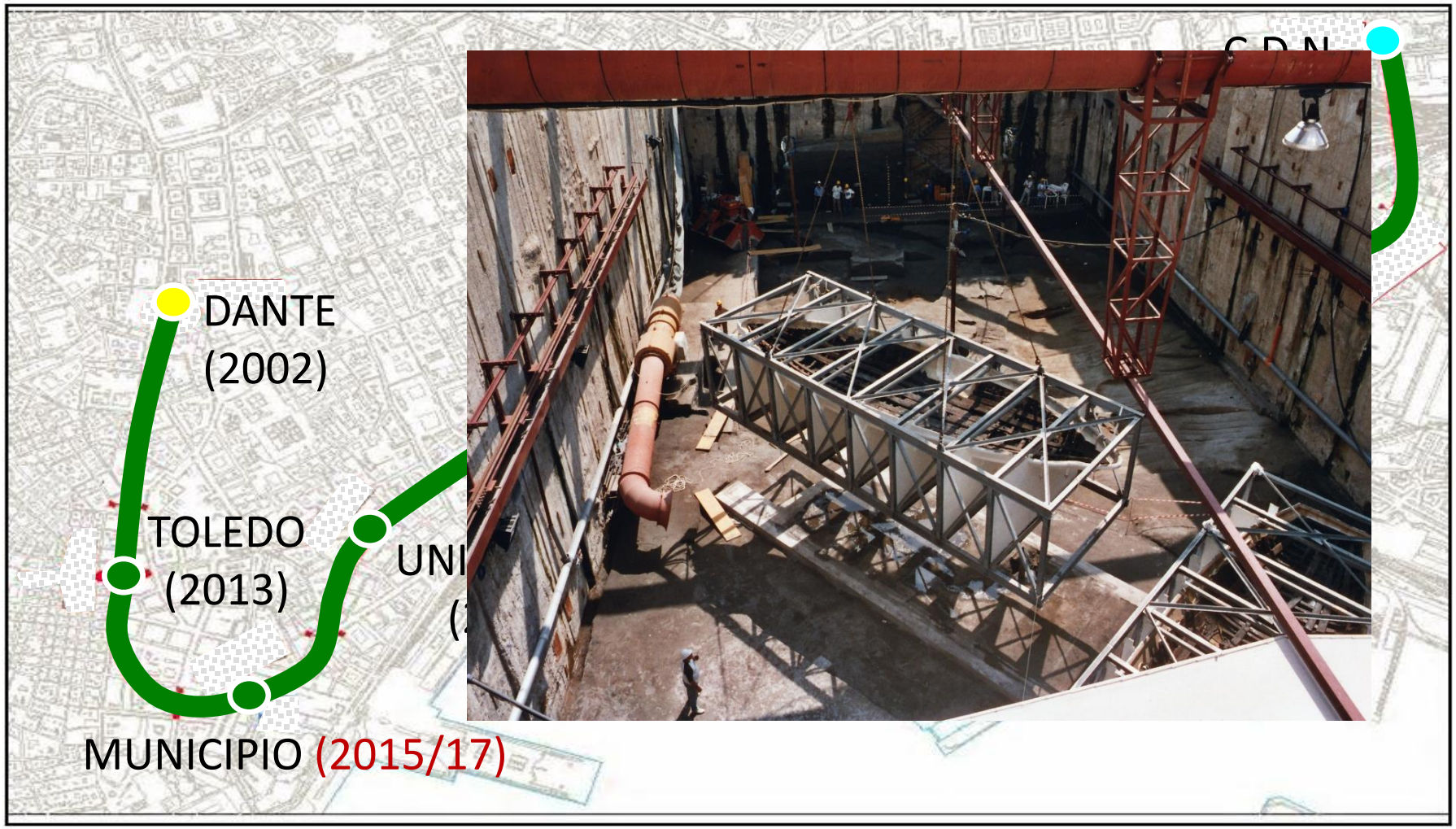
16 km (6)
construction

1 km (0)
design

LINE 1 project overview



LINE 1 project overview



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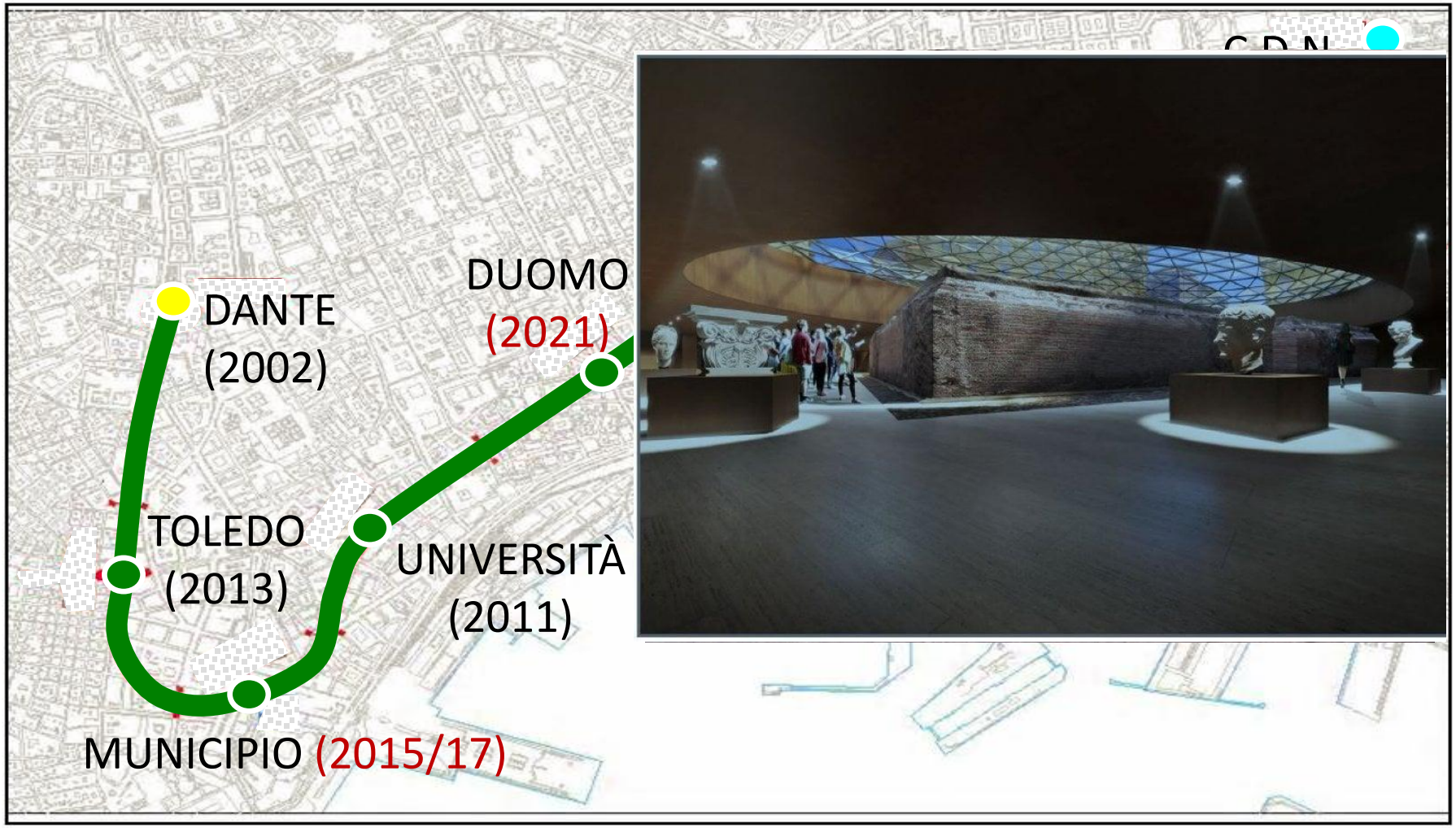

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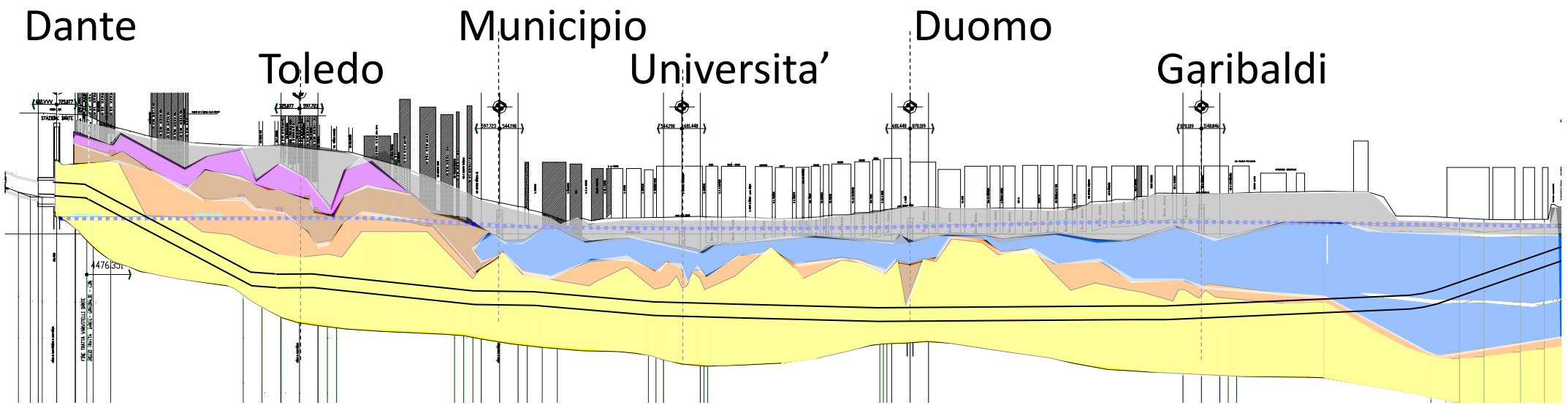


- made ground
- Neapolitan pyroclastic pile
- altered pozzolane
- marine and palustrine deposits
- pozzolane
- neapolitan yellow tuff

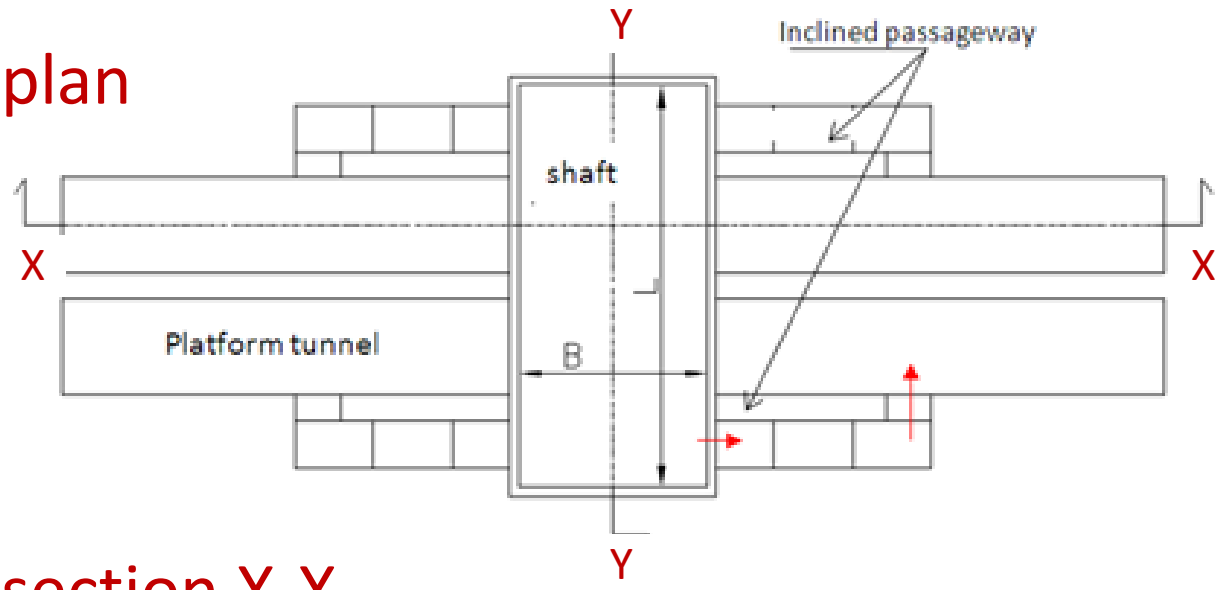
} III Phlegrean Phase

} II Phlegrean Phase

} cohesionless granular deposits

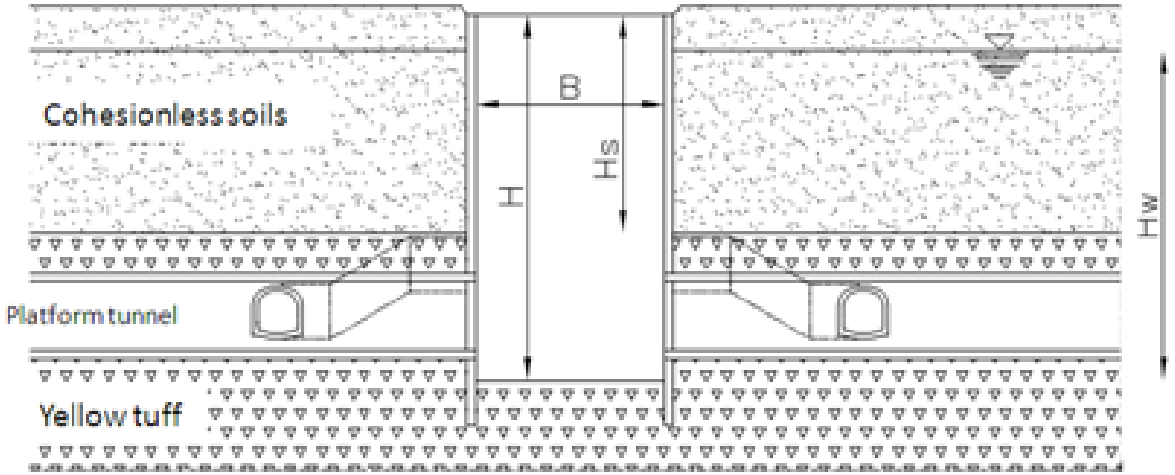
LINE 1 stations

plan

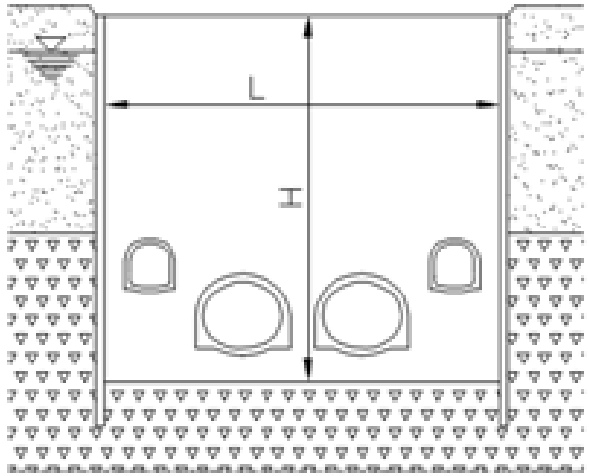


station	B (m)	L (m)	H (m)	Hs (m)	Hw (m)
Municipio	23.40	46.19	36.05	17.20	29.65
Università	16.20	43.55	34.85	20.40	33.50
Duomo	16.20	43.45	35.20	17.00÷24.70	35.20
Garibaldi	21.00	46.00	44.70	29.00	35.30

section X-X



section Y-Y



LINE 1 stations

- bottom of excavation 35 to 50 m b.g.l.
- plan area ~ 1000 m^2
- thickness of granular soils 20 to 30 m
- thickness of soft rock 10 to 15 m
- high water table 30 to 35 m a.d.l.

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construction techniques

- RC diaphragm walls (hydromill)

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- props and anchors

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construction techniques

- RC diaphragm walls (hydromill)
- props and anchors
- top-down construction

LINE 1 station tunnels

platform tunnels — fractured soft rock (yellow tuff)

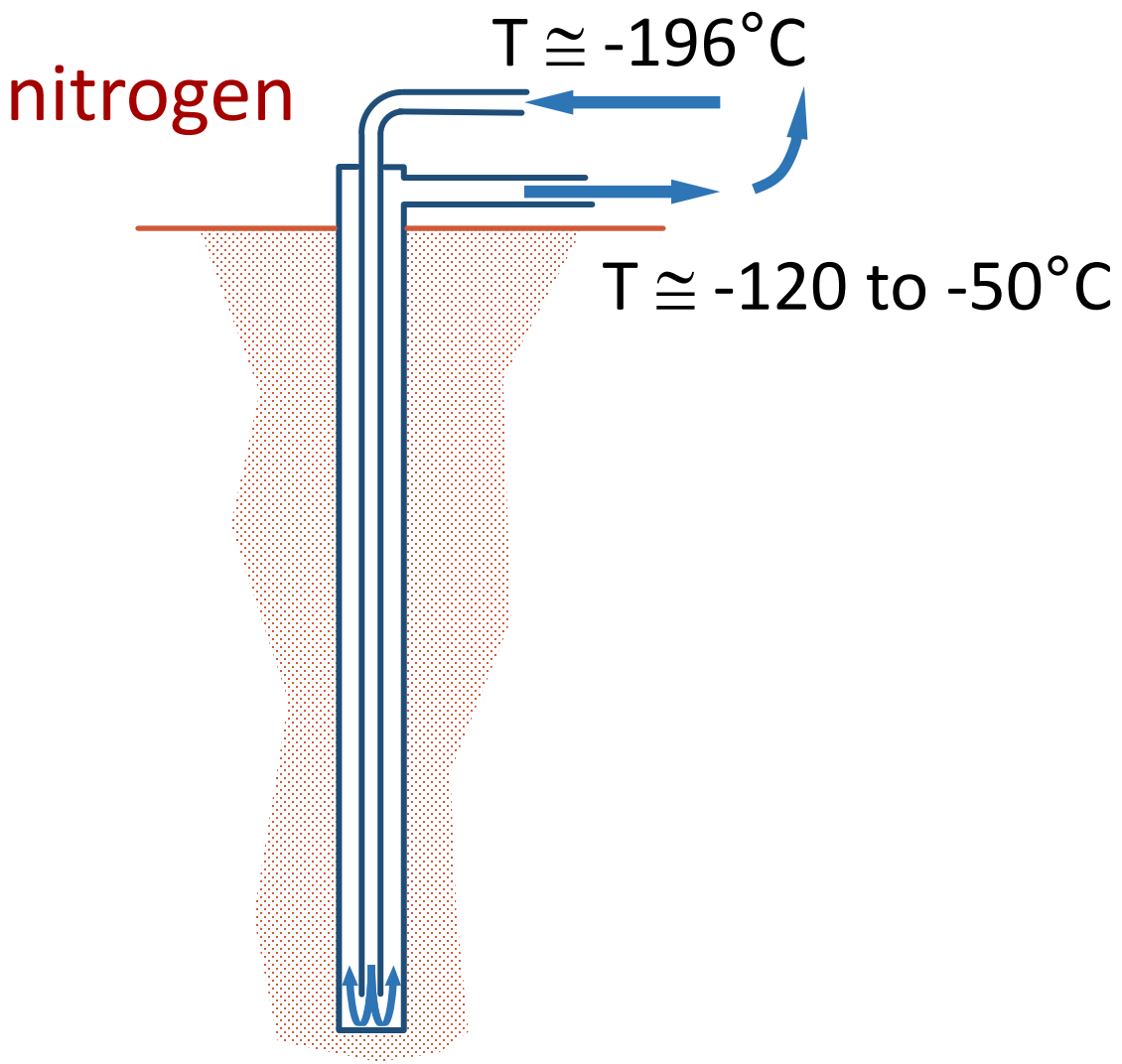
inclined passageways — granular soil (pozzolana)

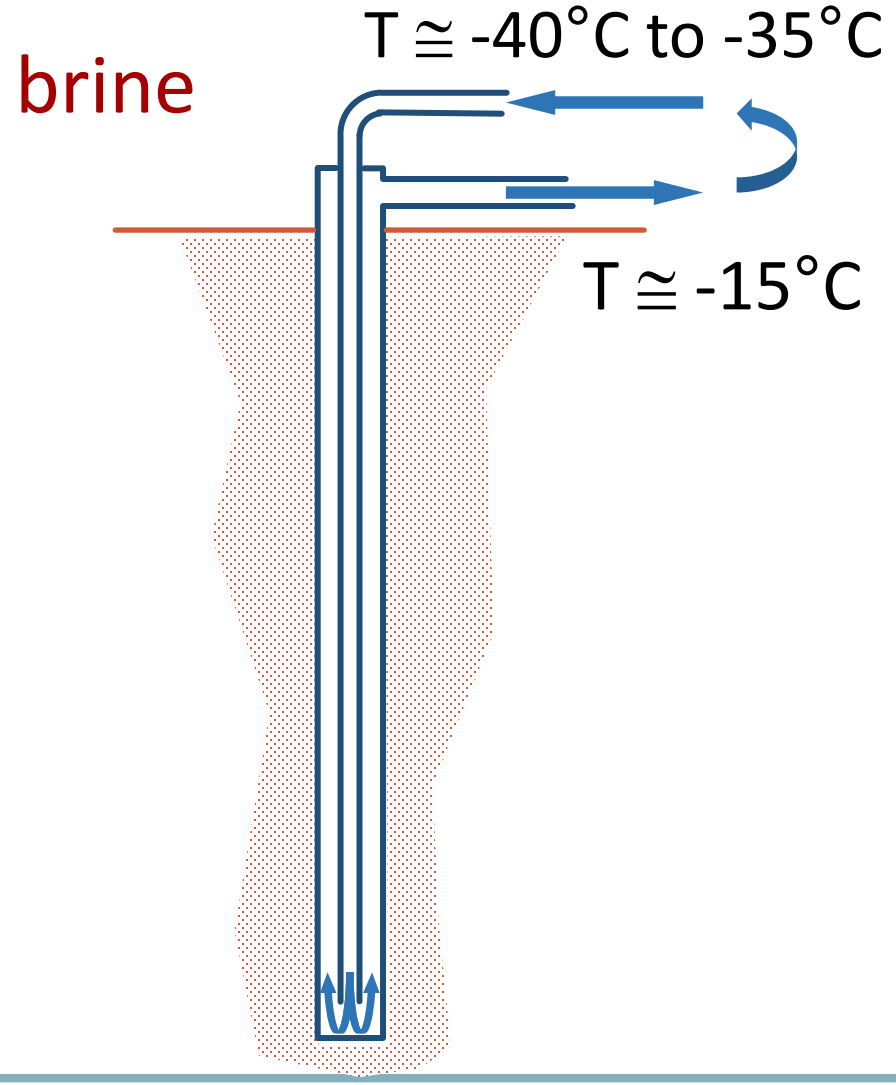
below the water table

construction techniques

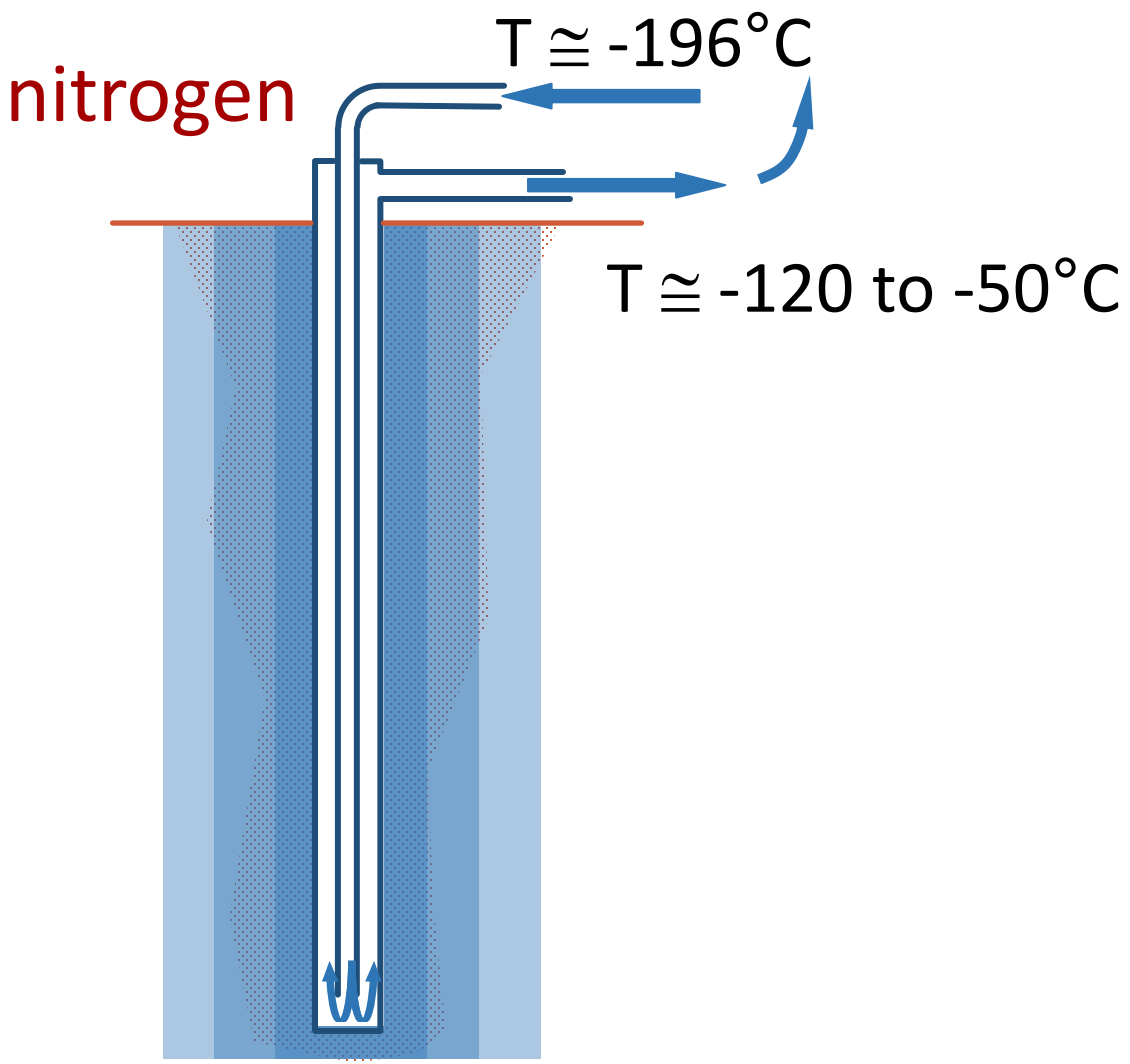
❄ Artificial Ground Freezing

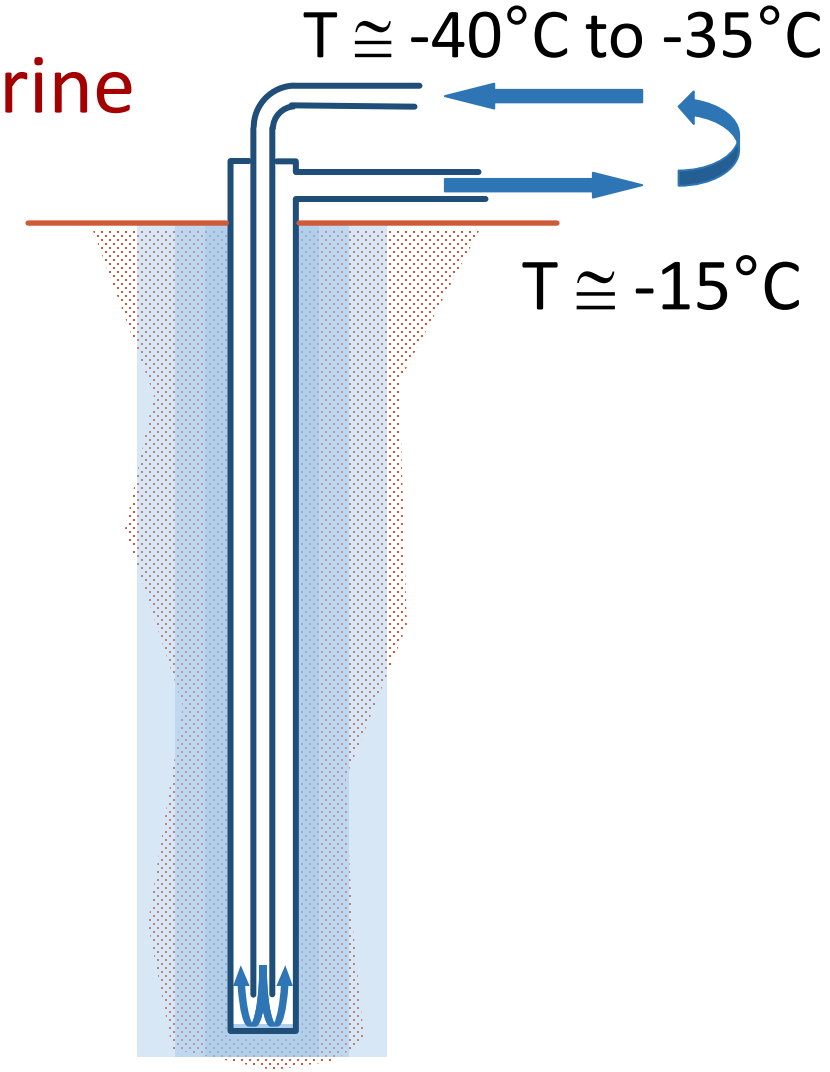
ARTIFICIAL GROUND FREEZING



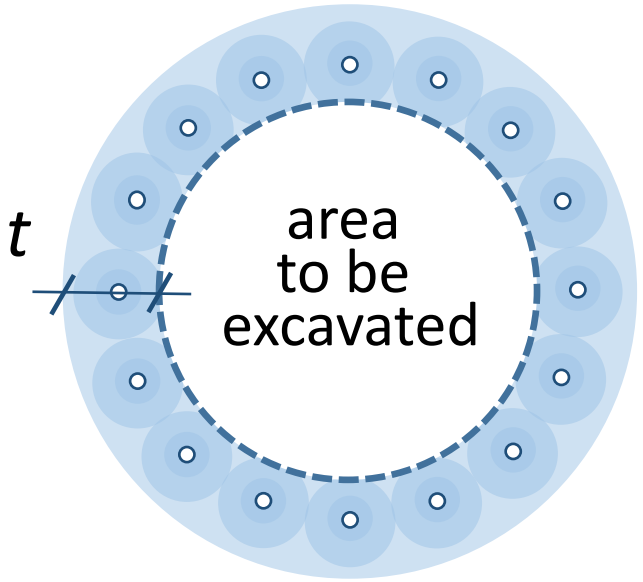


ARTIFICIAL GROUND FREEZING





ARTIFICIAL GROUND FREEZING



- ✓ increased strength
- ✓ low permeability

LINE 1 station tunnels

platform tunnels — fractured soft rock (yellow tuff)

inclined passageways — granular soil (pozzolana)

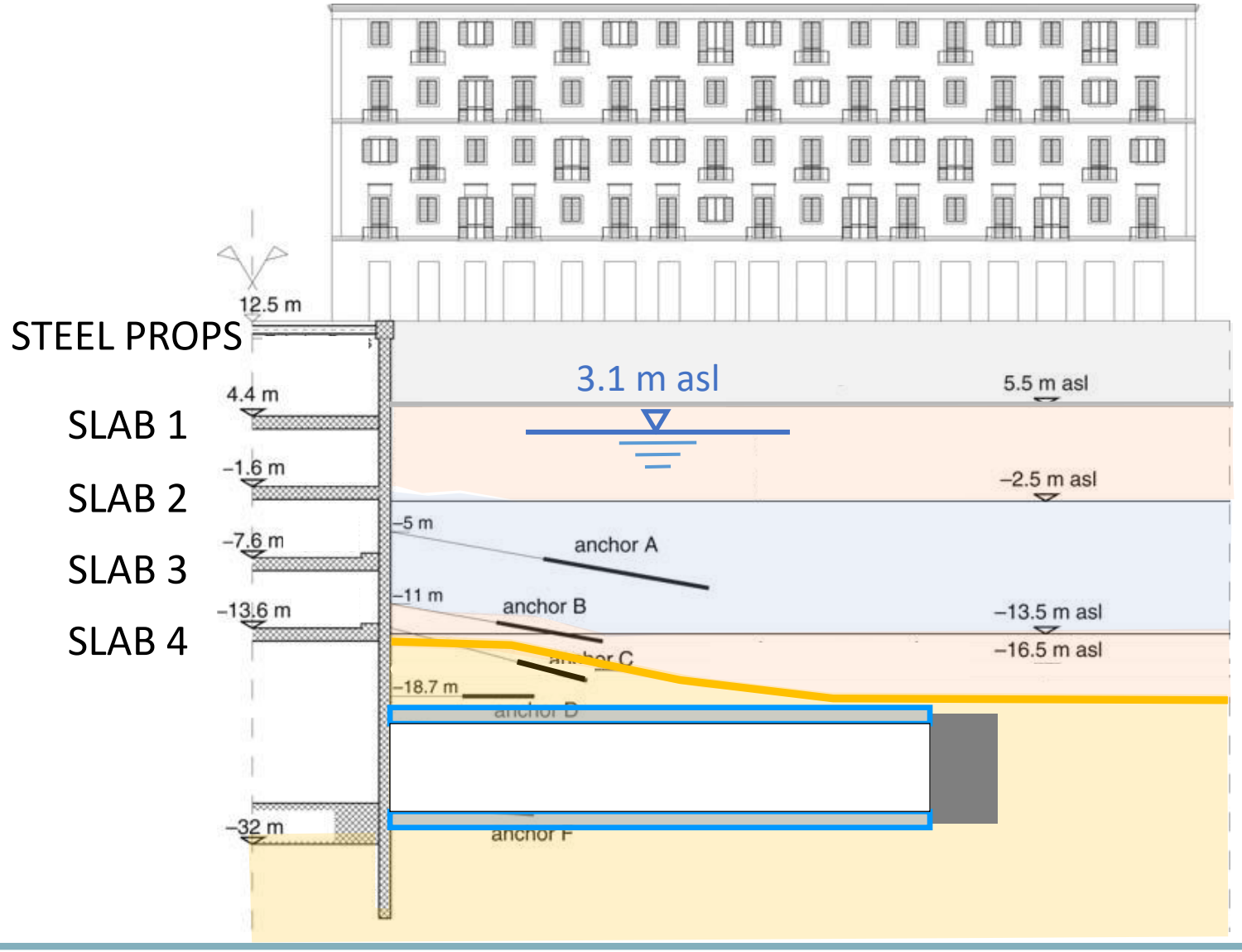
below the water table

construction techniques

- Artificial Ground Freezing
  - static — inclined passageways
  - hydraulic — platform tunnels/passageways

GARIBALDI (2002-2013)

GARIBALDI section



made ground

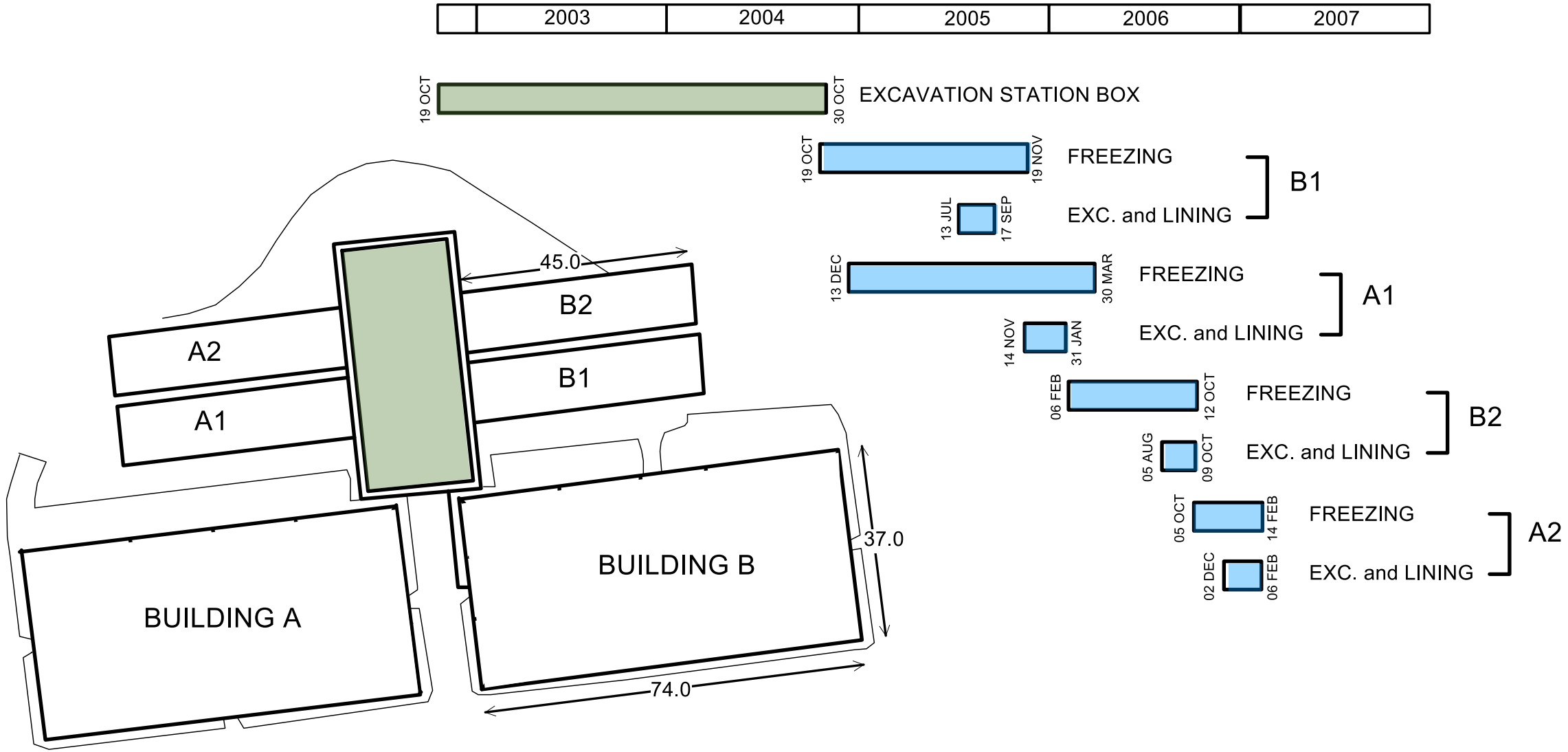
pyroclastic sand

seabed deposits

pozzolana

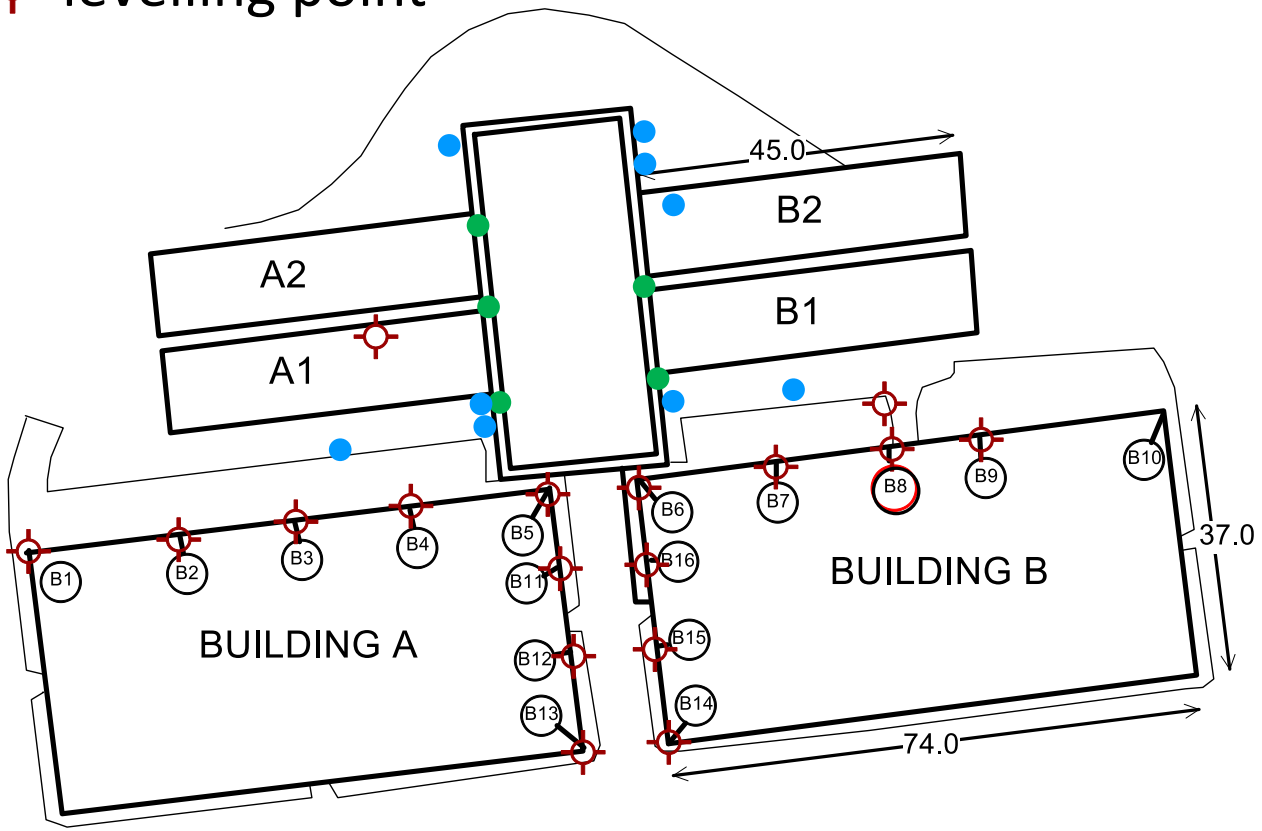
yellow tuff

GARIBALDI construction phases



GARIBALDI monitoring

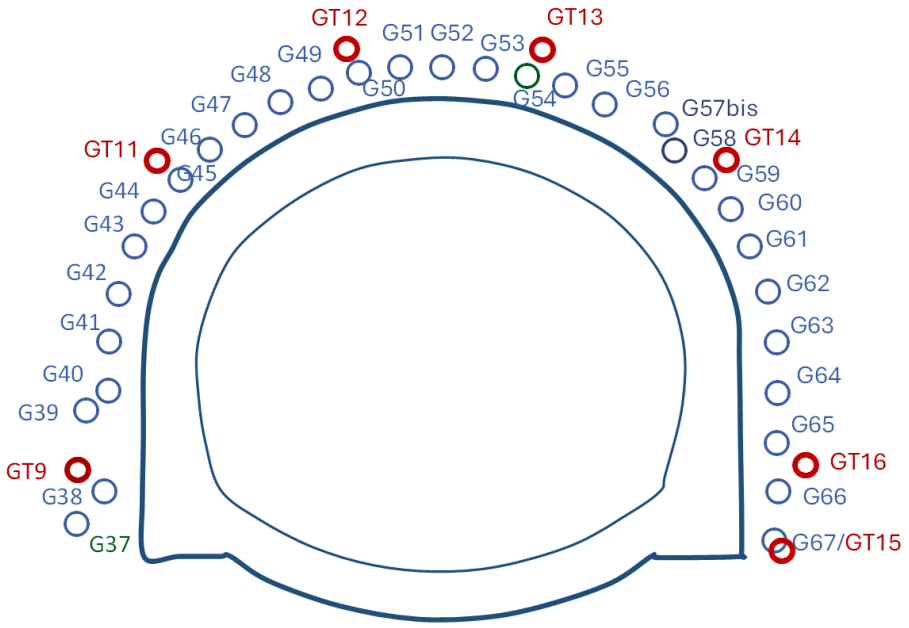
- Casagrande piezometer
- inclinometer
- levelling point

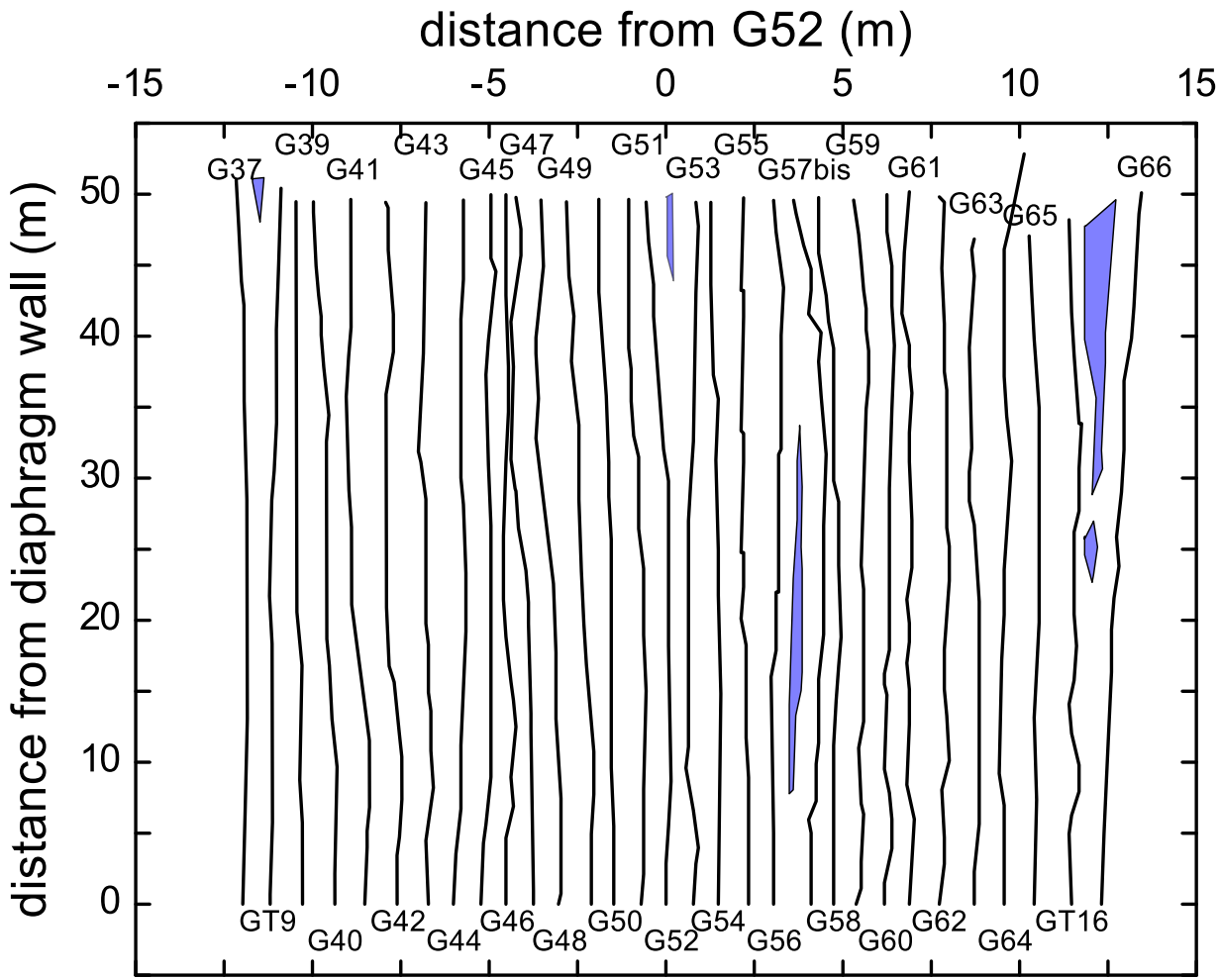


anchor load cells

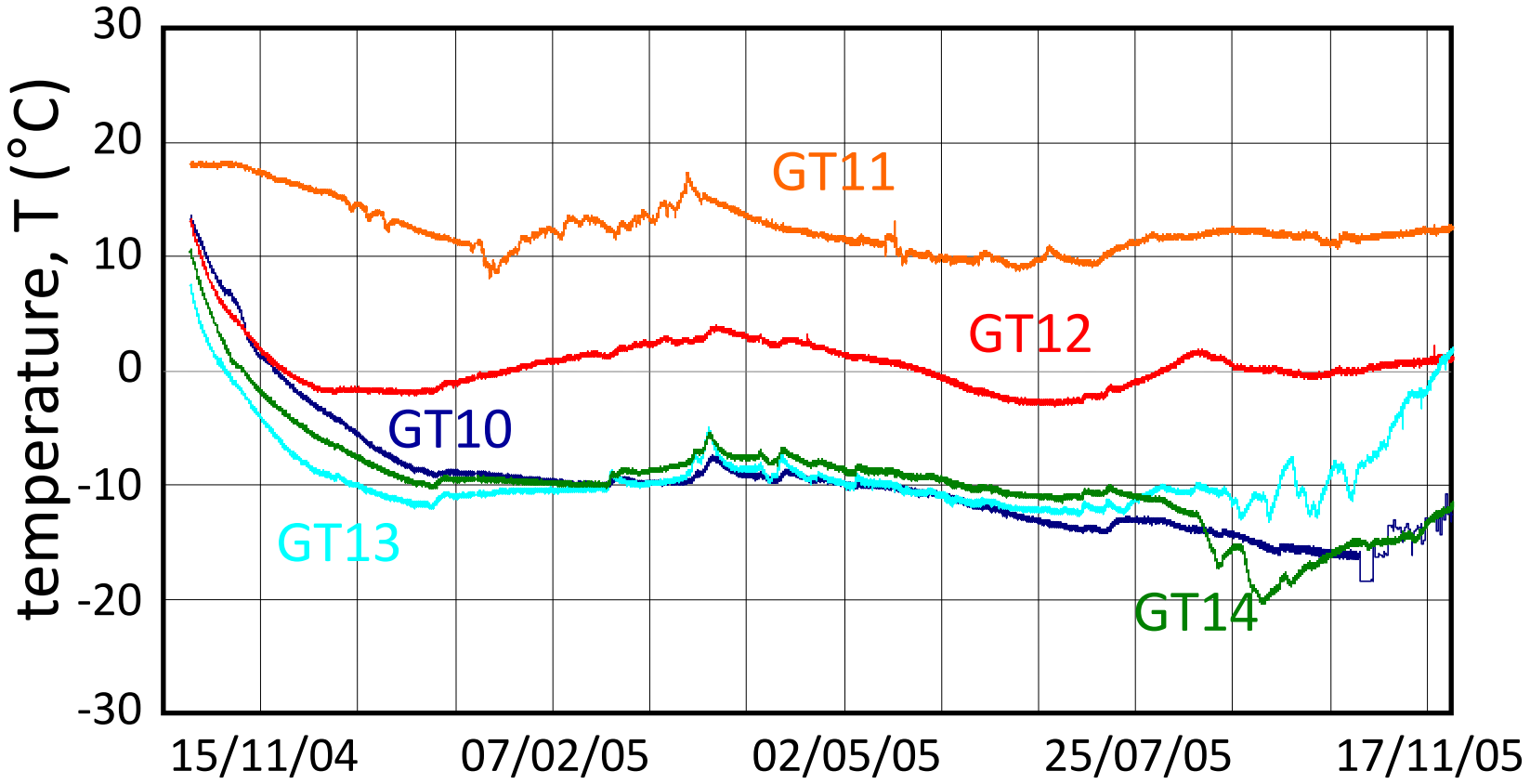
temperatures in the ground
(TC in observation holes)

GARIBALDI freezing and observation tubes

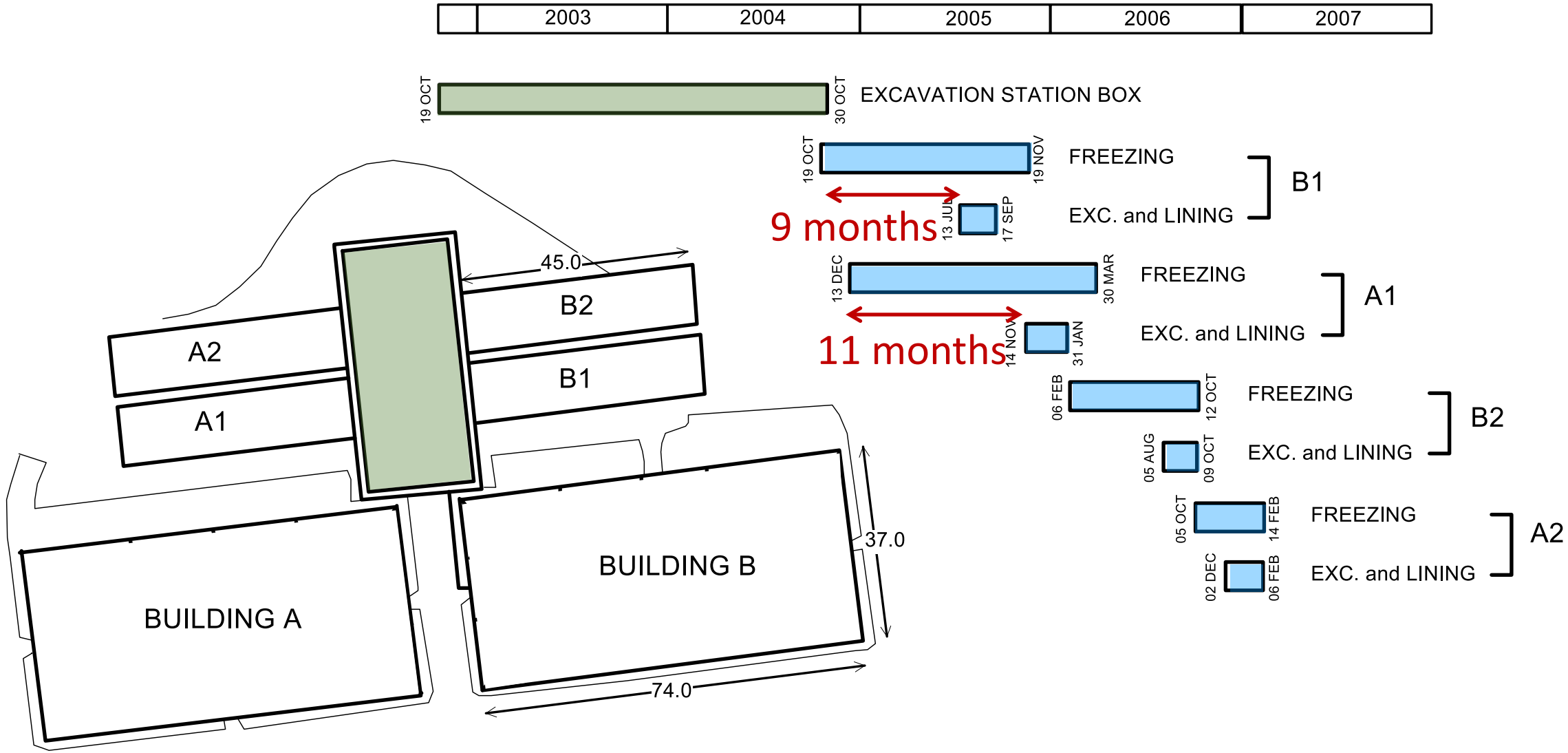




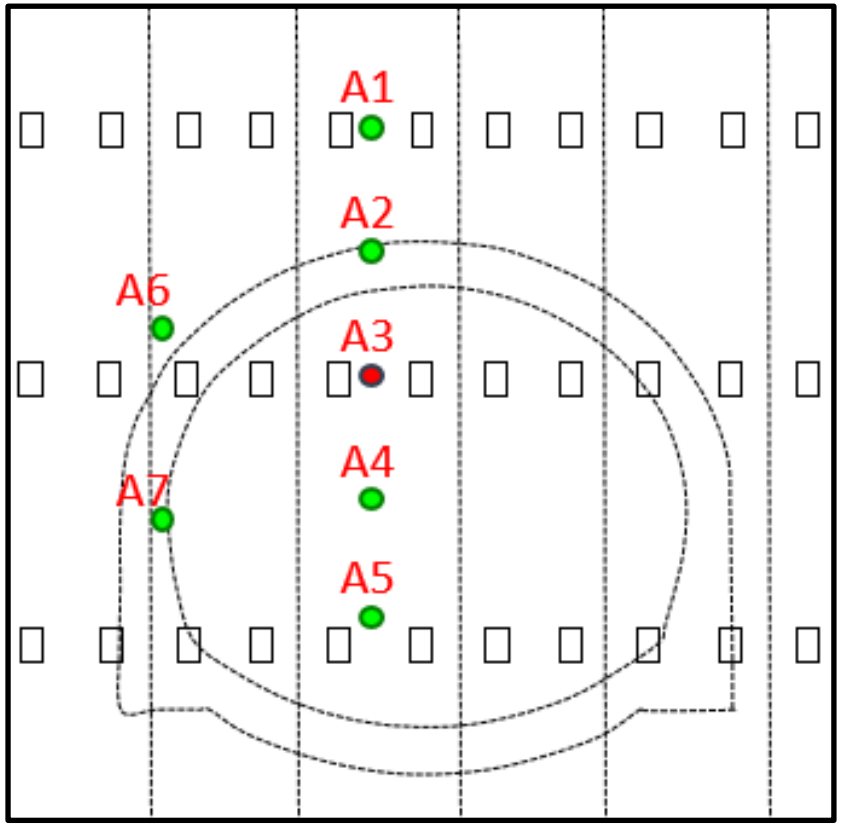
GARIBALDI temperatures

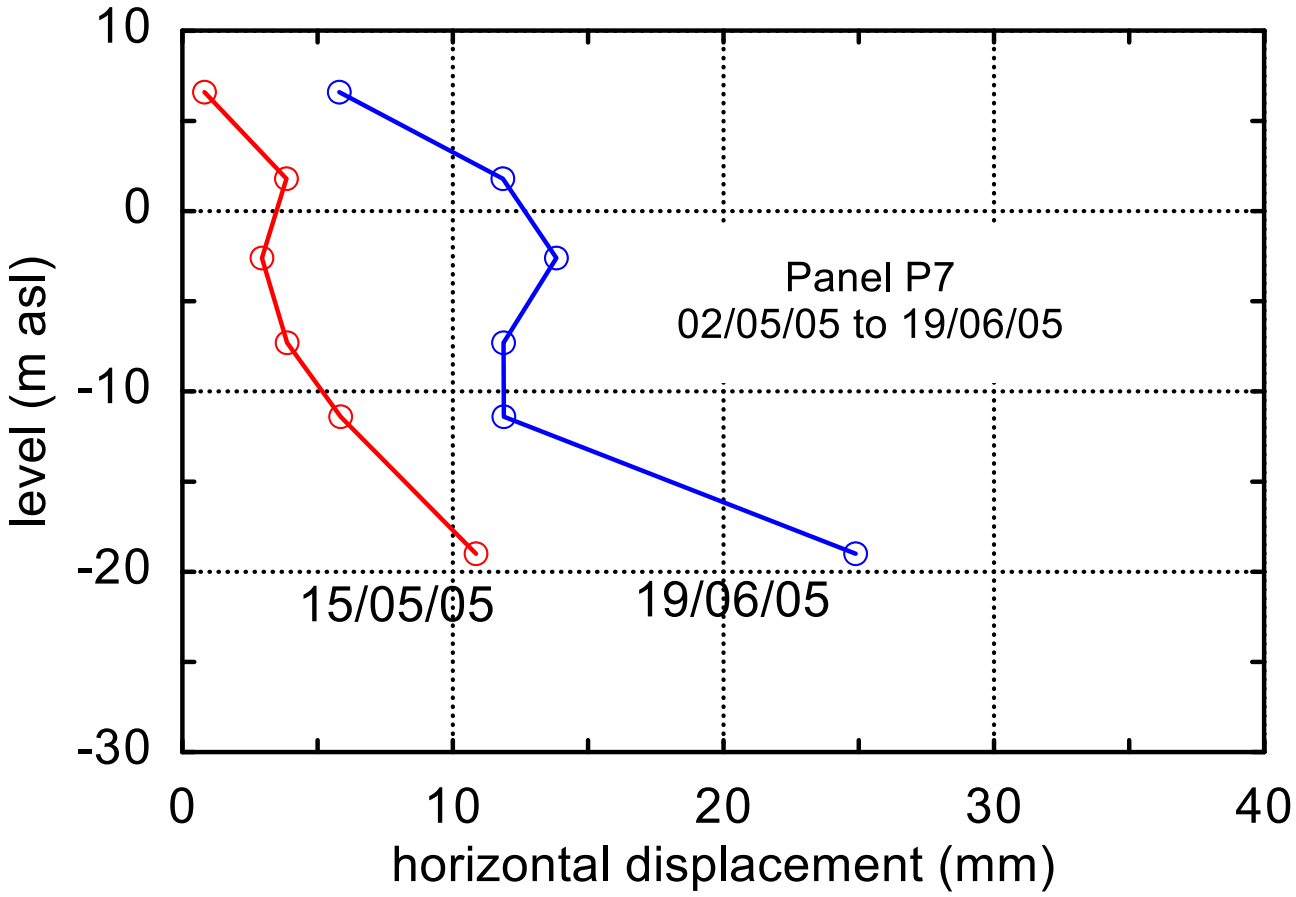


GARIBALDI construction phases

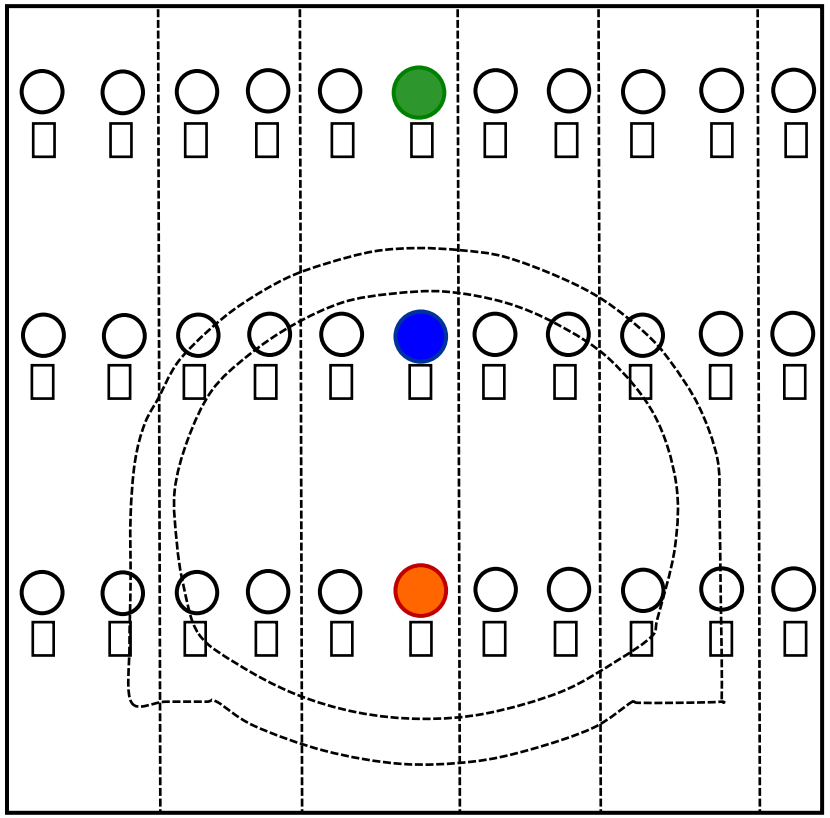


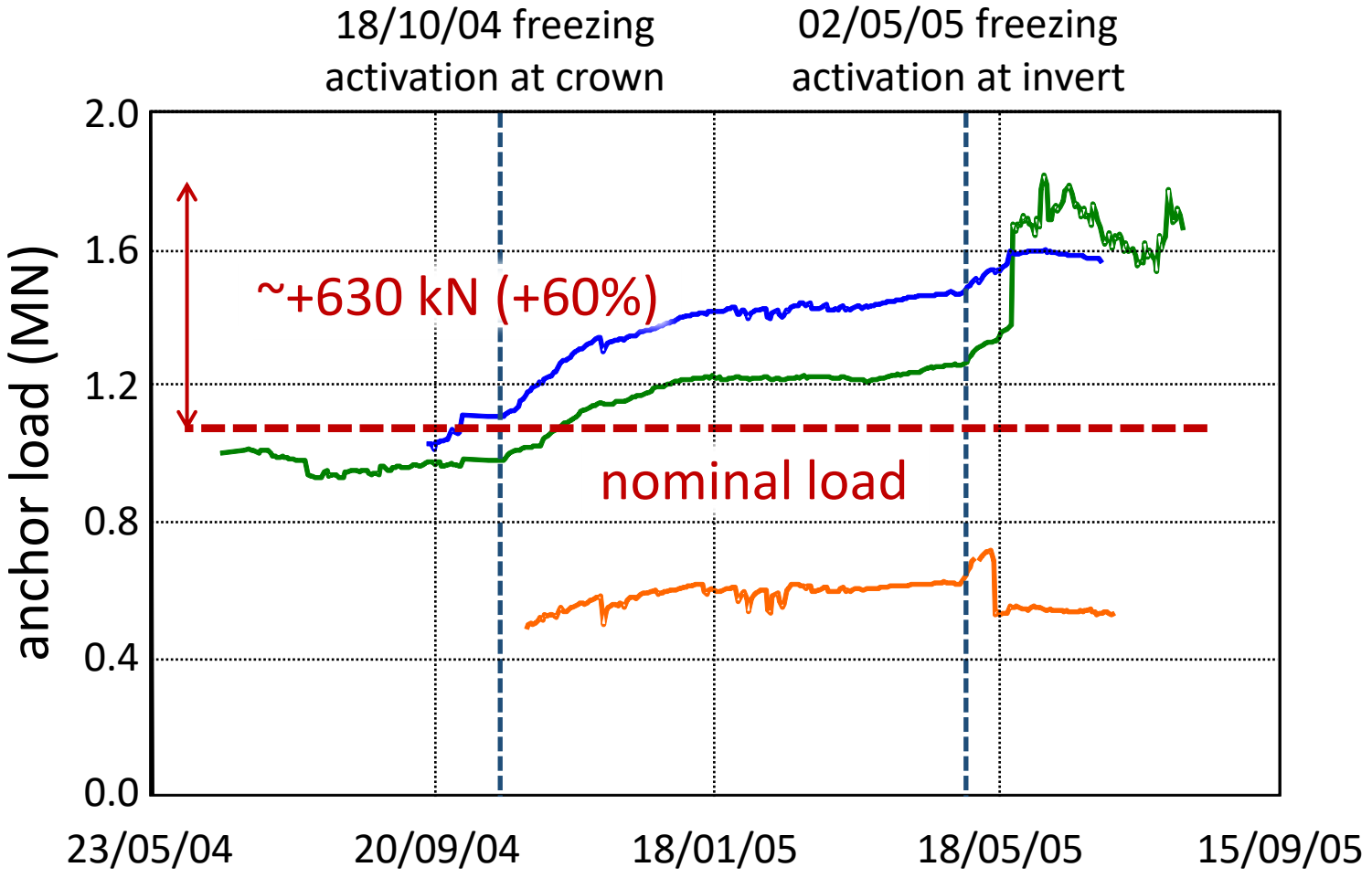
GARIBALDI convergence



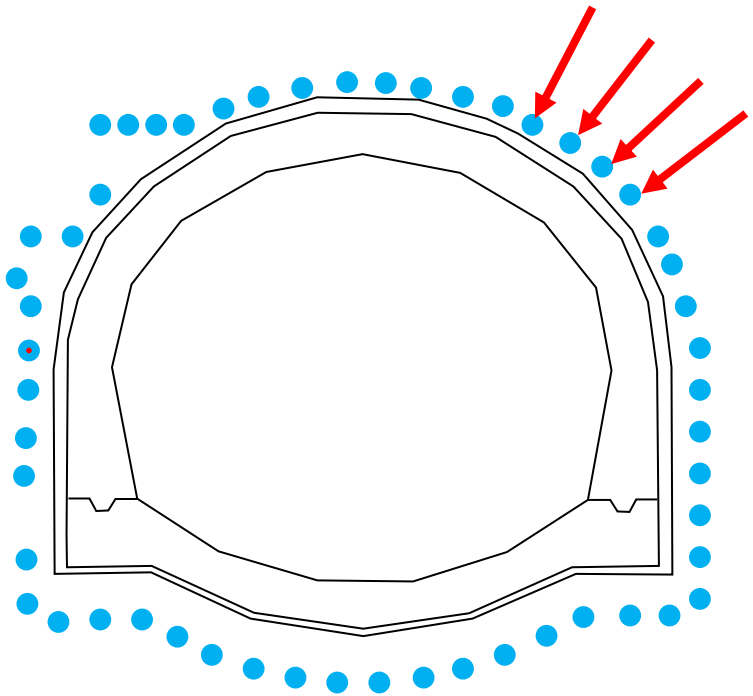


GARIBALDI anchor loads



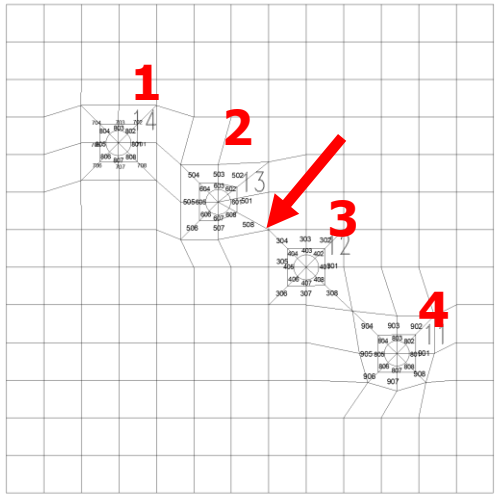


HEAT PROPAGATION ANALYSES



diameter 10.6 m
53 freezing tubes

temperature @ mid point
frozen thickness



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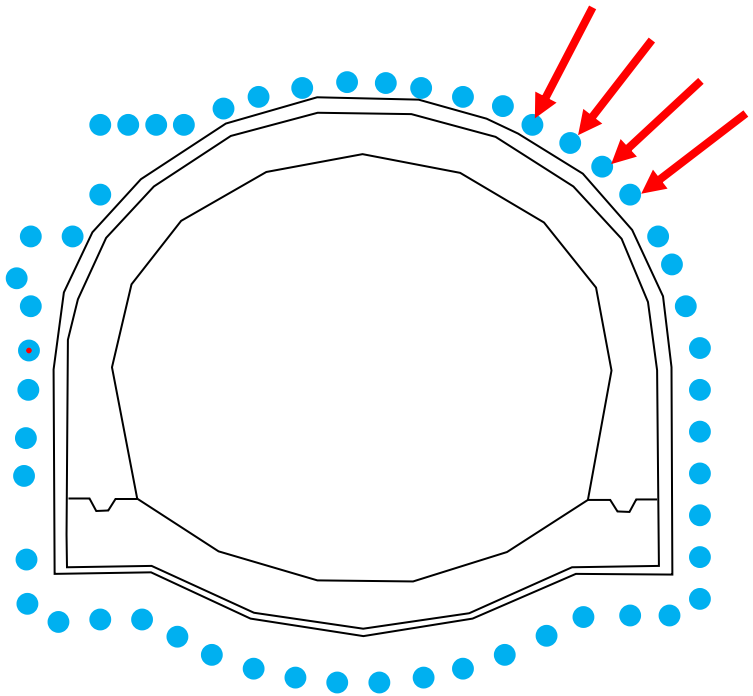
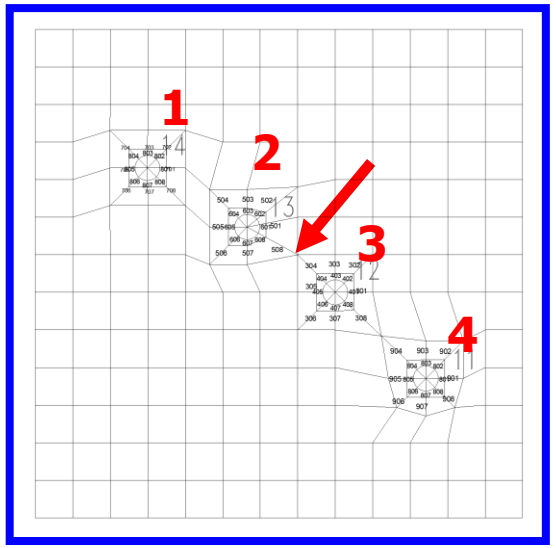


boundary conditions

15 °C @ mesh boundary

-174/-40 °C @ freeze tubes



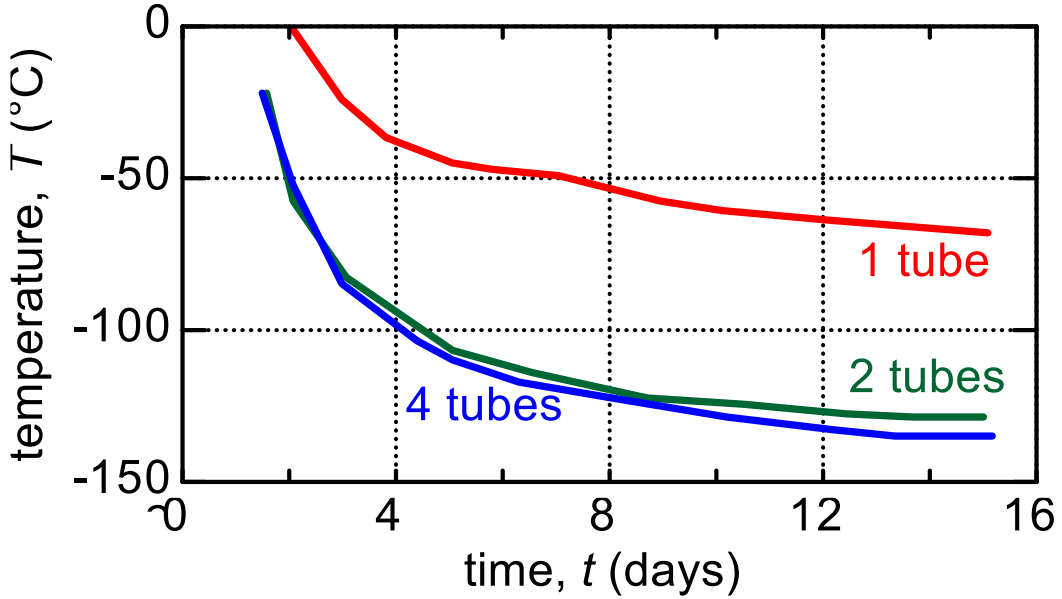
thermal conductivity 1.49 ÷ 2.69 W/m°C

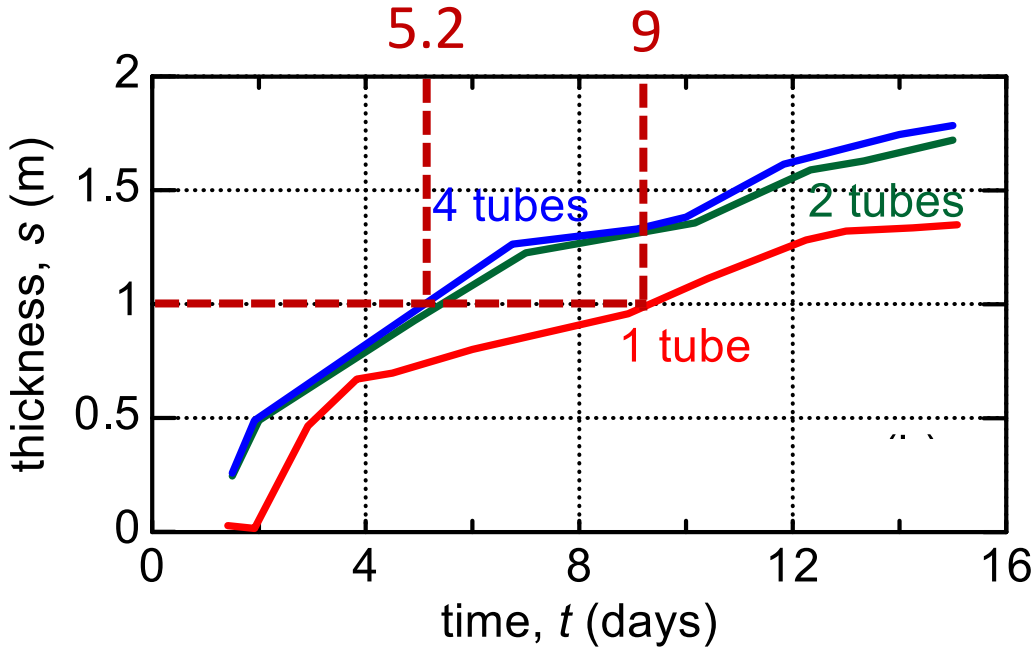
heat capacity 1604 ÷ 1134 J/(kg°C)

specific heat 0.84 ÷ 0.60 J/m^3°C

HEAT PROPAGATION ANALYSES

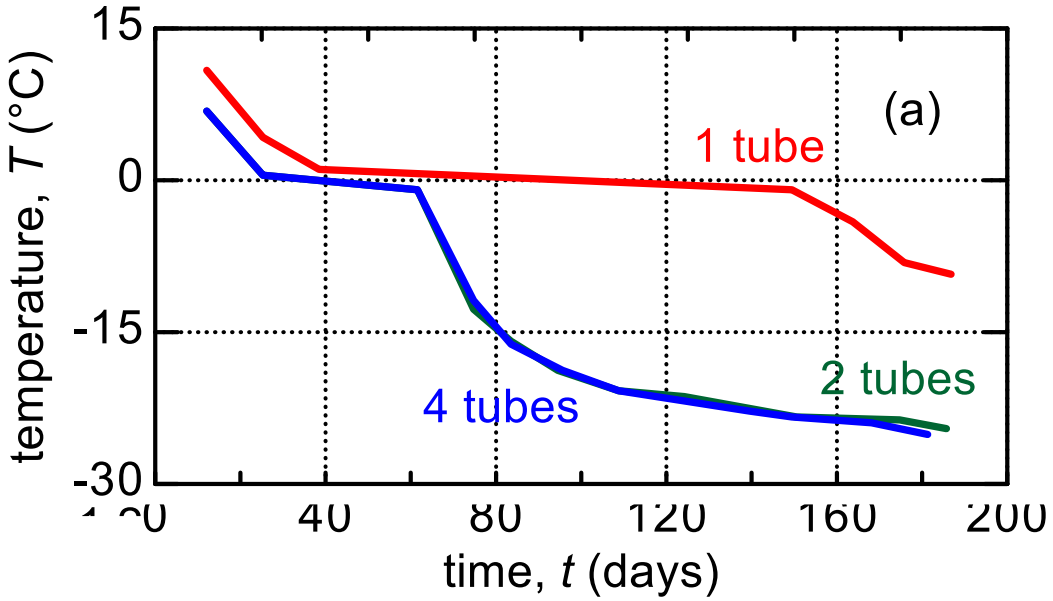
nitrogen activation

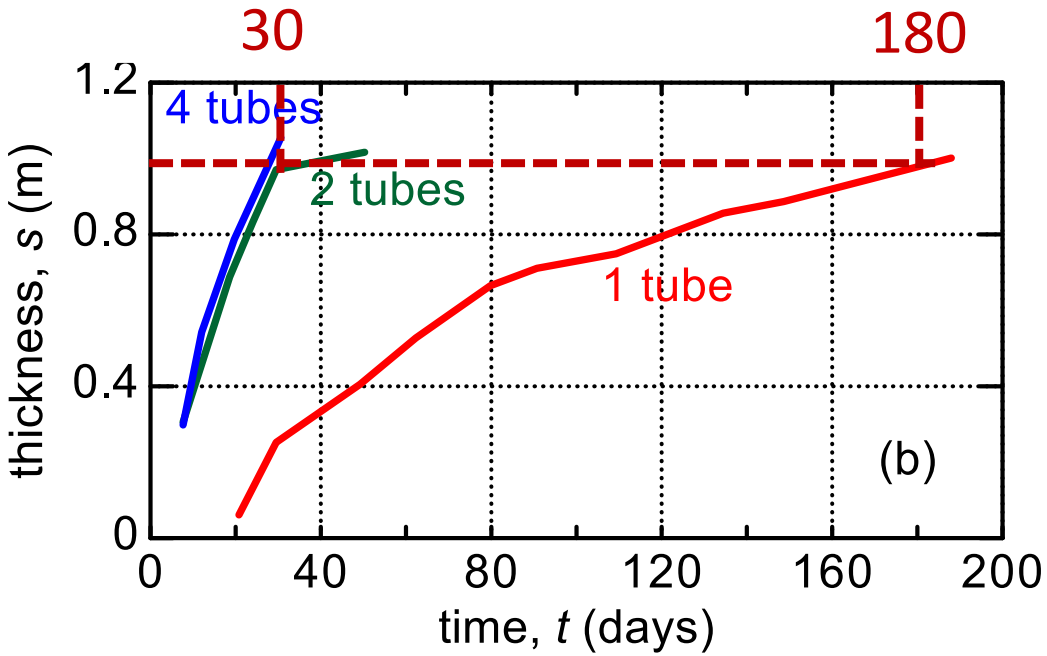




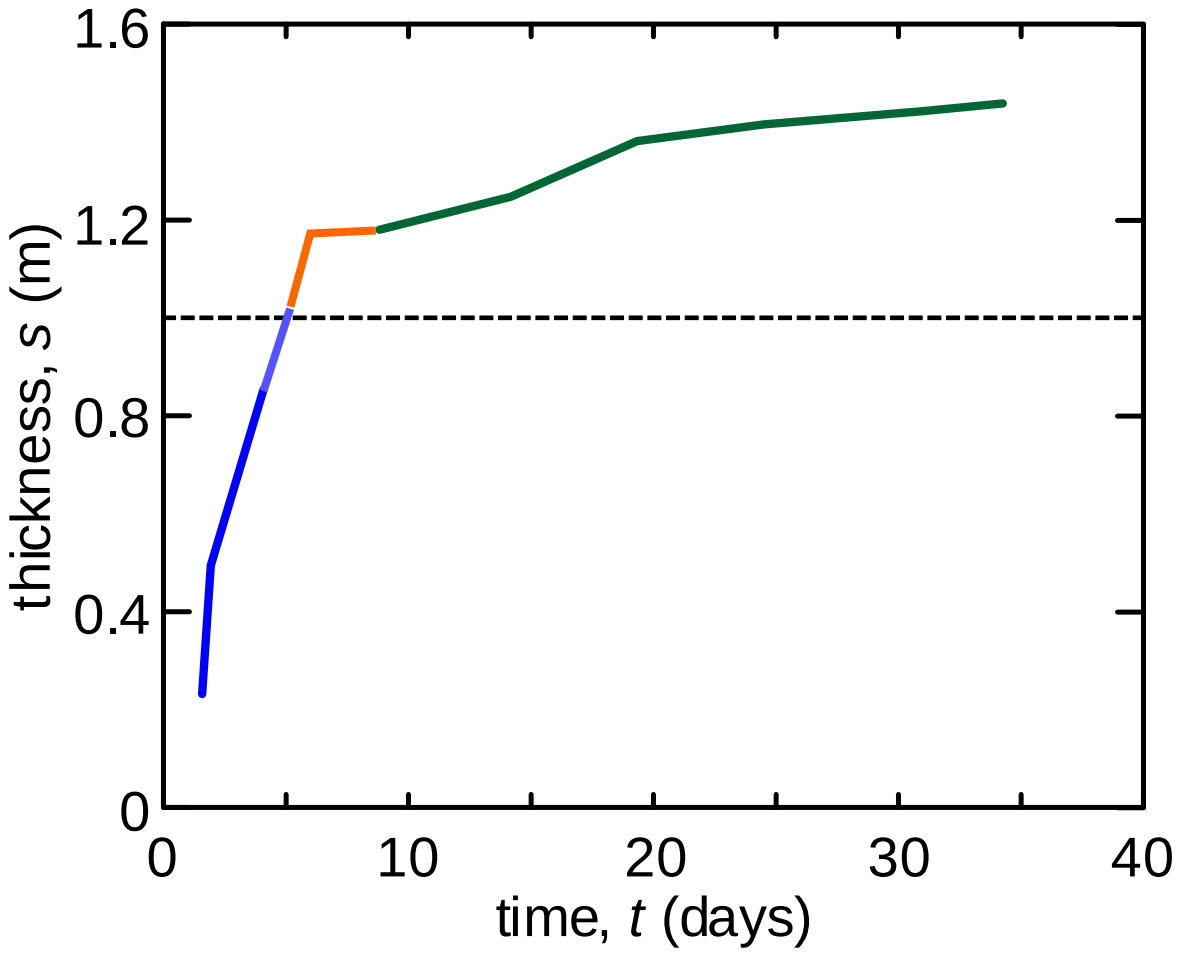
HEAT PROPAGATION ANALYSES

brine activation





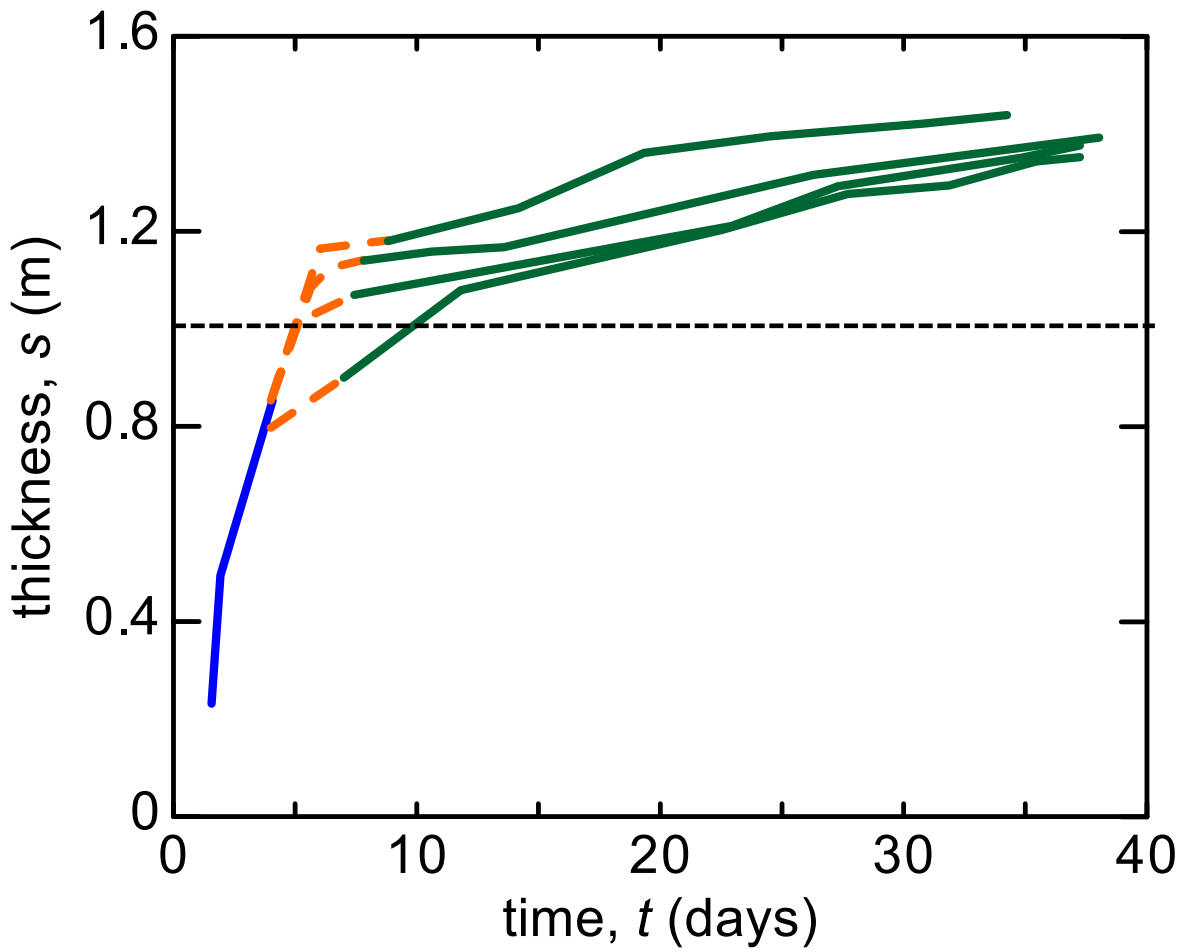
OPTIMISATION



nitrogen activation
thawing
brine maintenance

1.00 m 1.18 m 1.48 m

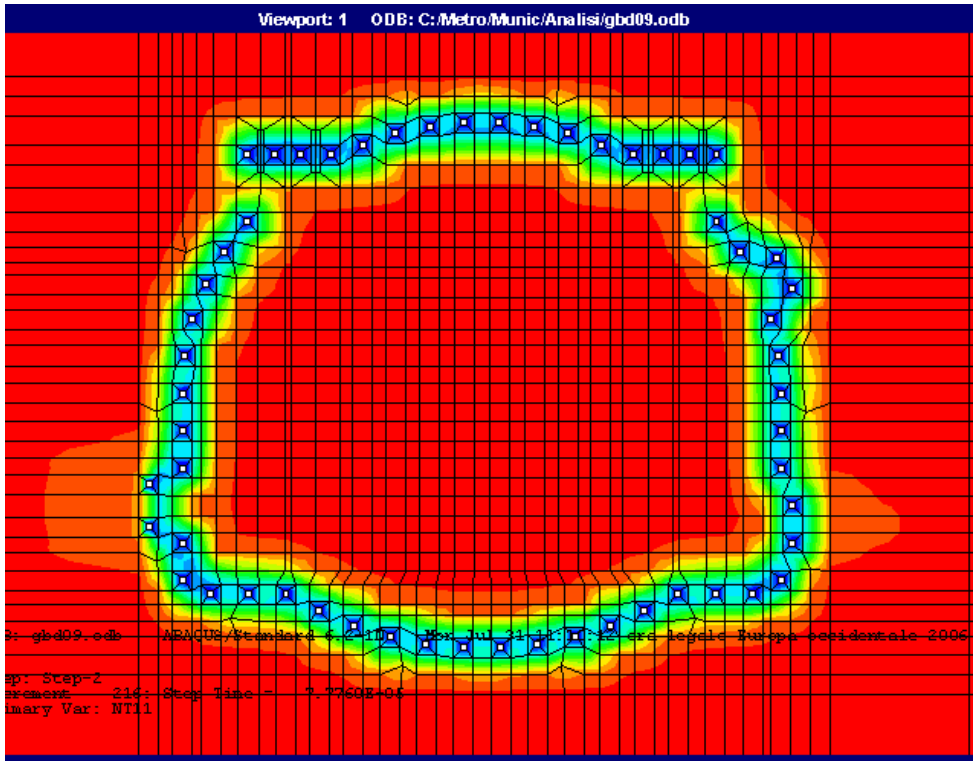
OPTIMISATION



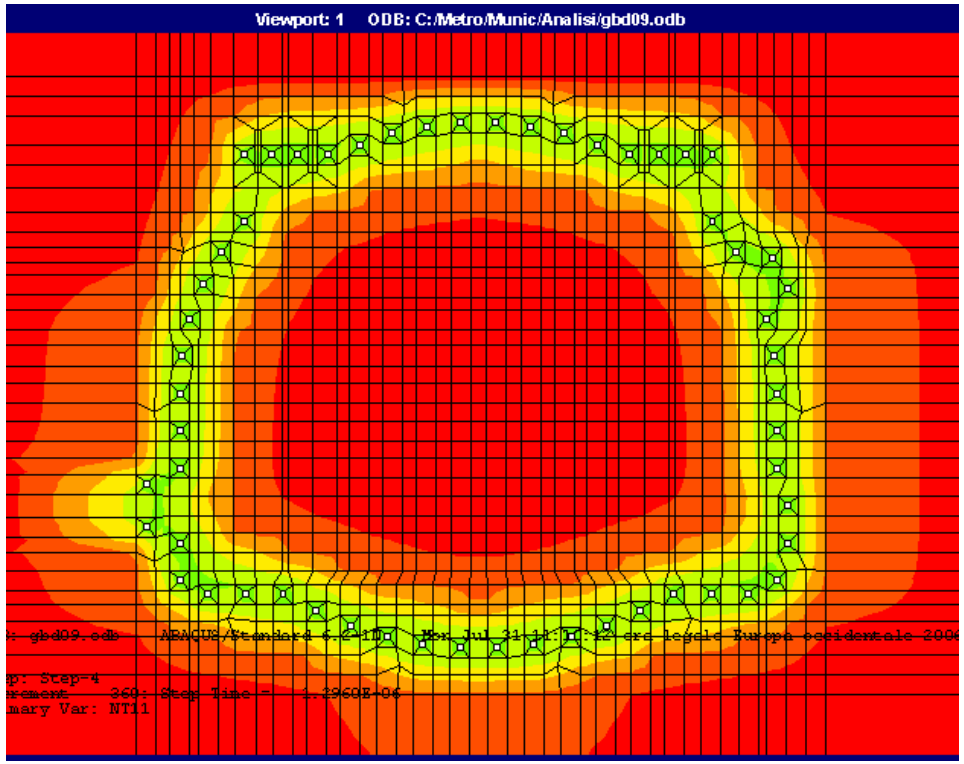
nitrogen activation
thawing
brine maintenance

1.00 m	1.18 m	1.48 m
0.90 m	1.14 m	1.37 m
0.85 m	1.05 m	1.34 m
0.80 m	0.90 m	1.35 m

CONTROL OF CONSTRUCTION

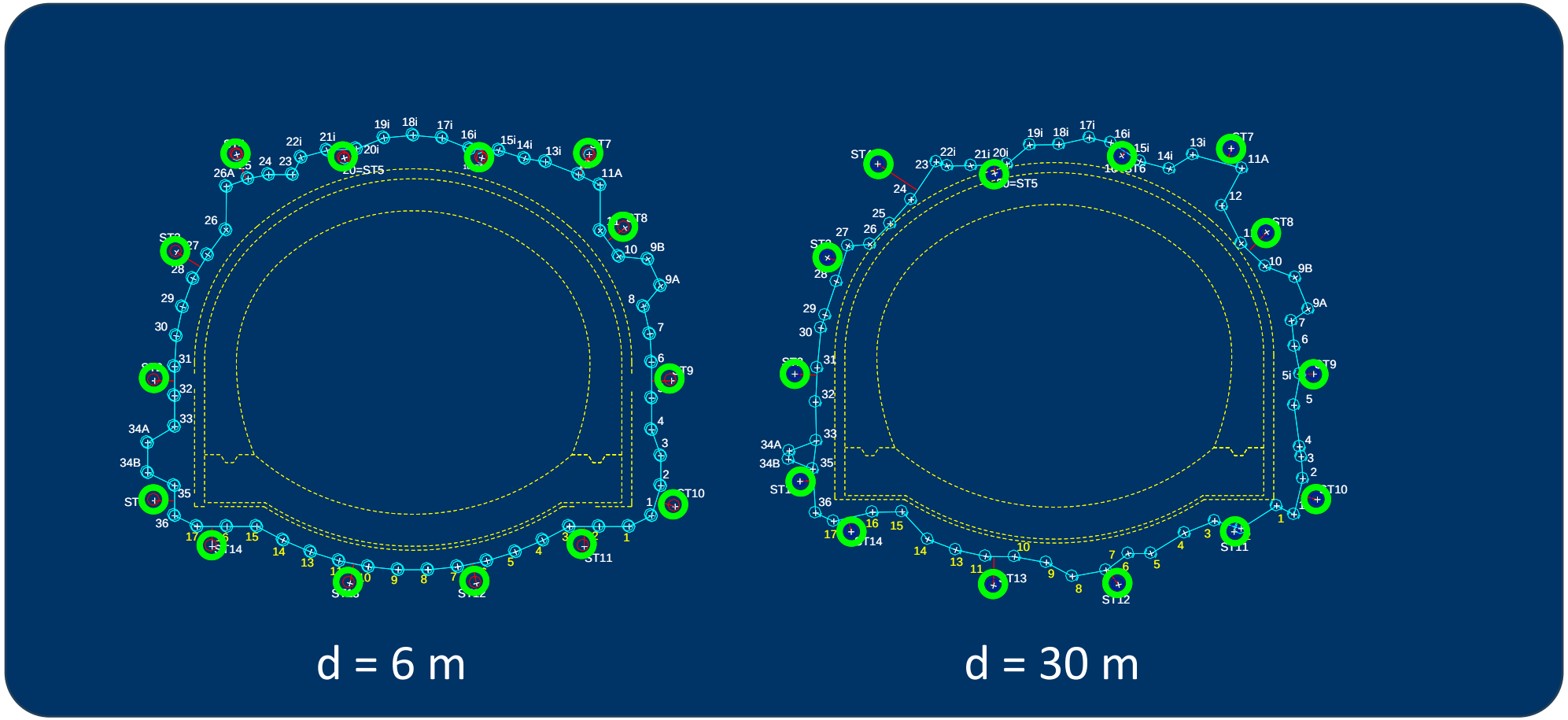


end of nitrogen activation (7dd)



after brine maintenance (26 dd)

CONTROL OF CONSTRUCTION



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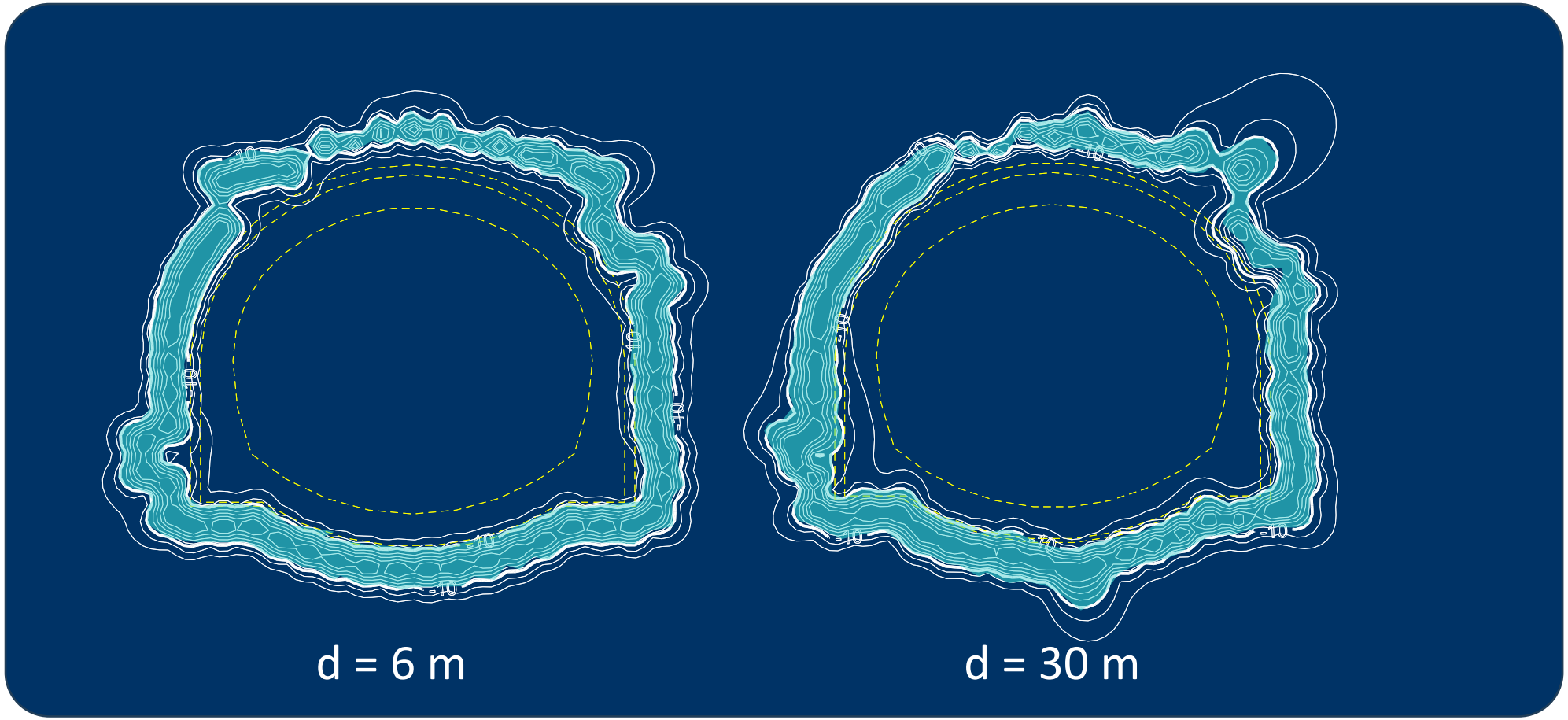
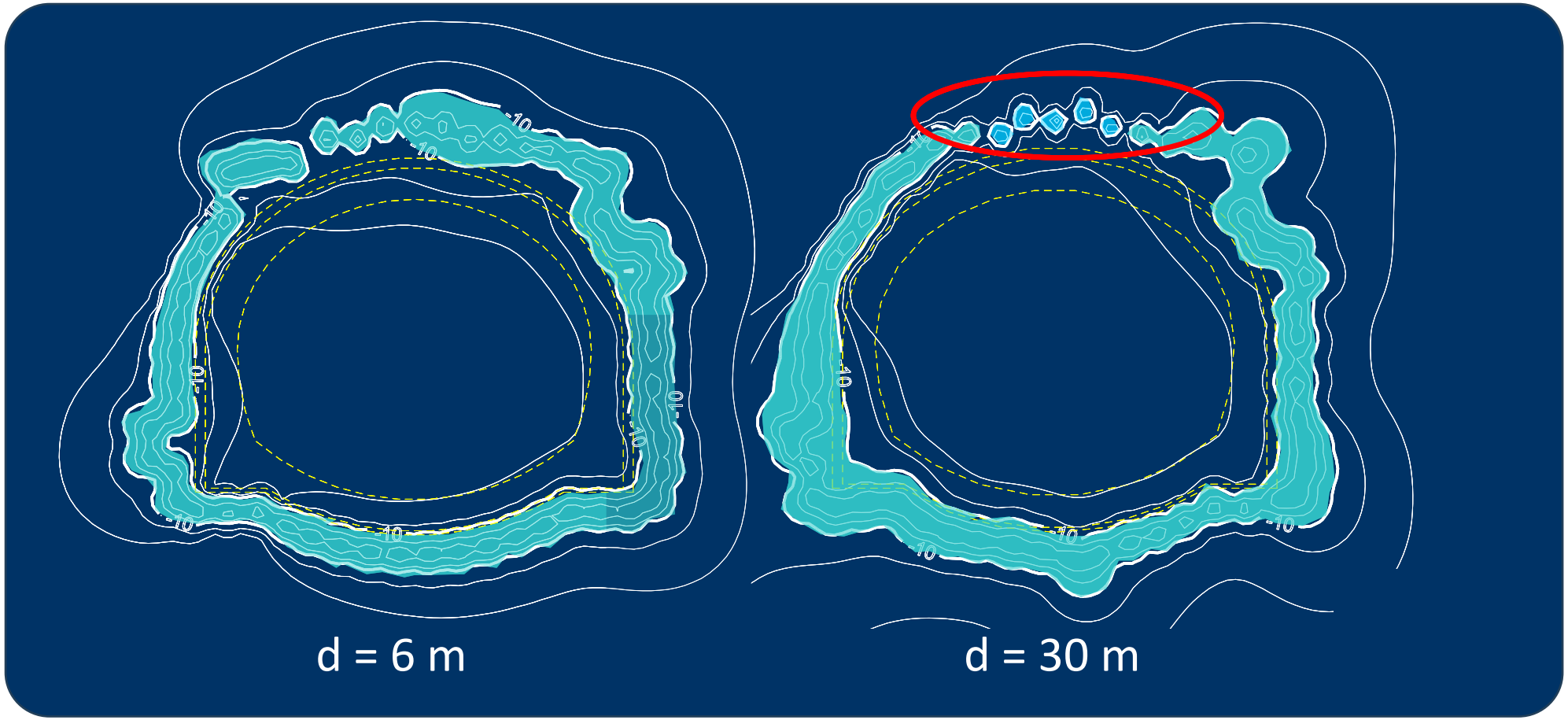


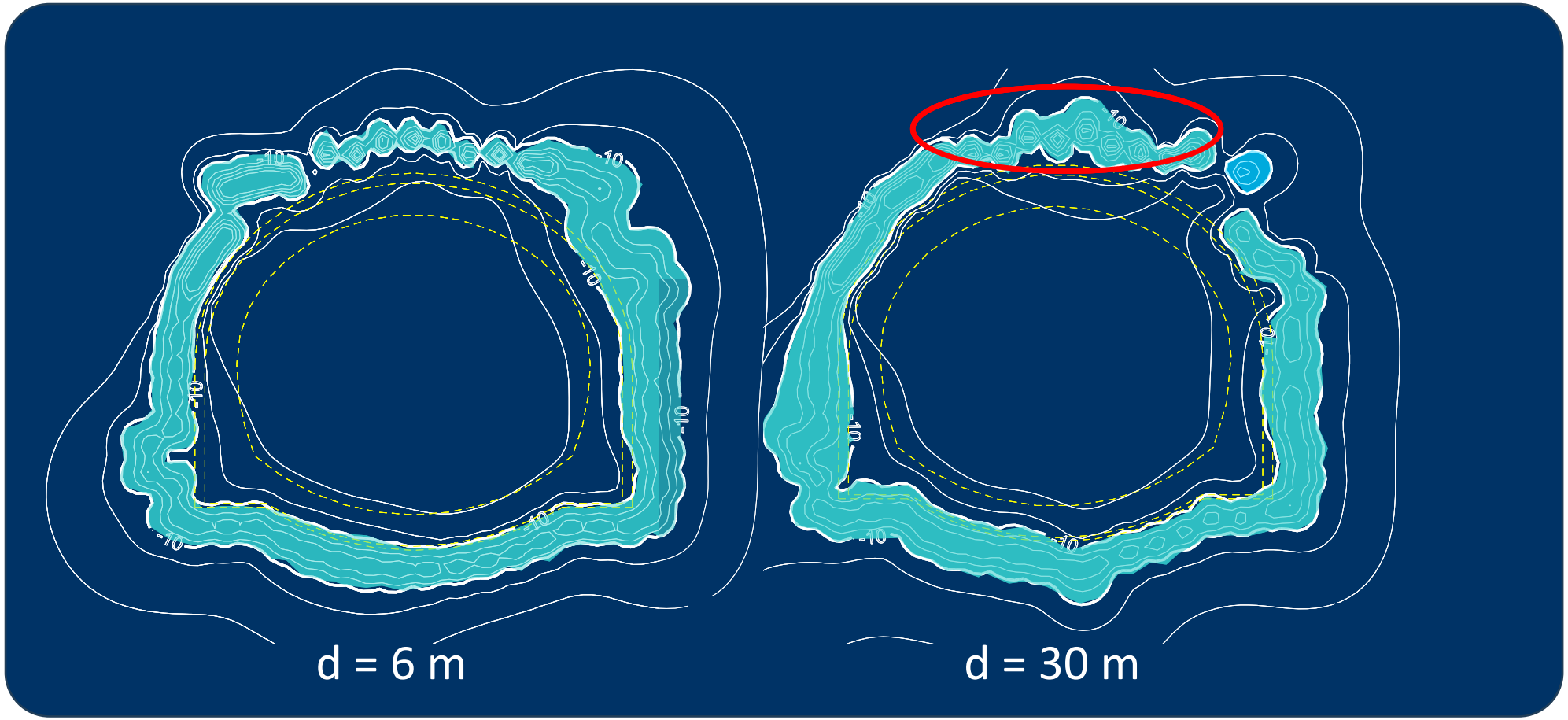
CONTROL OF CONSTRUCTION

after brine maintenance (26dd)

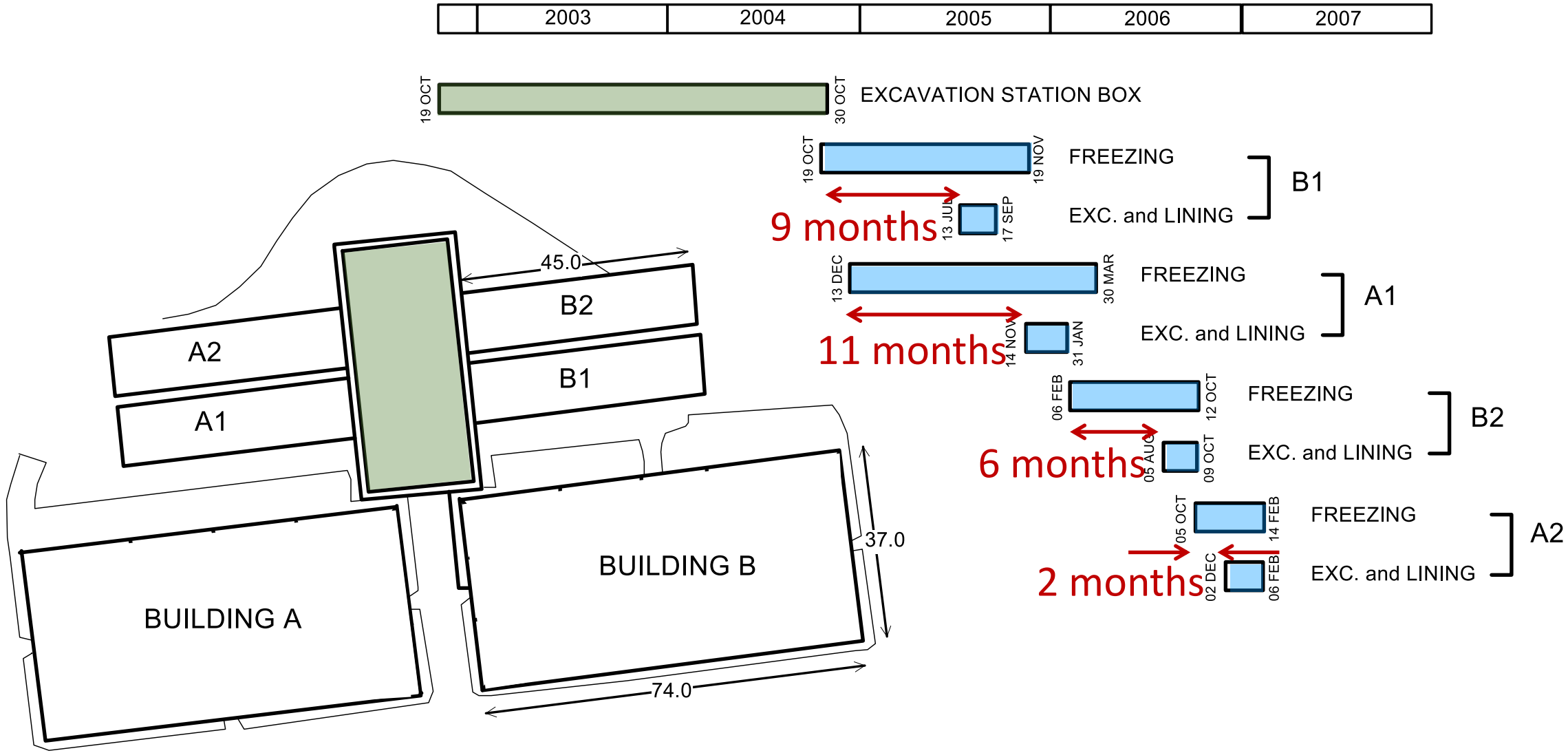


CONTROL OF CONSTRUCTION

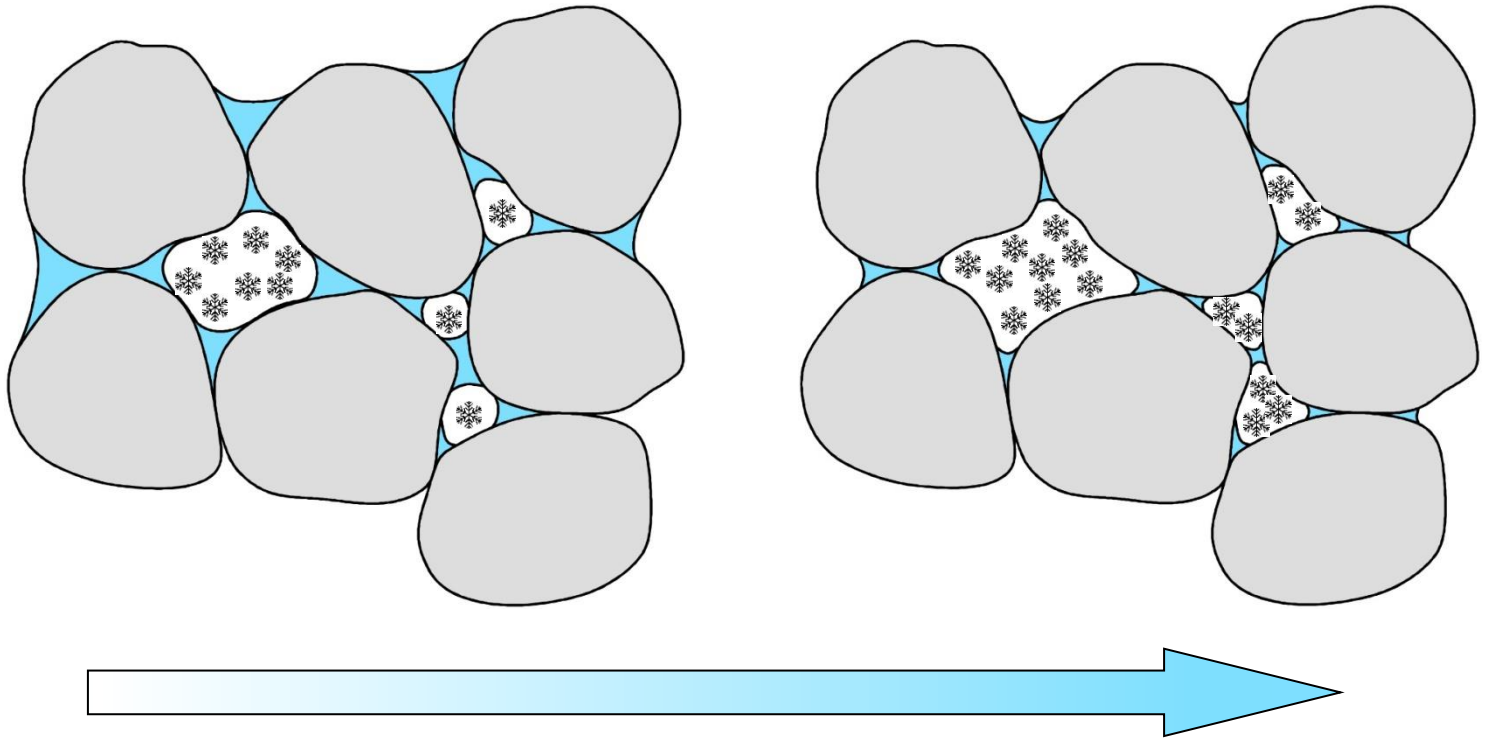
re-activation at crown with localised freezing



GARIBALDI construction phases

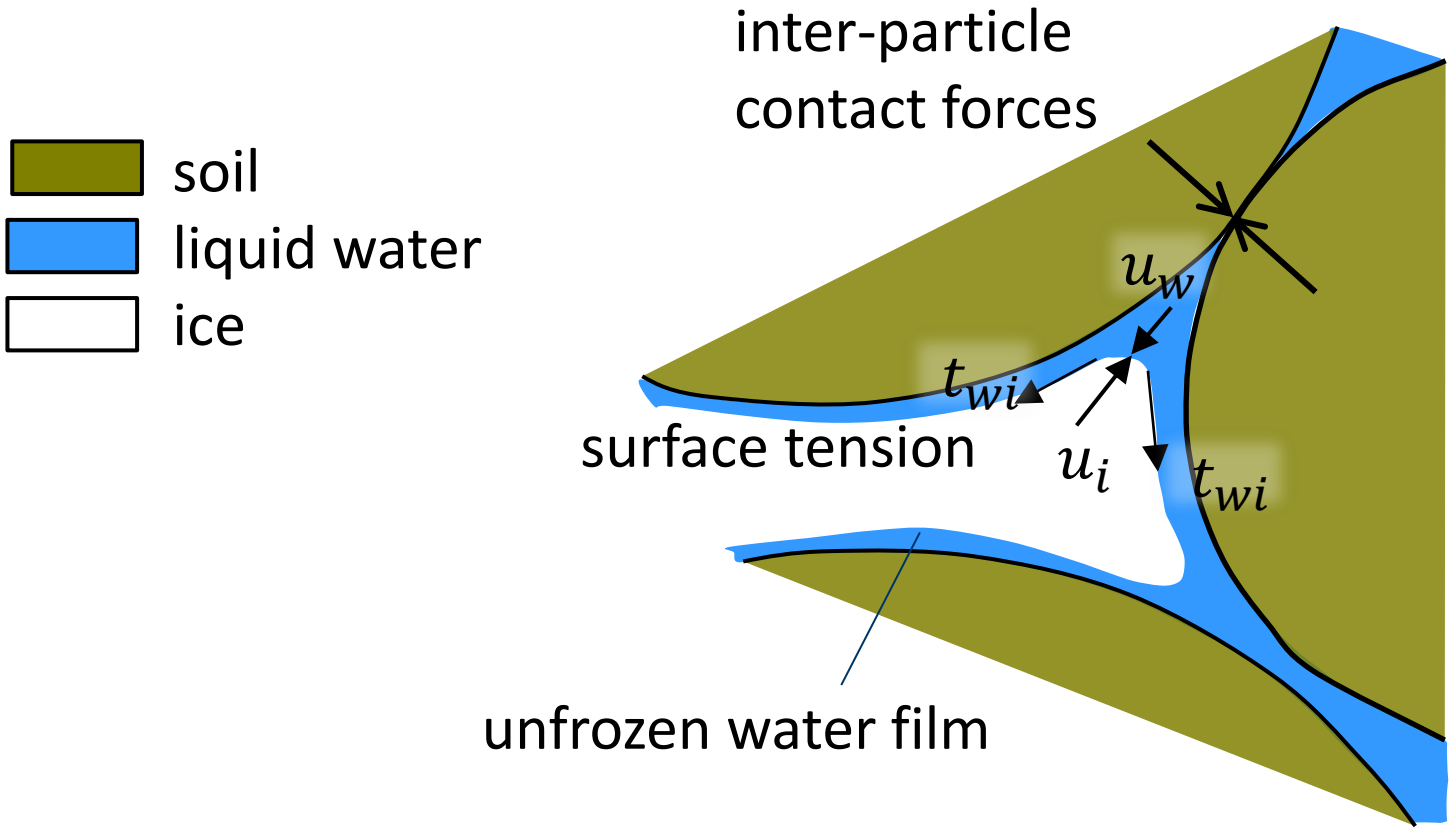


DEVELOPMENT OF SOIL FREEZING



reducing temperature

DEVELOPMENT OF SOIL FREEZING



COUPLED THM MODELLING

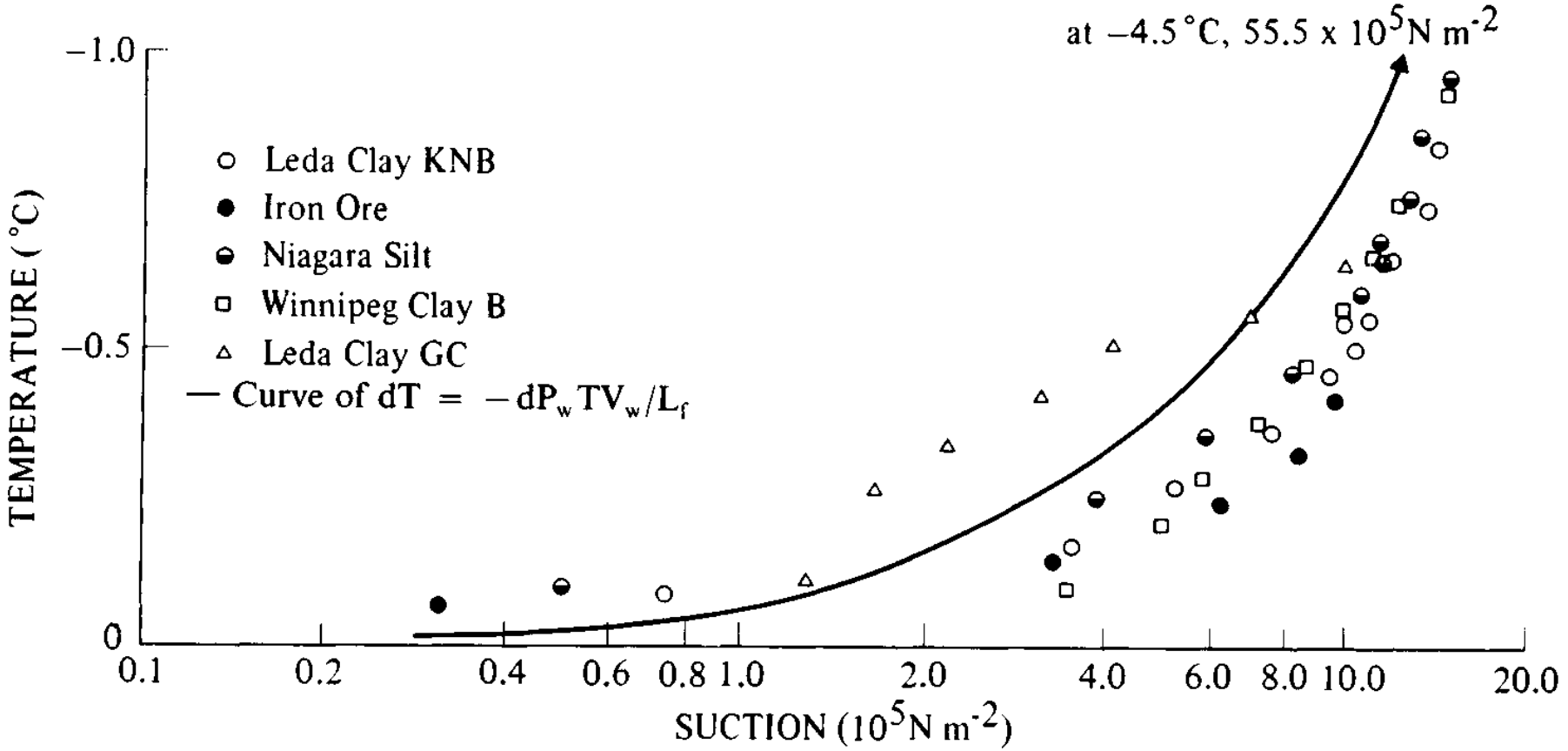
thermo-dynamical equilibrium
(Clausius-Clapeyron equation)

$$p_i = \frac{\rho_i}{\rho_w} p_w - \rho_i L \ln\left(\frac{T}{273.15\mathrm{K}}\right)$$

$$L = (s_l - s_i)T$$

latent heat of melting
(333.7 kJ/kg)

COUPLED THM MODELLING



COUPLED THM MODELLING

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$$p_i = \frac{\rho_i}{\rho_w} p_w - \rho_i L \ln\left(\frac{T}{273.15\mathrm{K}}\right)$$

ice retention curve
(van Genuchten equation)

$$S_w = S_{\mathrm{res}} + (1 - S_{\mathrm{res}}) \left[1 + \left(\frac{p_i - p_w}{P}\right)^{\frac{1}{1-M}}\right]^{-M}$$

COUPLED THM MODELLING

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(Clausius Clapeyron equation)

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$$S_w = S_{\mathrm{res}} + (1 - S_{\mathrm{res}}) \left[1 + \left(\frac{\left(\frac{\rho_i}{\rho_w} - 1\right) p_w - \rho_i L \ln\frac{T}{273.15}}{P}\right)^{\frac{1}{1-M}}\right]^{-M}$$

COUPLED THM MODELLING

thermo-dynamical equilibrium
(Clausius Clapeyron equation)

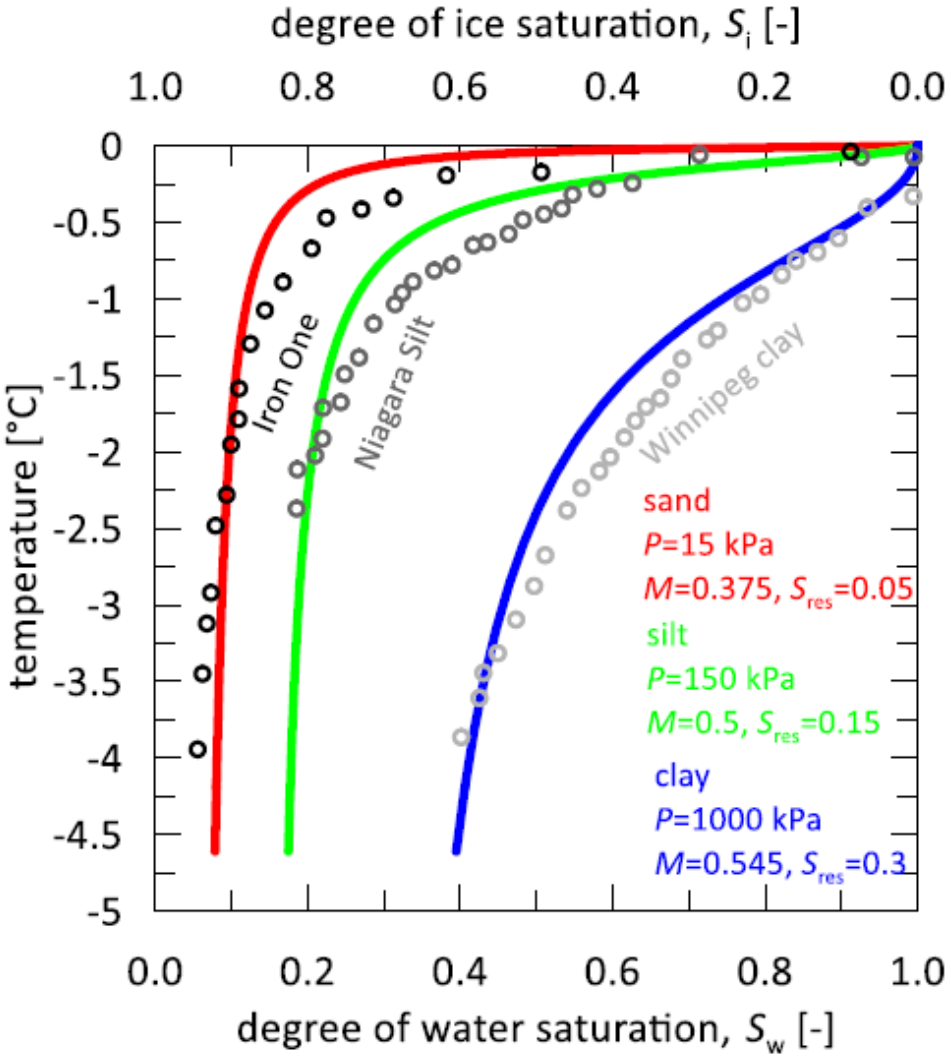
$$p_i = \frac{\rho_i}{\rho_w} p_w - \rho_i L \ln\left(\frac{T}{273.15\mathrm{K}}\right)$$

freezing retention curve
(van Genuchten equation)

$$S_w = S_{\mathrm{res}} + (1 - S_{\mathrm{res}}) \left[1 + \left(\frac{p_i - p_w}{P}\right)^{\frac{1}{1-M}}\right]^{-M}$$

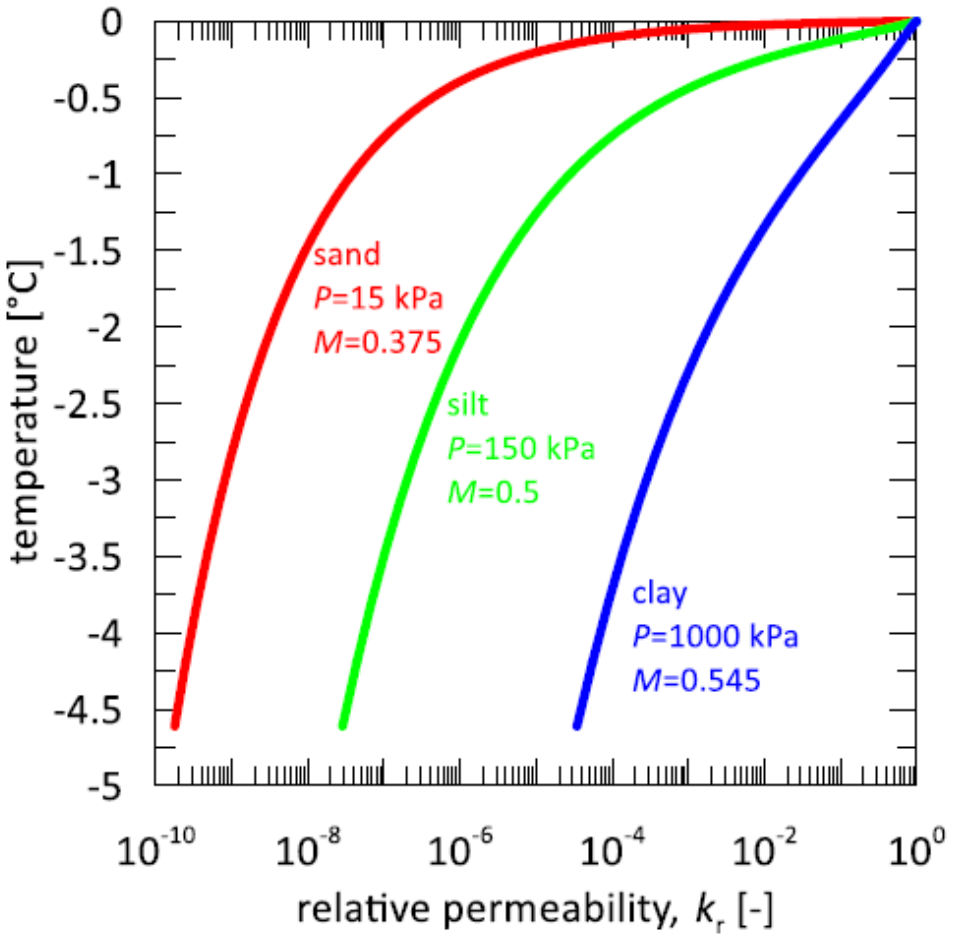
$$S_w = S_{\mathrm{res}} + (1 - S_{\mathrm{res}}) \left[1 + \left(\frac{-\rho_i L \ln \frac{T}{273.15}}{P}\right)^{\frac{1}{1-\mu}}\right]^{-\mu}$$

COUPLED THM MODELLING



hydraulic conductivity

$$\mathbf{K} = k_r(S_w)\mathbf{K_{sat}}$$



COUPLED THM MODELLING

mass balance of mineral (solid)

$$\frac{\partial}{\partial t}\left(\theta_s(1-n)\right) + \nabla(\mathbf{j}_s) = 0$$

mass balance of water (liquid and ice)

$$\frac{\partial}{\partial t}\left(\theta_l^w S_l n + \theta_i^w S_i n\right) + \nabla(\mathbf{j}_l^w + \mathbf{j}_i^w) = f^w$$

internal energy balance for the medium

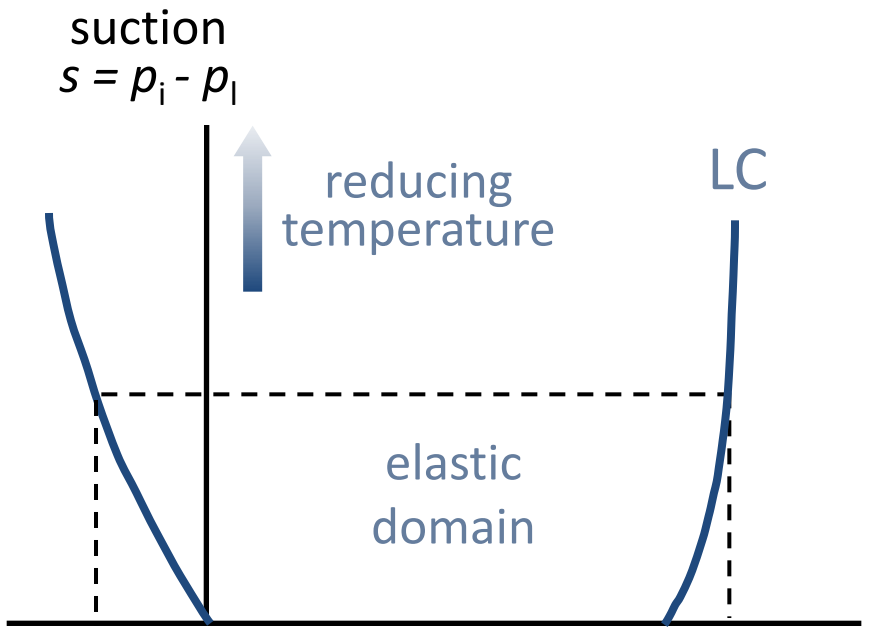
$$\frac{\partial}{\partial t}\left(E_s\rho_s(1-n) + E_l\rho_l S_l n + E_i\rho_i S_i n\right) + \nabla(\mathbf{i}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Ei}) = f^Q$$

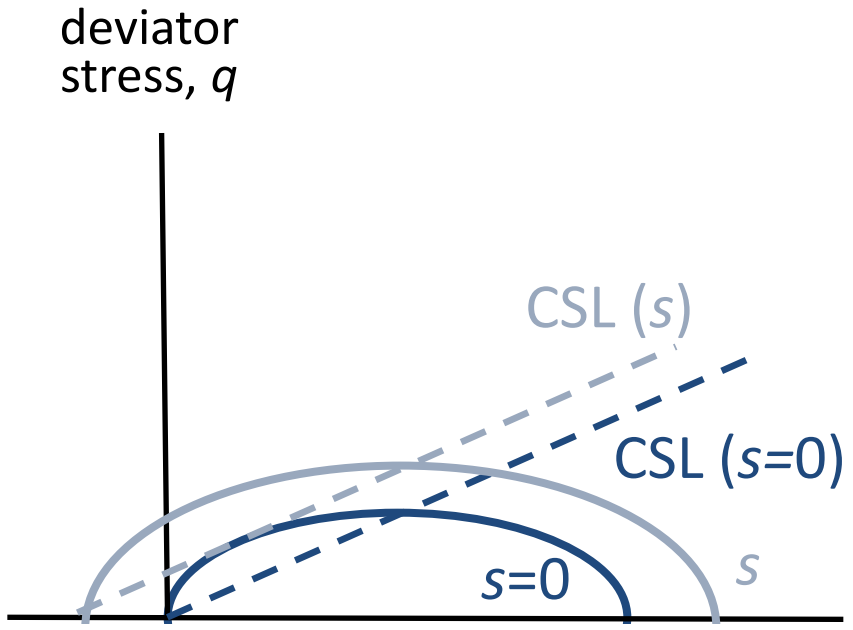
momentum balance for the medium (equilibrium)

$$\nabla\boldsymbol{\sigma} + \mathbf{b} = 0$$

COUPLED THM MODELLING

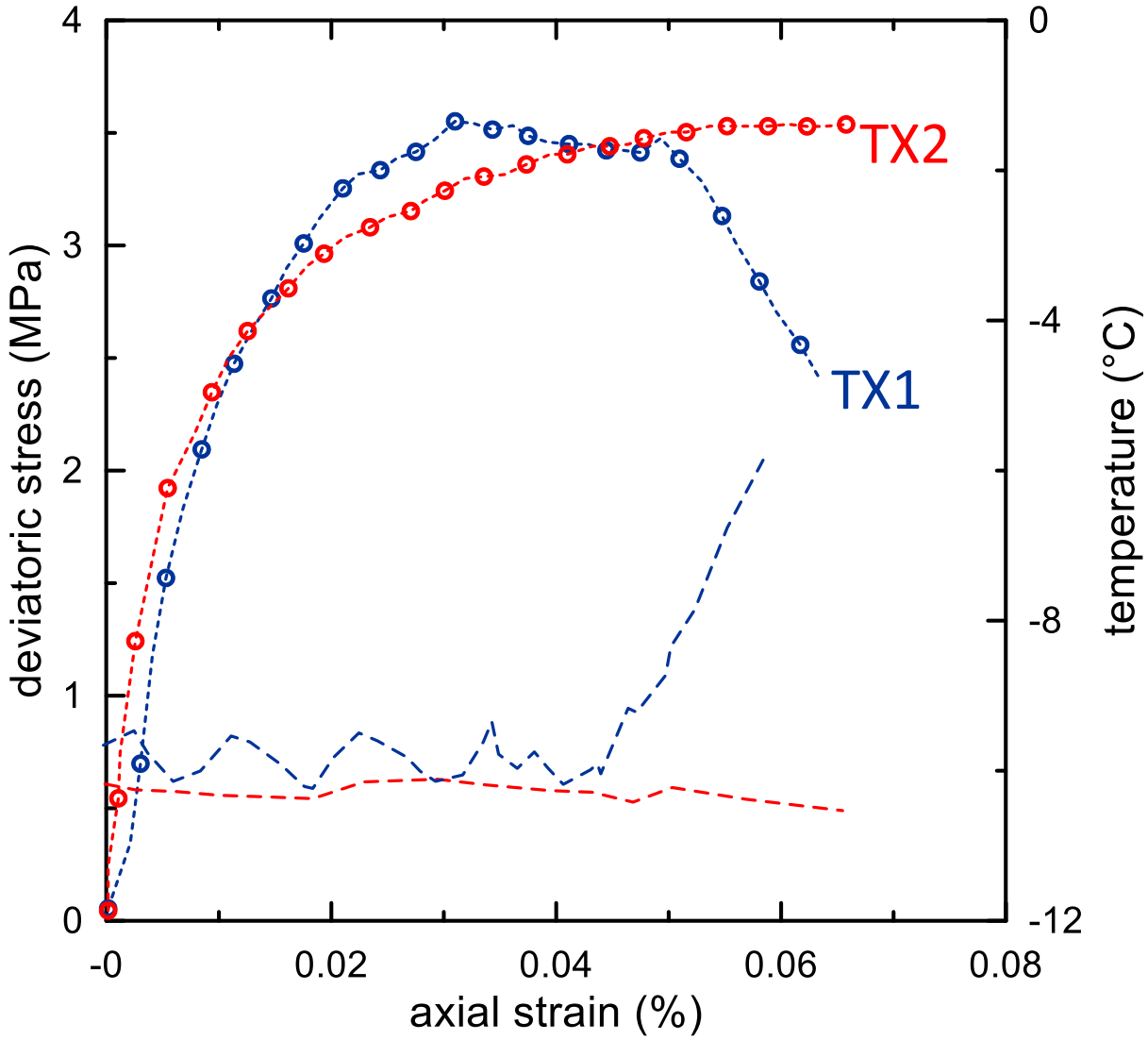
adaptation of BBM (two stress variable elasto-plastic model)





Nishimura et al. (2009)

COUPLED THM MODELLING TX data



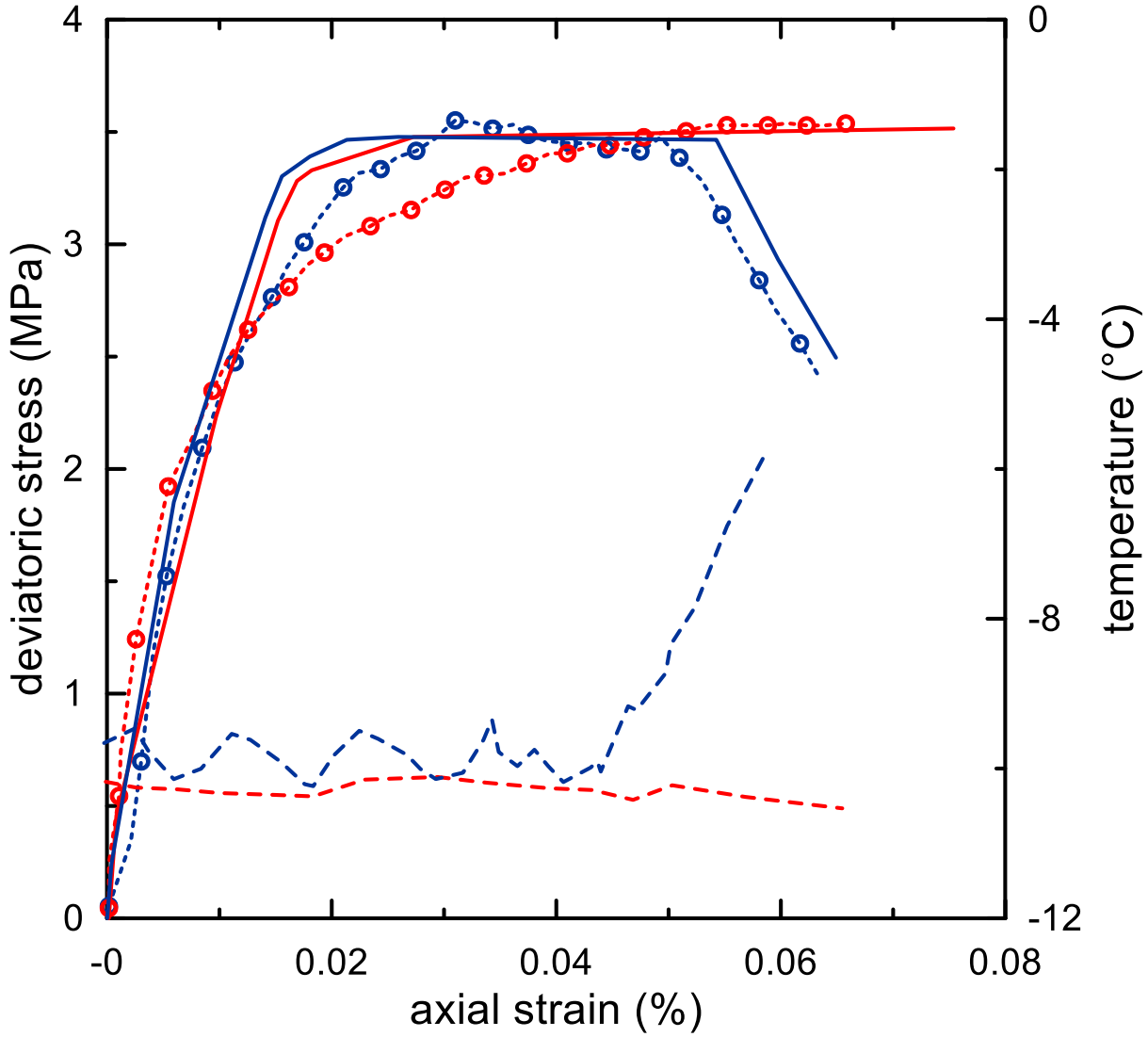
POZZOLANA

200 kPa

350 kPa

$\dot{\varepsilon}_{ax} = 0.06$ mm/min

COUPLED THM MODELLING TX data vs model



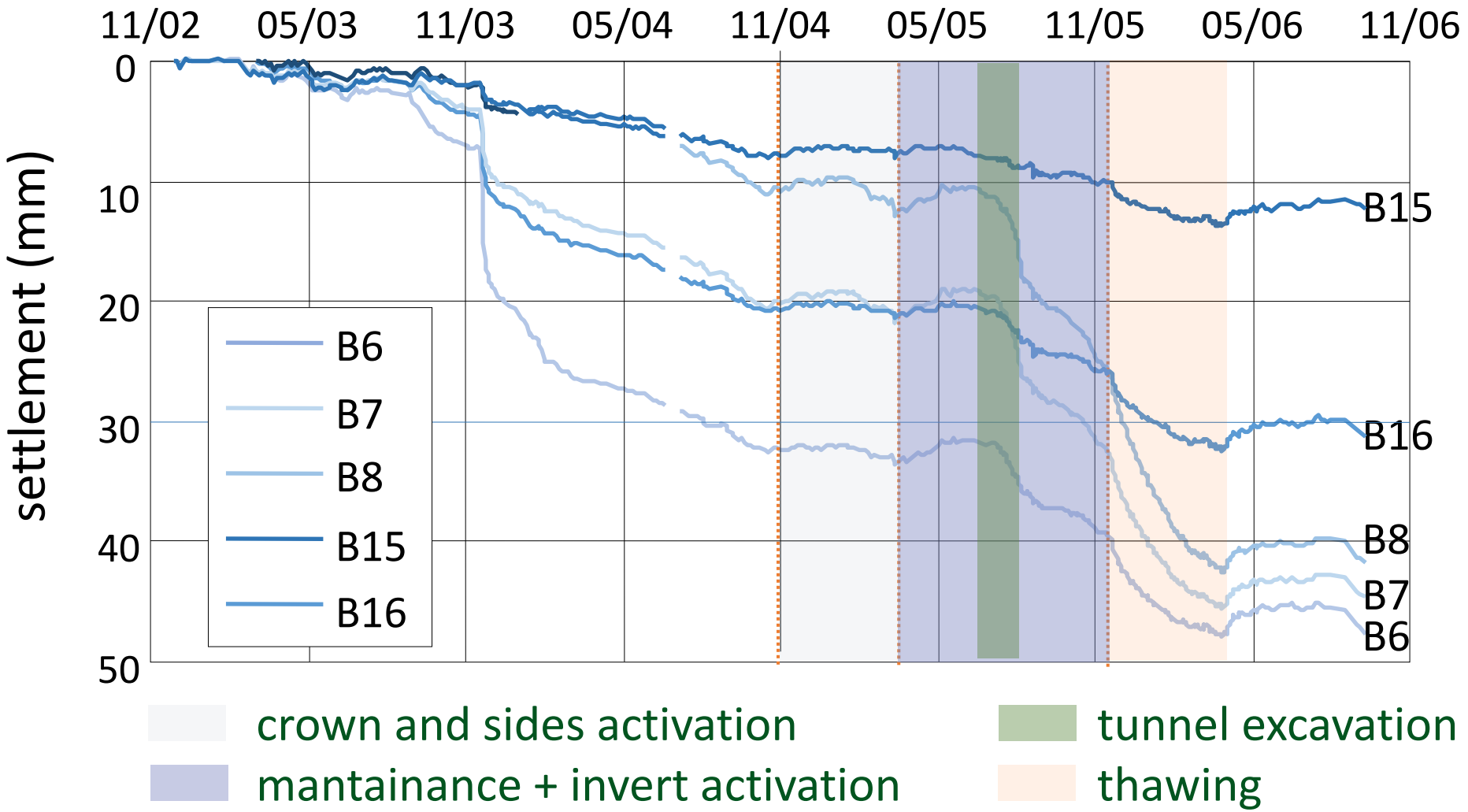
POZZOLANA

200 kPa

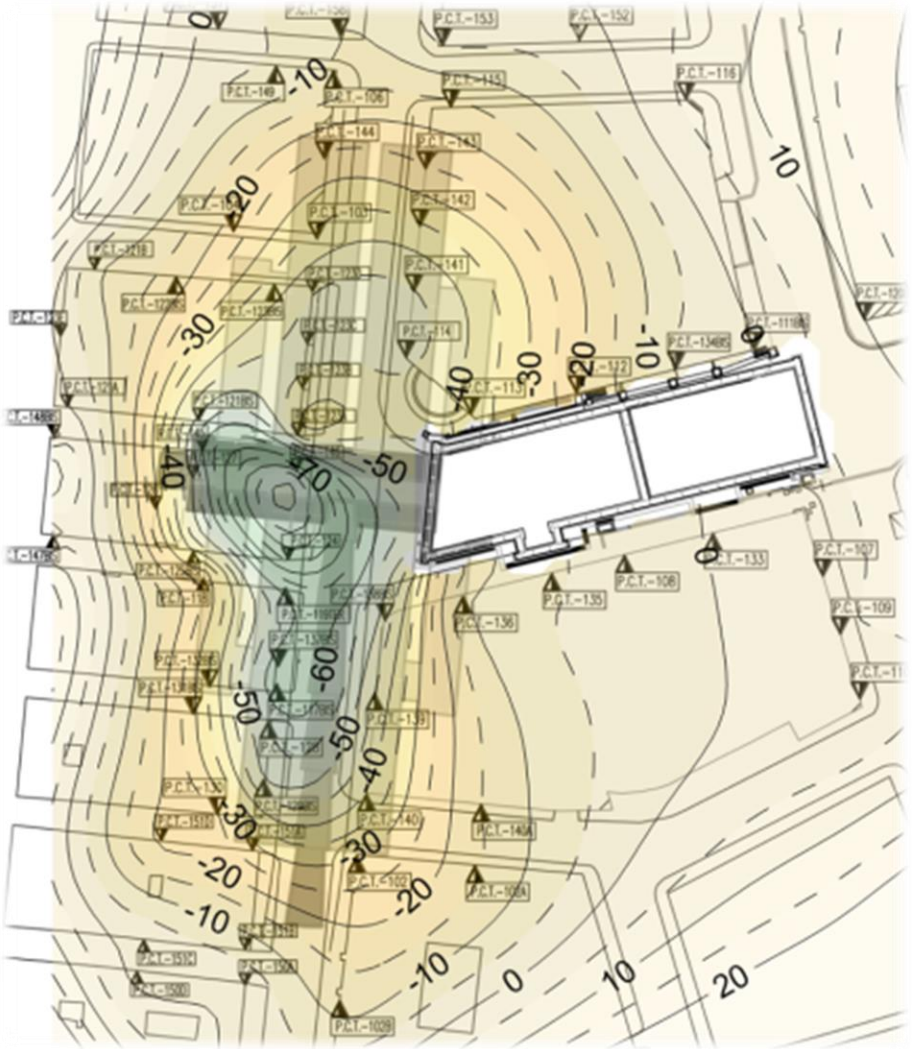
350 kPa

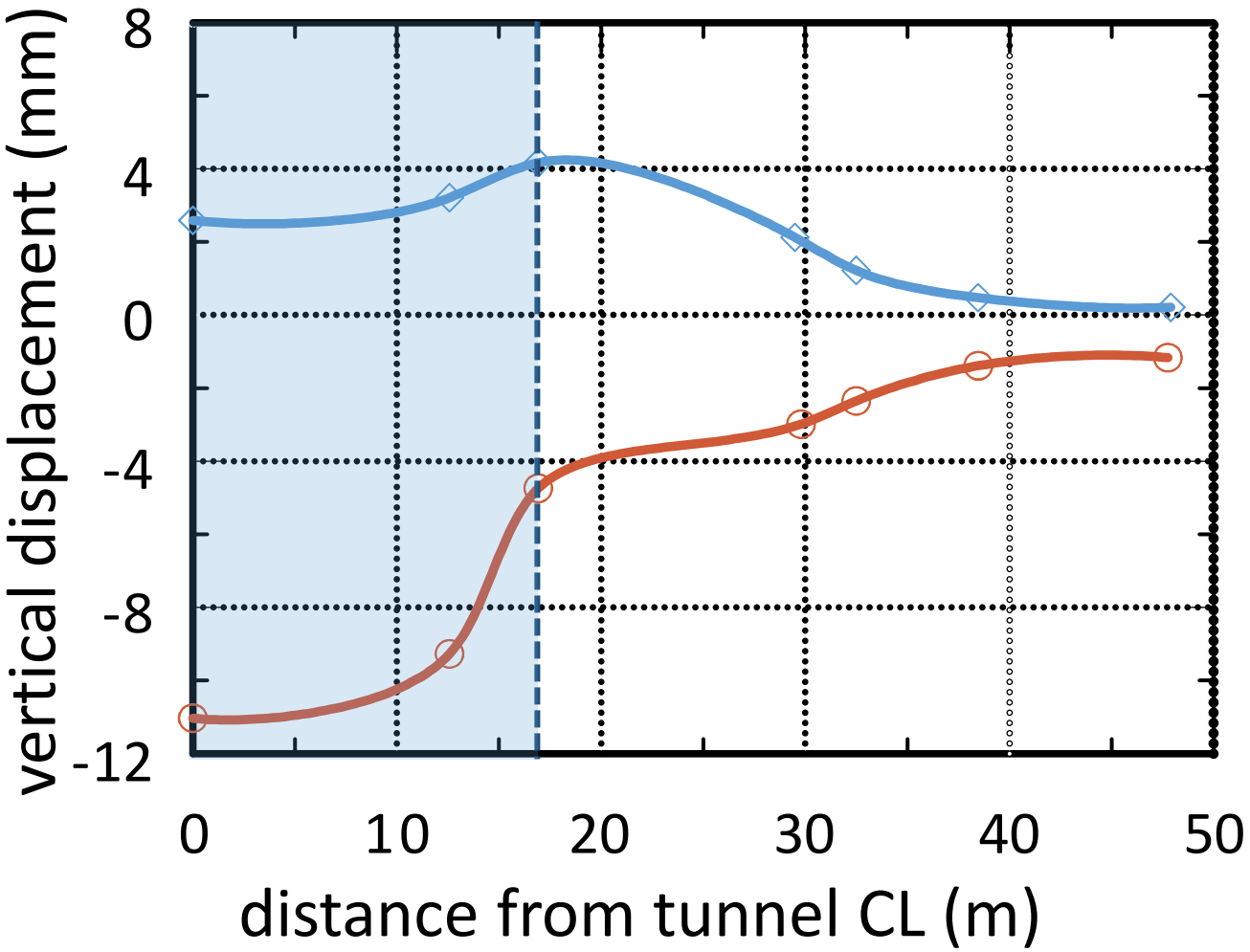
$\dot{\varepsilon}_{ax} = 0.06$ mm/min

GARIBALDI surface settlements

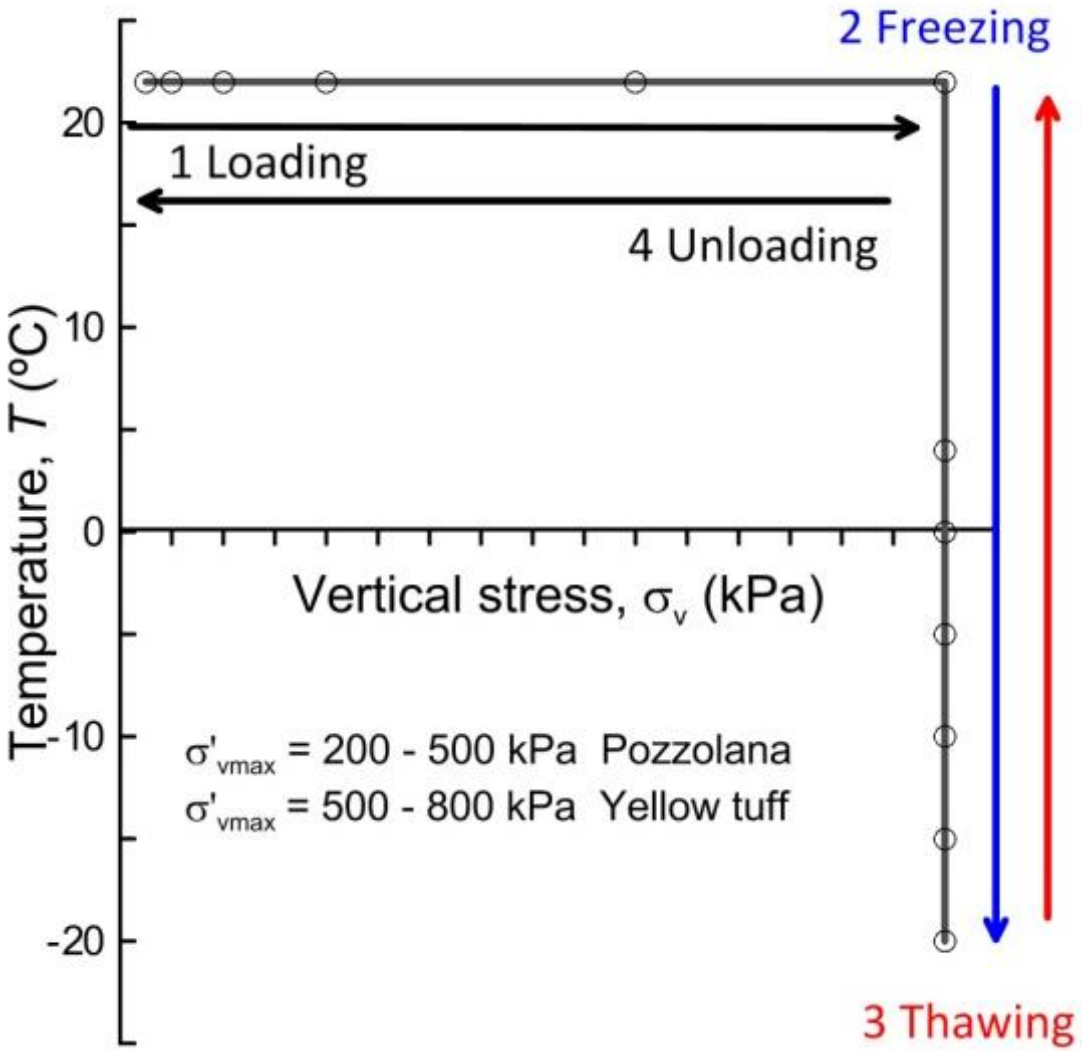


TOLEDO surface settlements

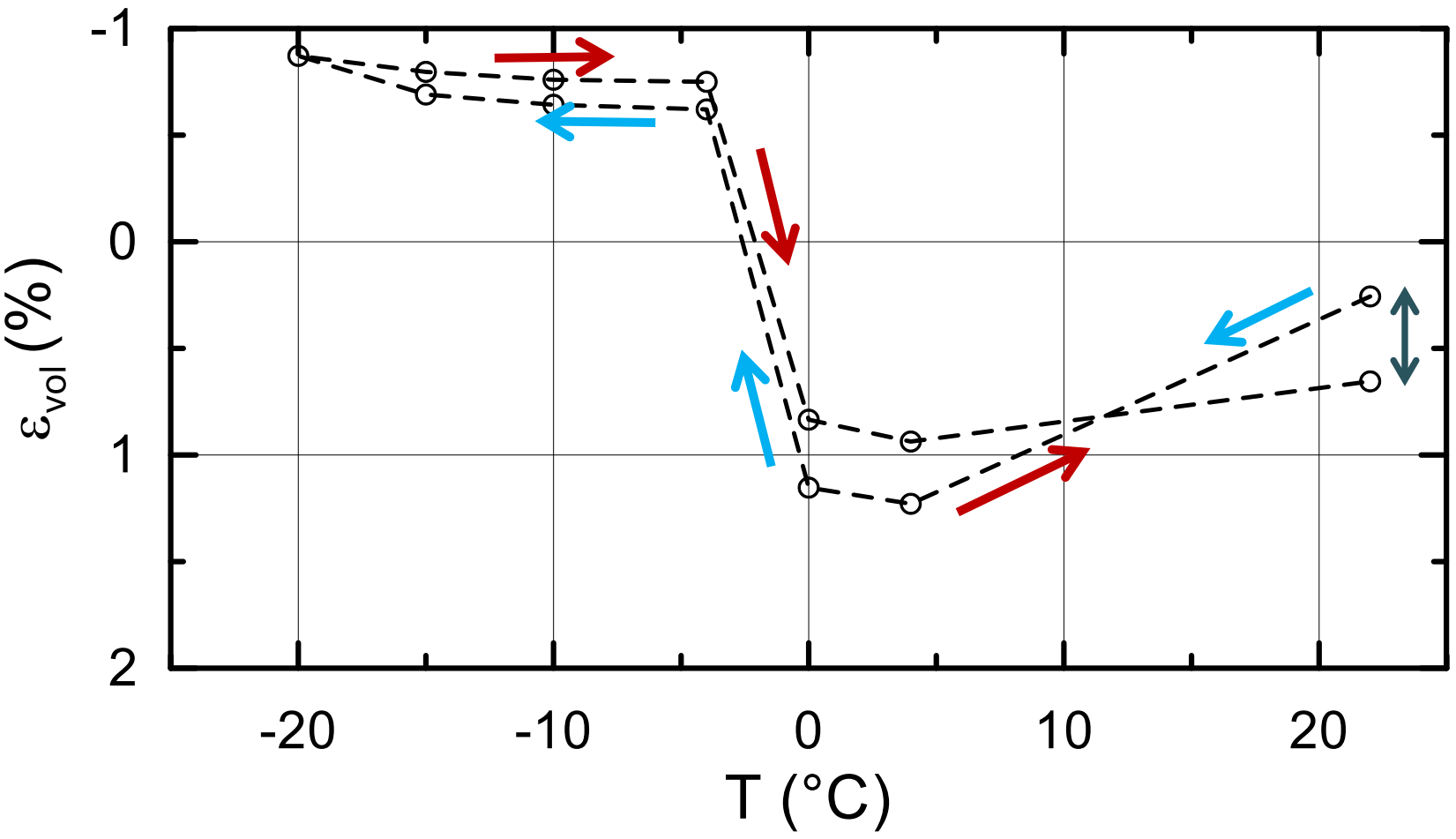




THAW BEHAVIOUR testing programme



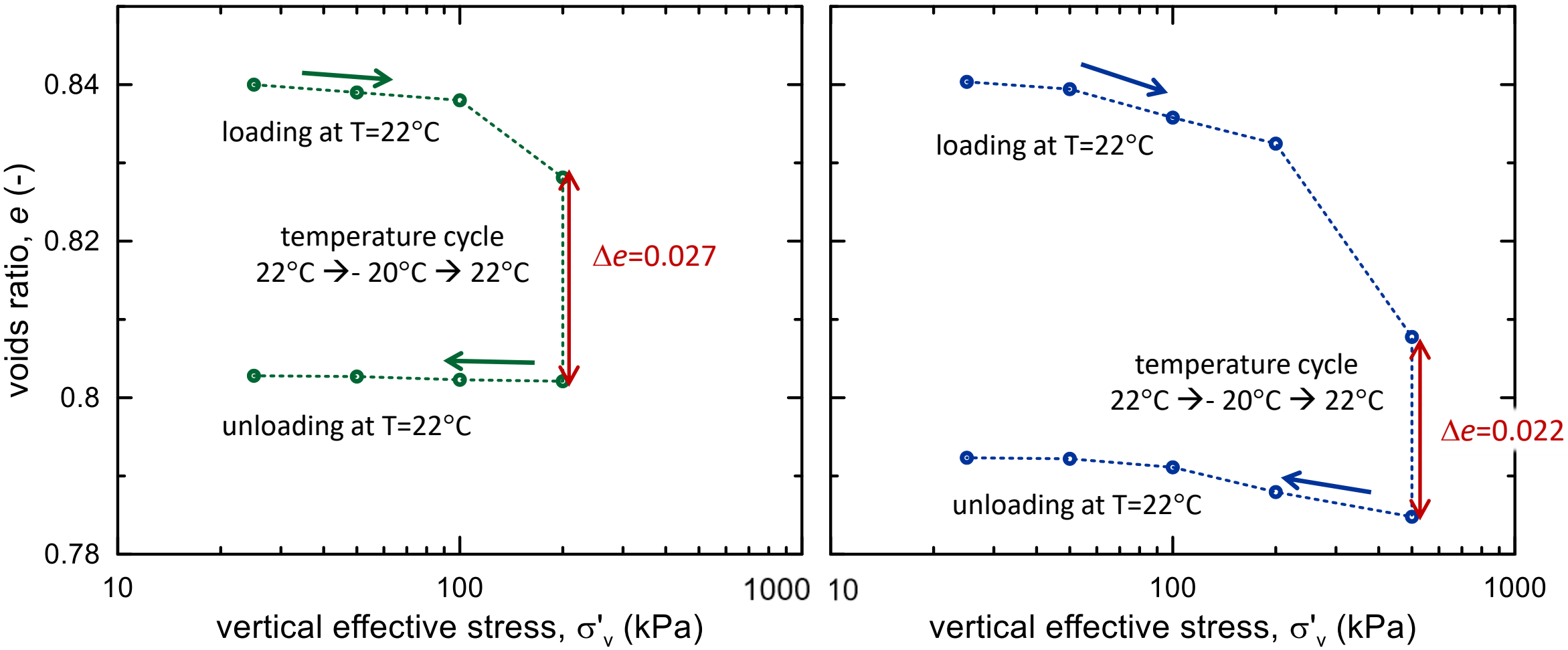
THAW BEHAVIOUR results



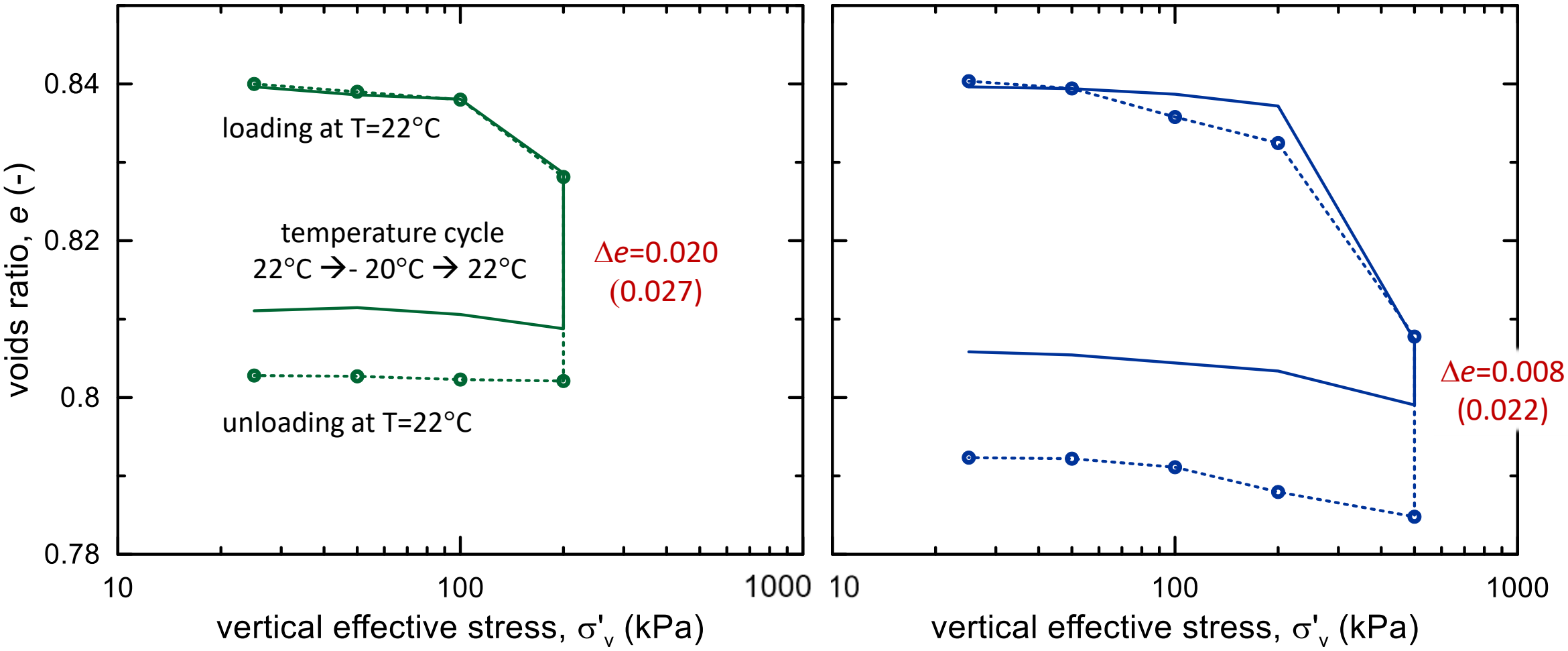
$\Delta\varepsilon_{vol}$= 0.37%

TUFF
800 kPa

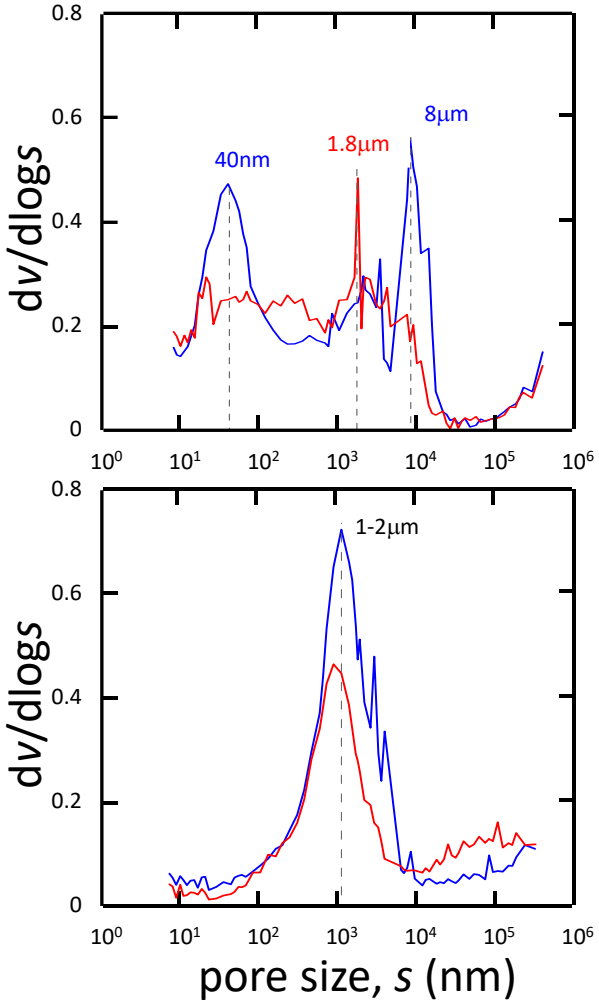
THAW BEHAVIOUR results

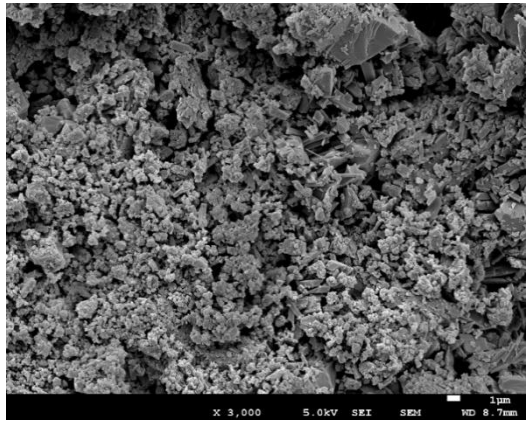


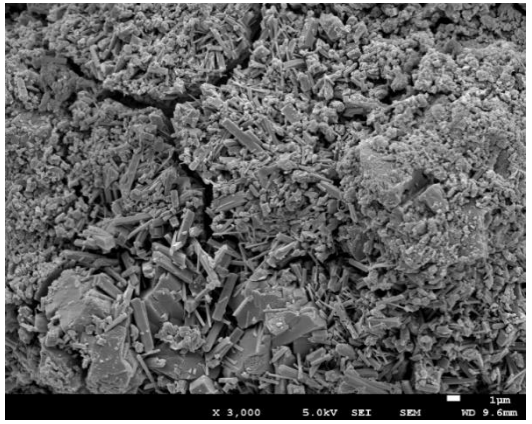
THAW BEHAVIOUR results



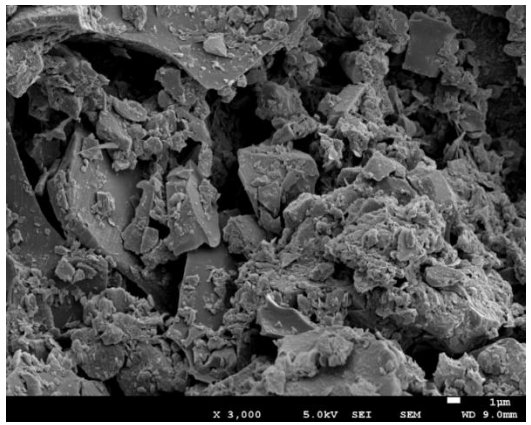
THAW BEHAVIOUR microstructure

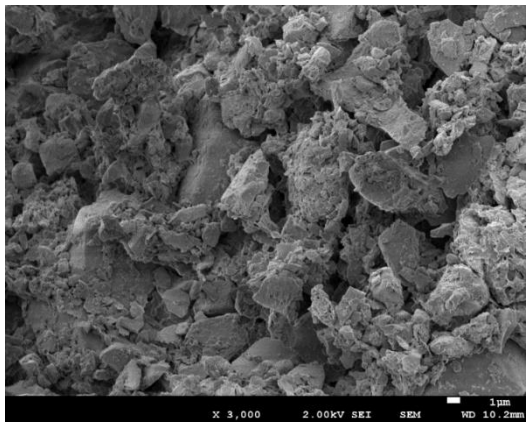






TUFF





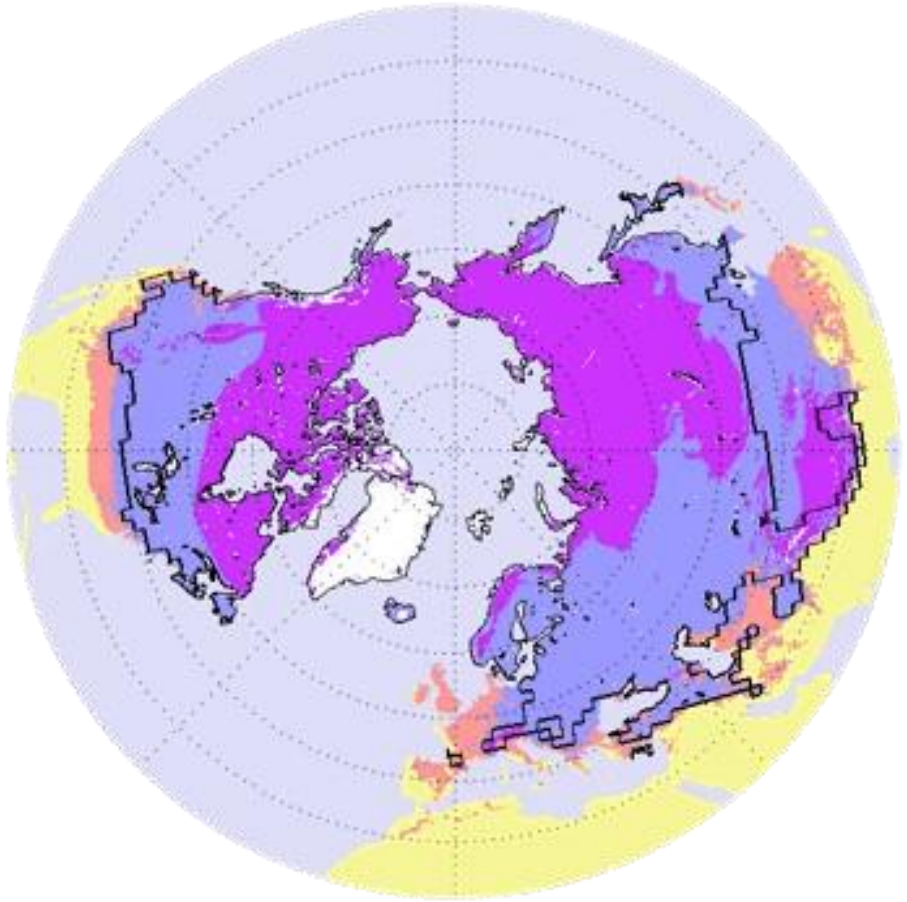
POZZOLANA

before freezing

after freezing

SEASONAL FREEZING/THAWING

55 to 60% of exposed land surface in northern hemisphere freezes & thaws seasonally



- permanently frozen ground
- seasonally frozen ground (≥15 days/year)
- intermittently frozen ground (<15 days/year)

SEASONAL FREEZING/THAWING effects on infrastructure

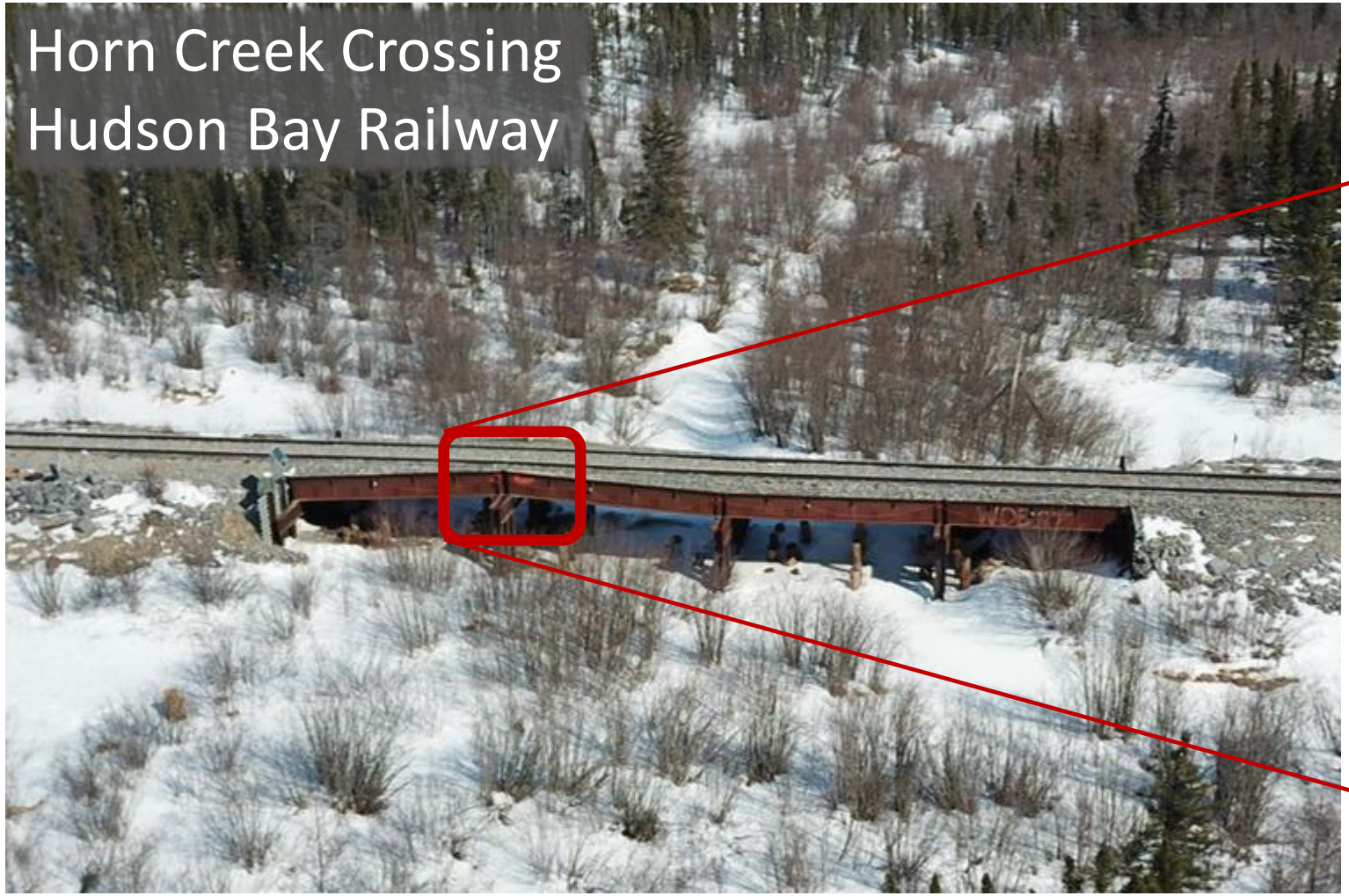
irrigation canals

Li *et al.*, 2019

road pavements

Ystenes, 2011

SEASONAL FREEZING/THAWING effects on infrastructure

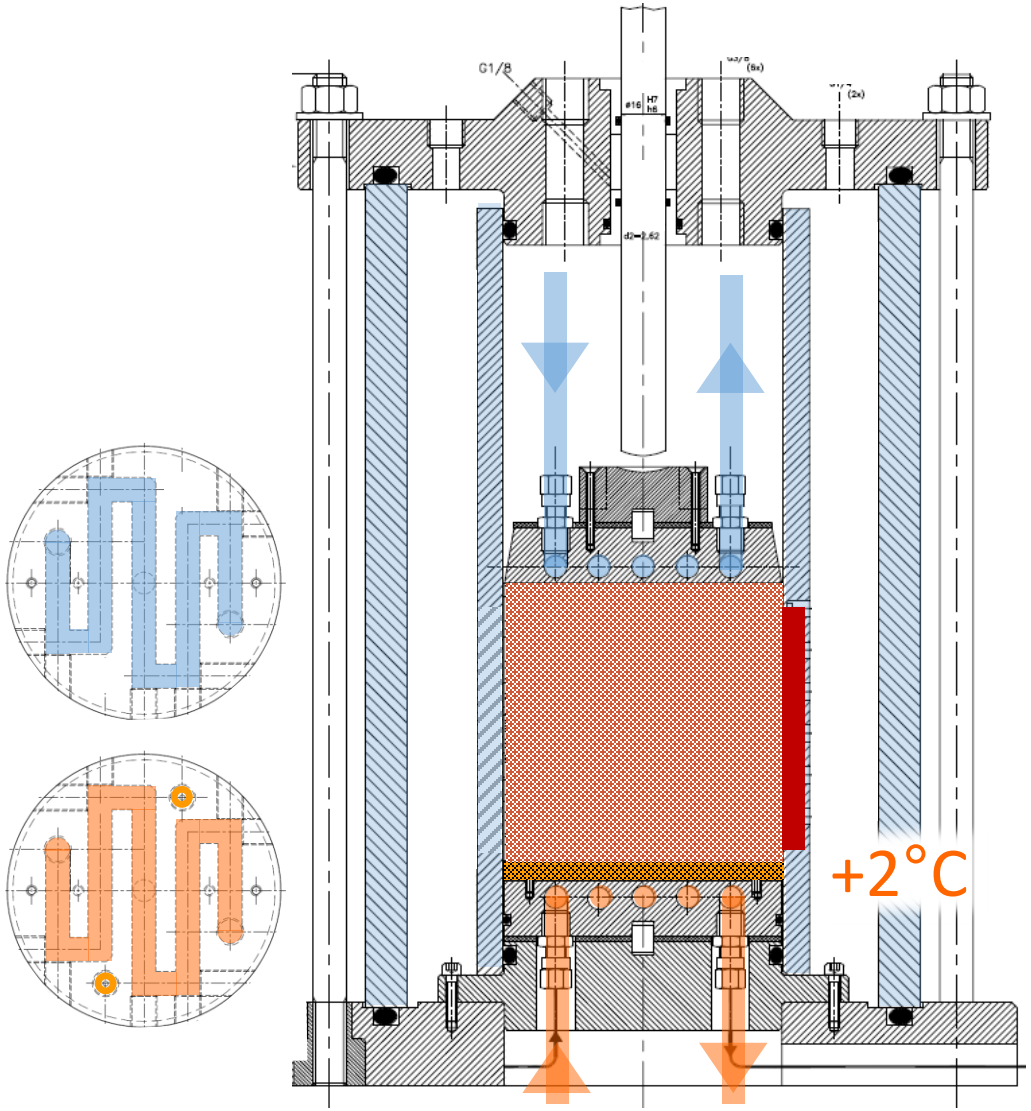


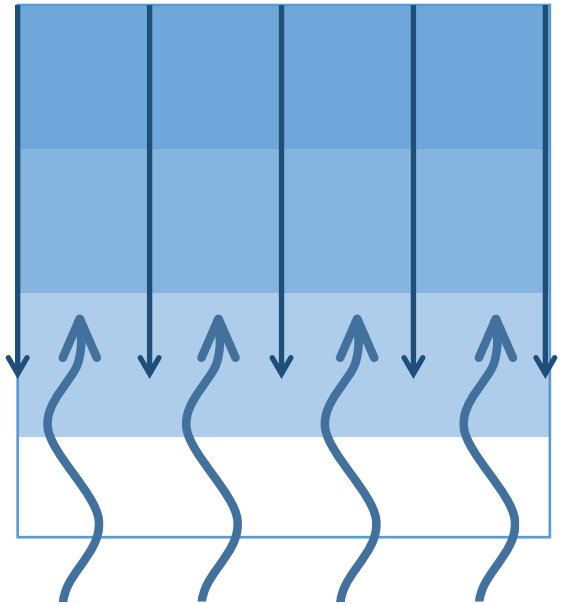
bridges

Arpin, Beddoe & Take (2023)

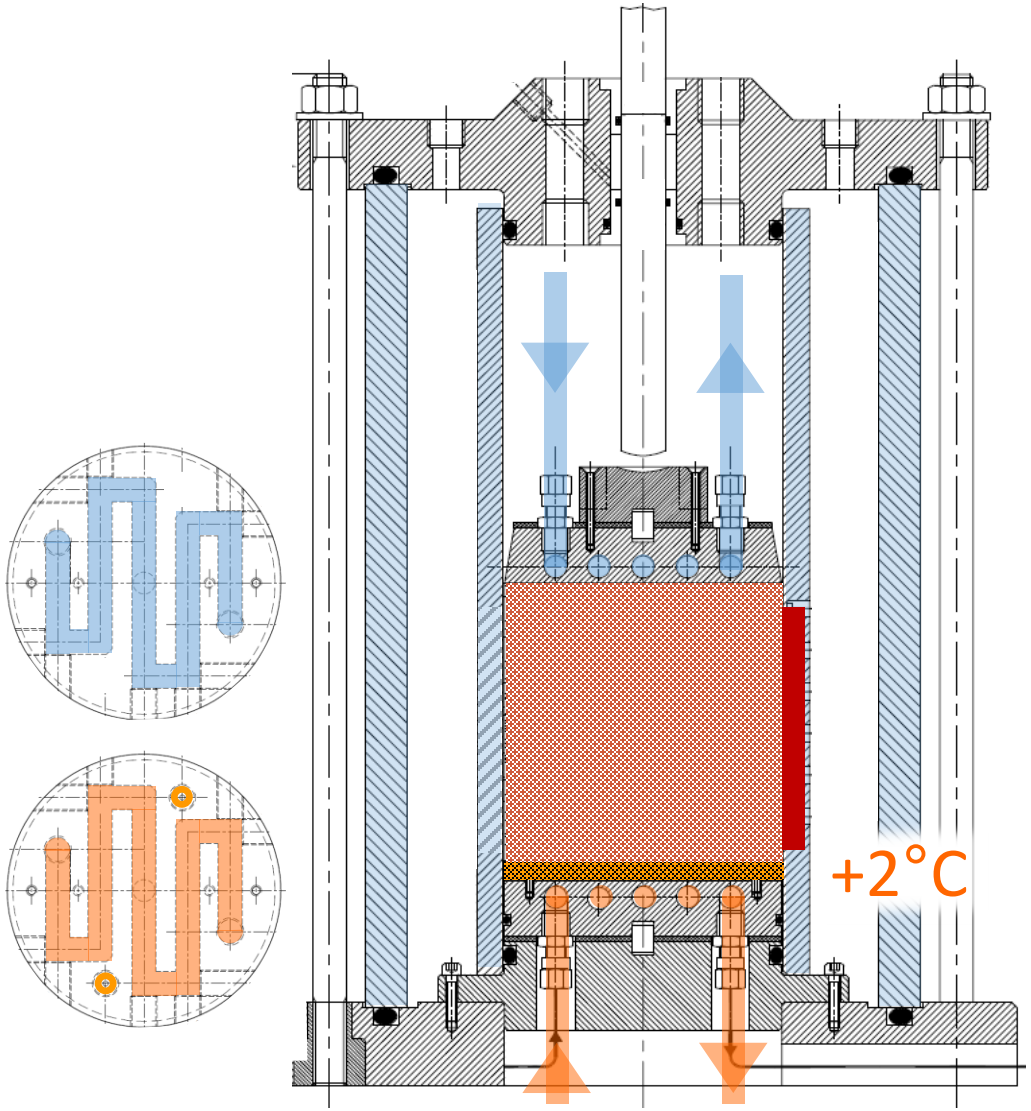
THAW BEHAVIOUR equipment

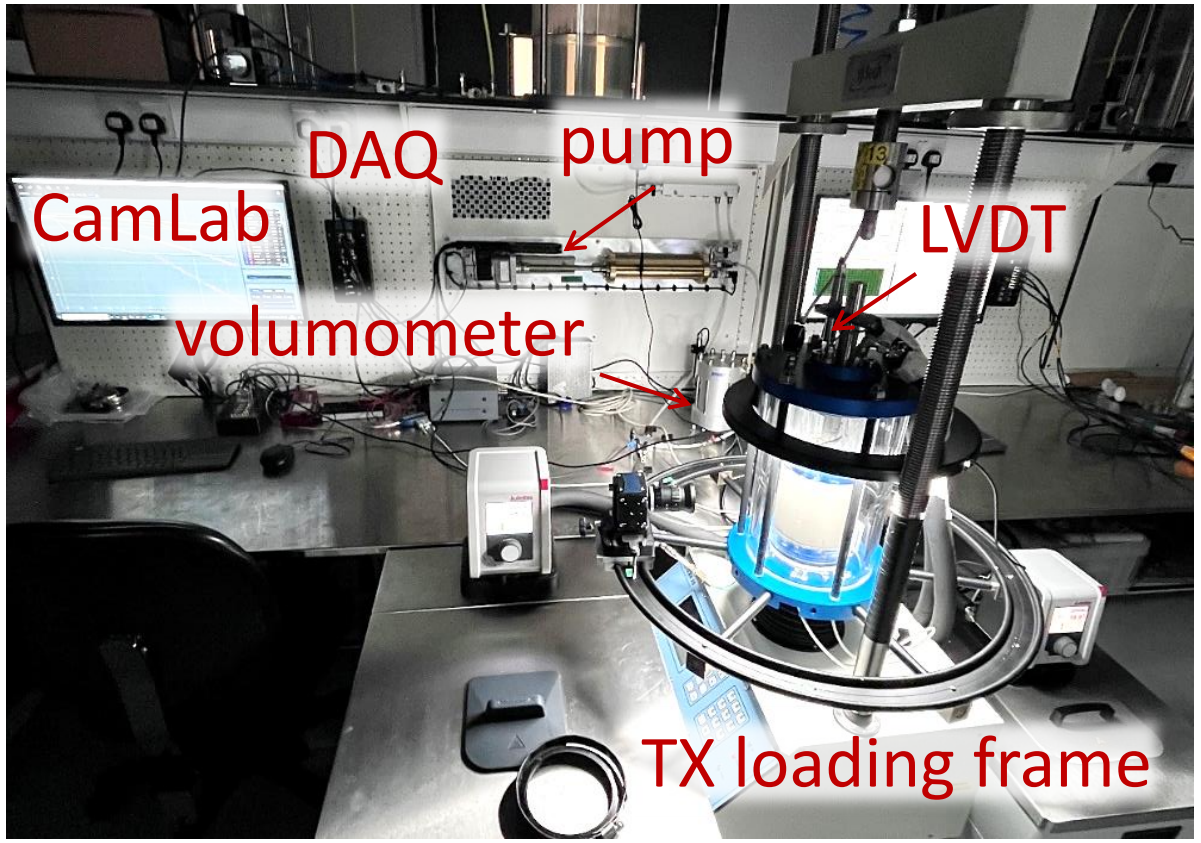
FROST HEAVE APPARATUS (FHA)



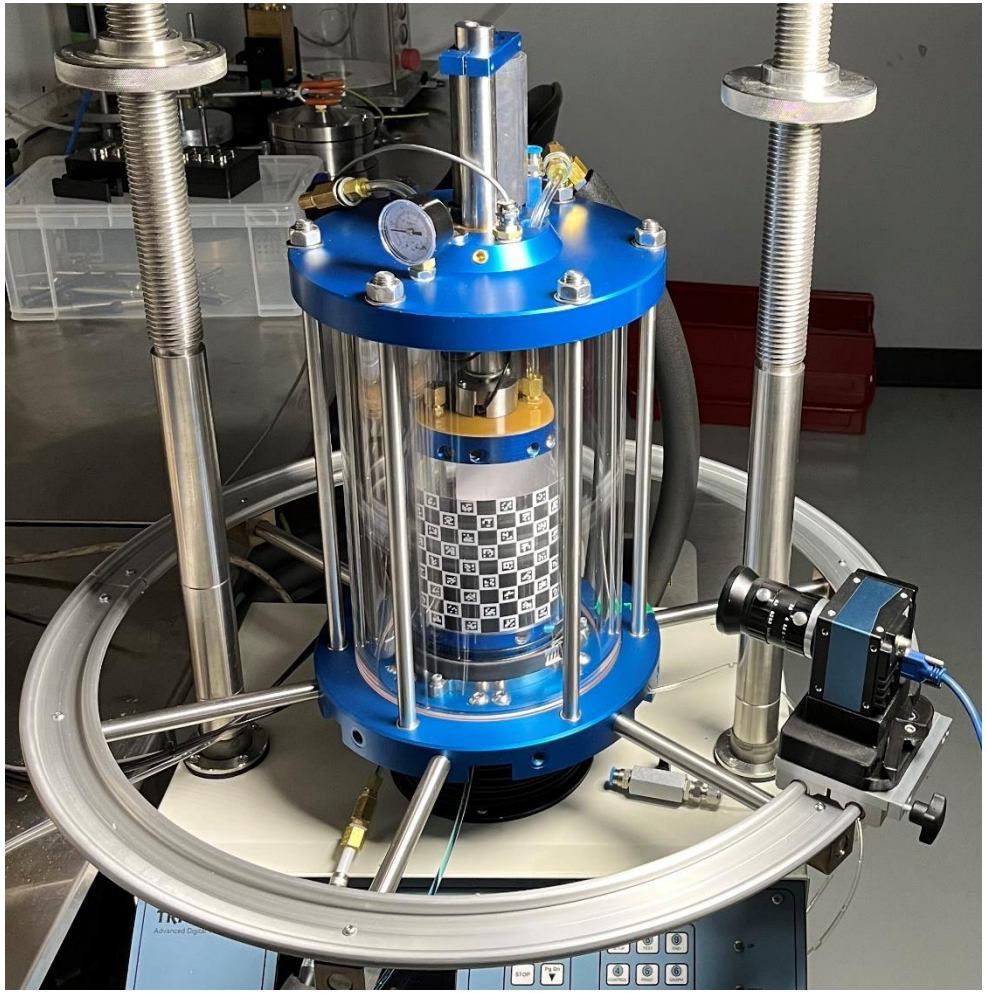


FROST HEAVE APPARATUS (FHA)





(PSEUDO) 3D PHOTOGRAMMETRIC MODEL



DaHeng Vision MARS1231 camera
(1/3 sample surface)

“one-shot” calibration
(constant radius constraint)

new photogrammetric model
cell wall-induced distortions

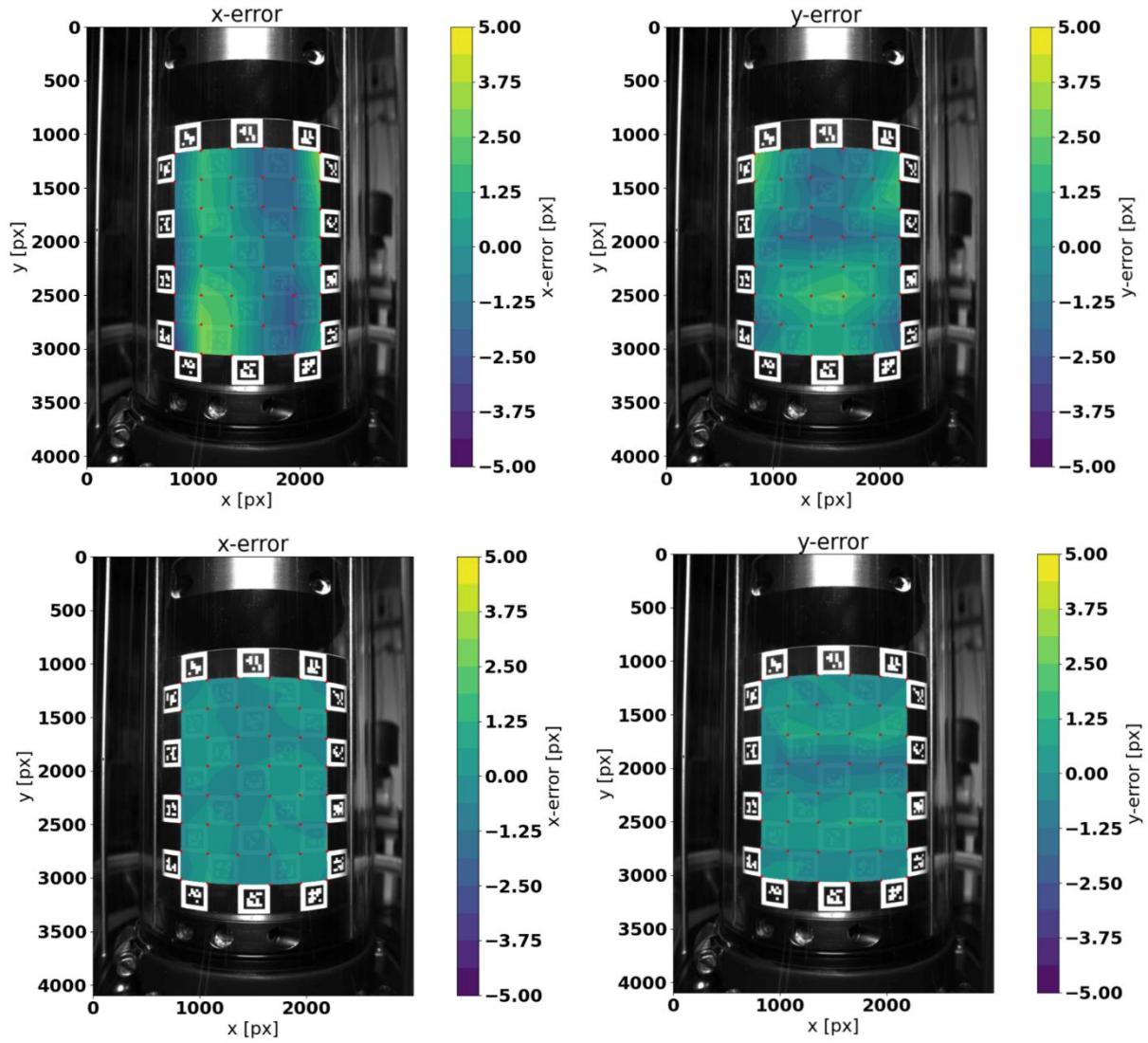
Stanier & Lattuada

(PSEUDO 3D) PHOTOGRAMMETRIC MODEL

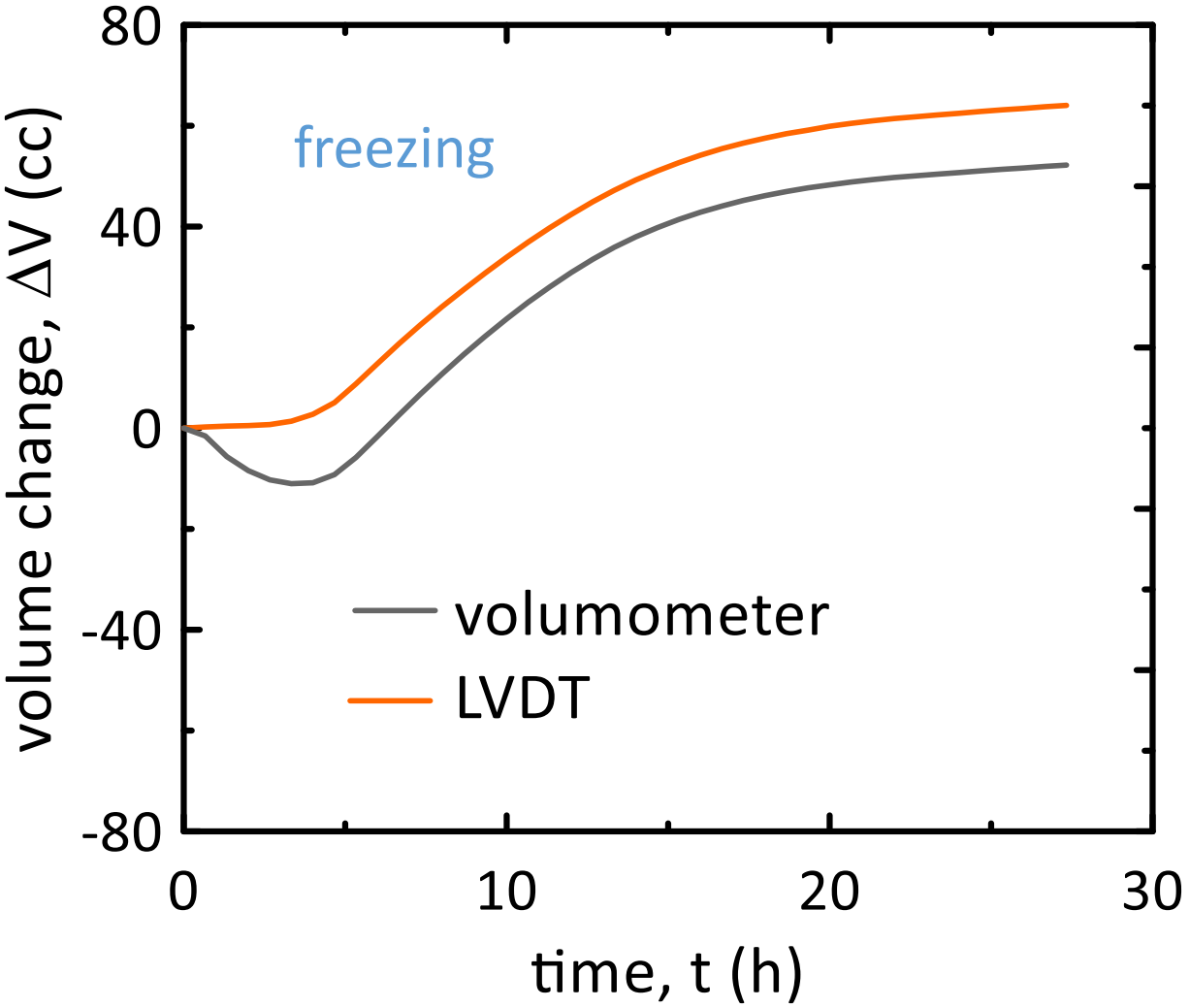
OpenCV model exhibits systematic residual errors

newly implemented cubic model reduces errors by ~66%

precision in the micron range possible



FREEZING



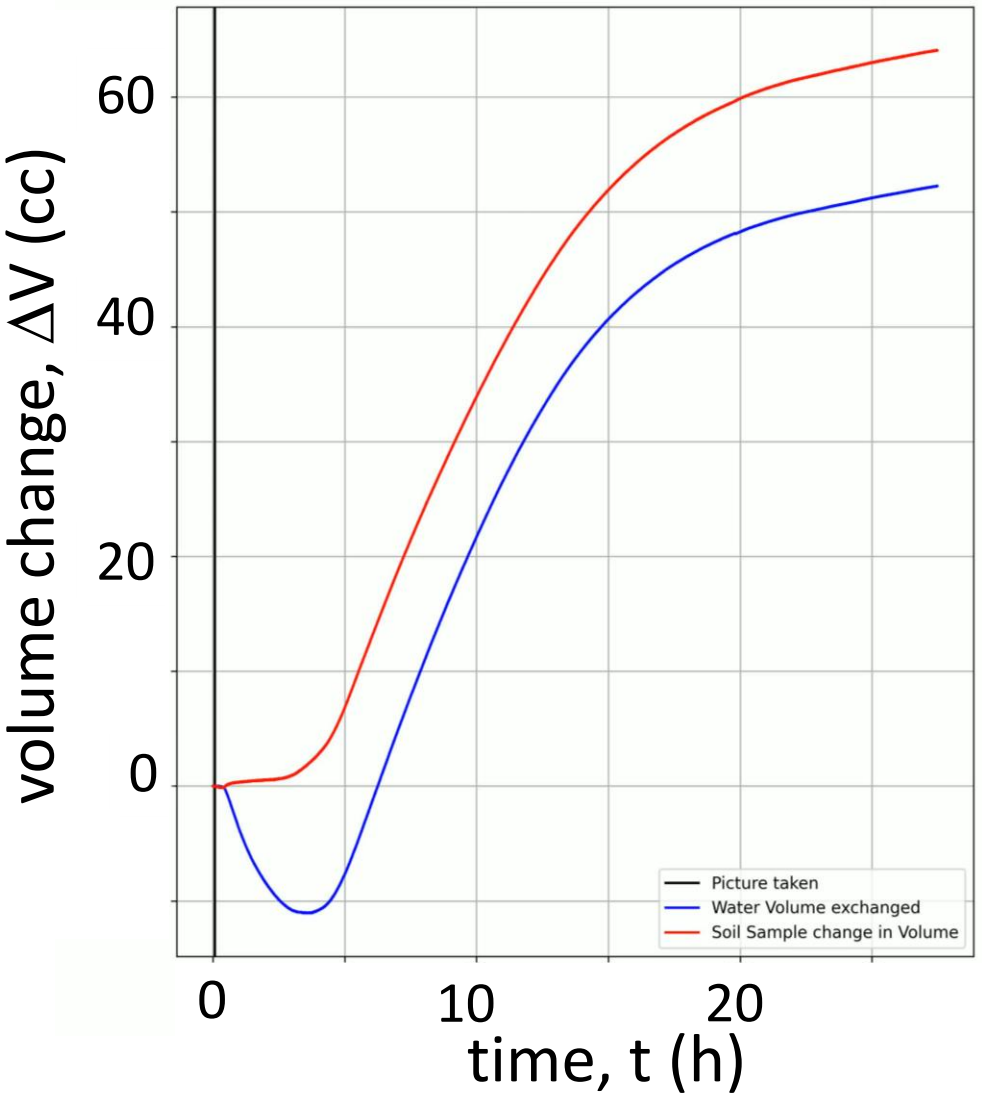
50% Kaolin + 50% Hostun Sand

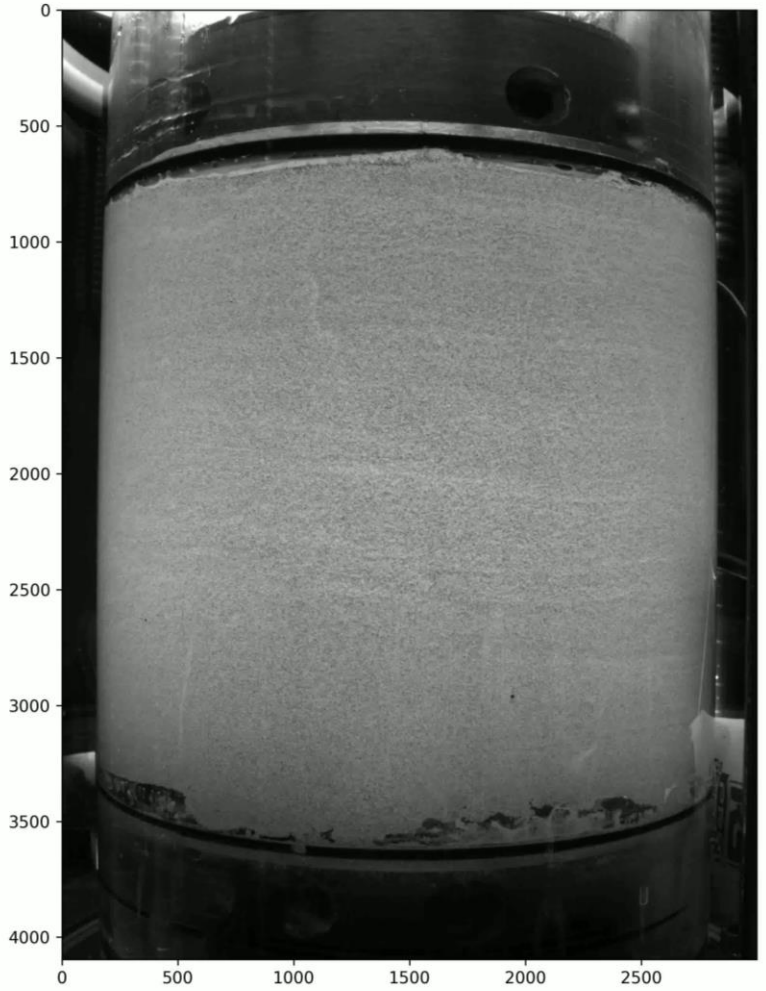
vertical stress: $\sigma_v = 100$ kPa

head temperature: +20°C to -10°C
base temperature: +2°C

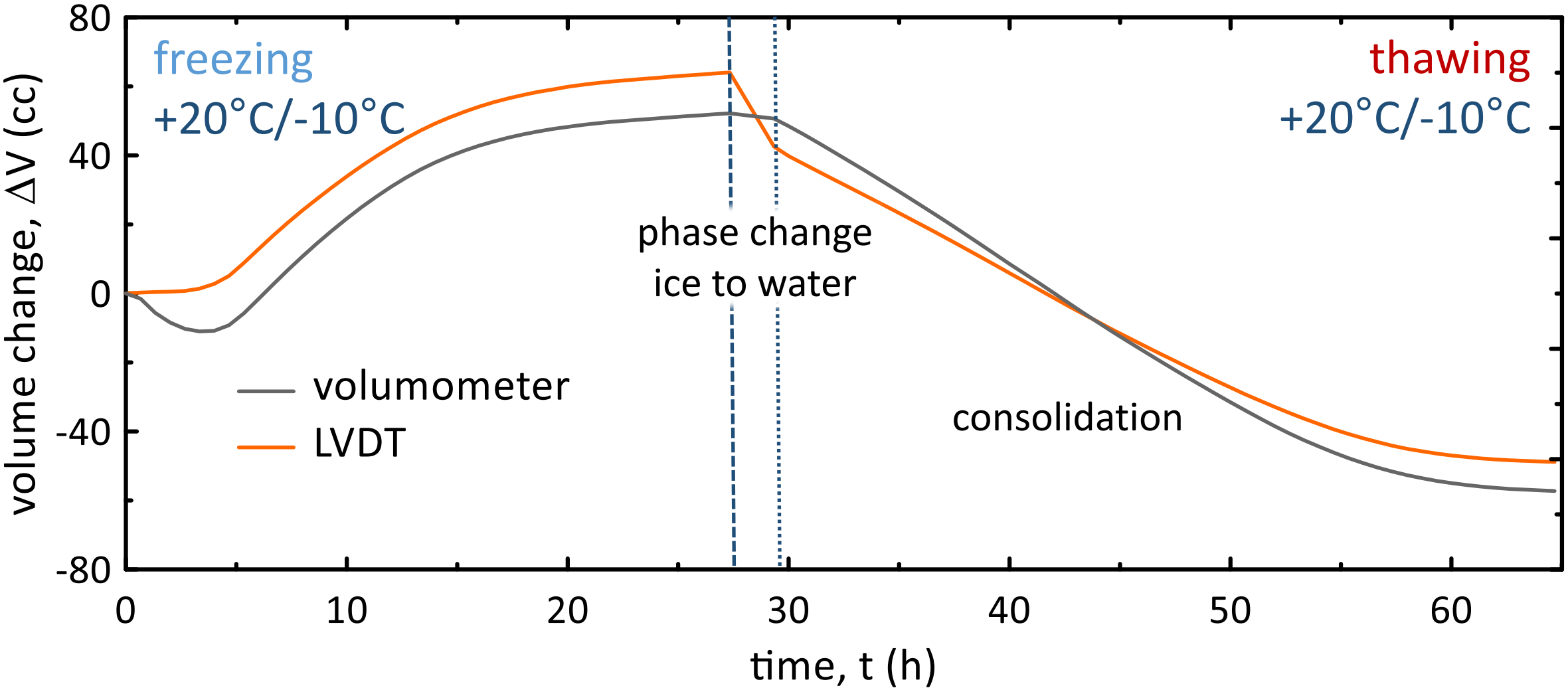
free drainage: $u_{base} = 0$

FREEZING

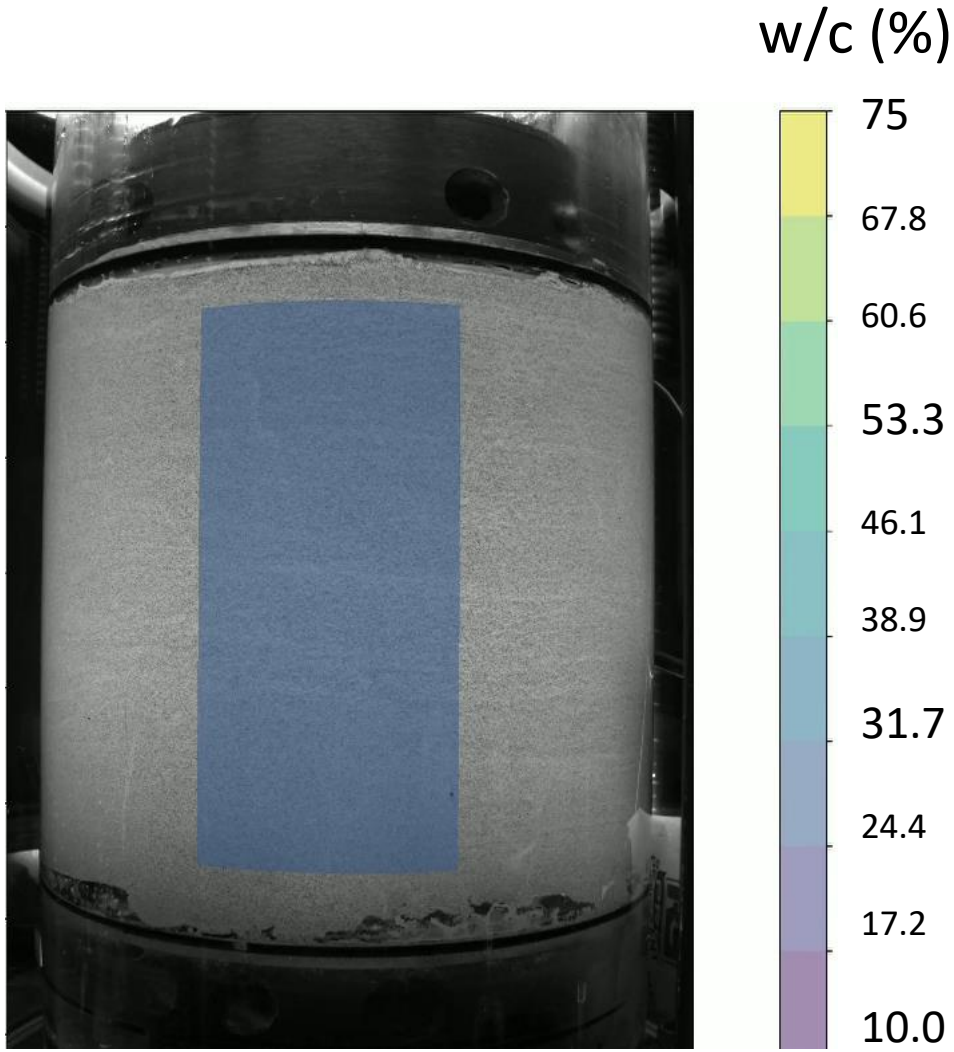

volume change, ΔV (cc)
60
40
20
0
0
10
20
time, t (h)
Picture taken
Water Volume exchanged
Soil Sample change in Volume


0
500
1000
1500
2000
2500
3000
3500
4000
0
500
1000
1500
2000
2500

FREEZING/THAWING 50%K-50%S -100kPa



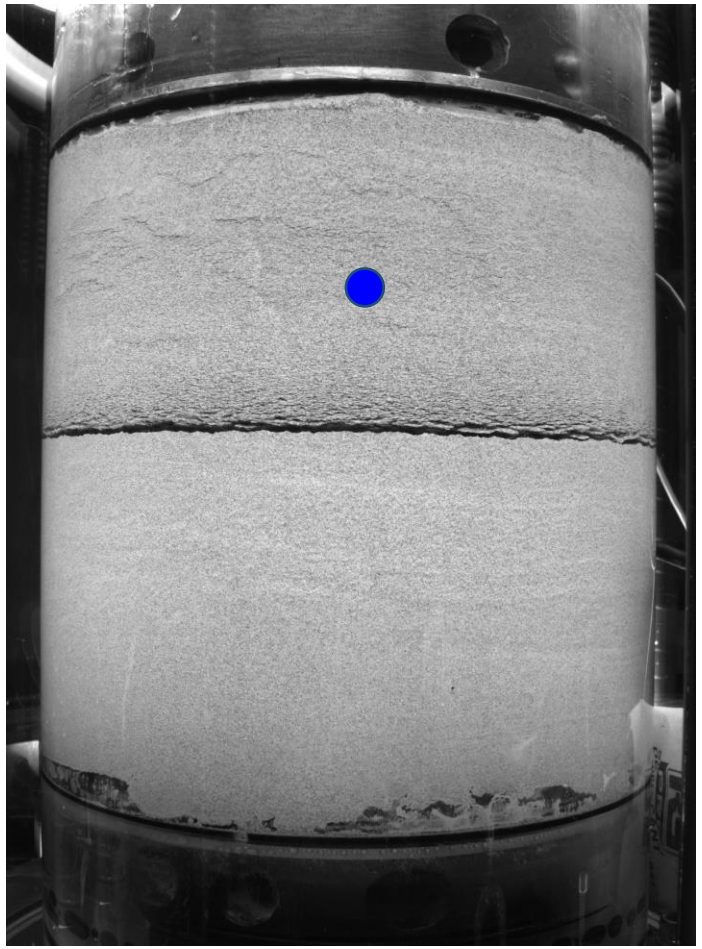
FREEZING/THAWING w/c contours by PIV

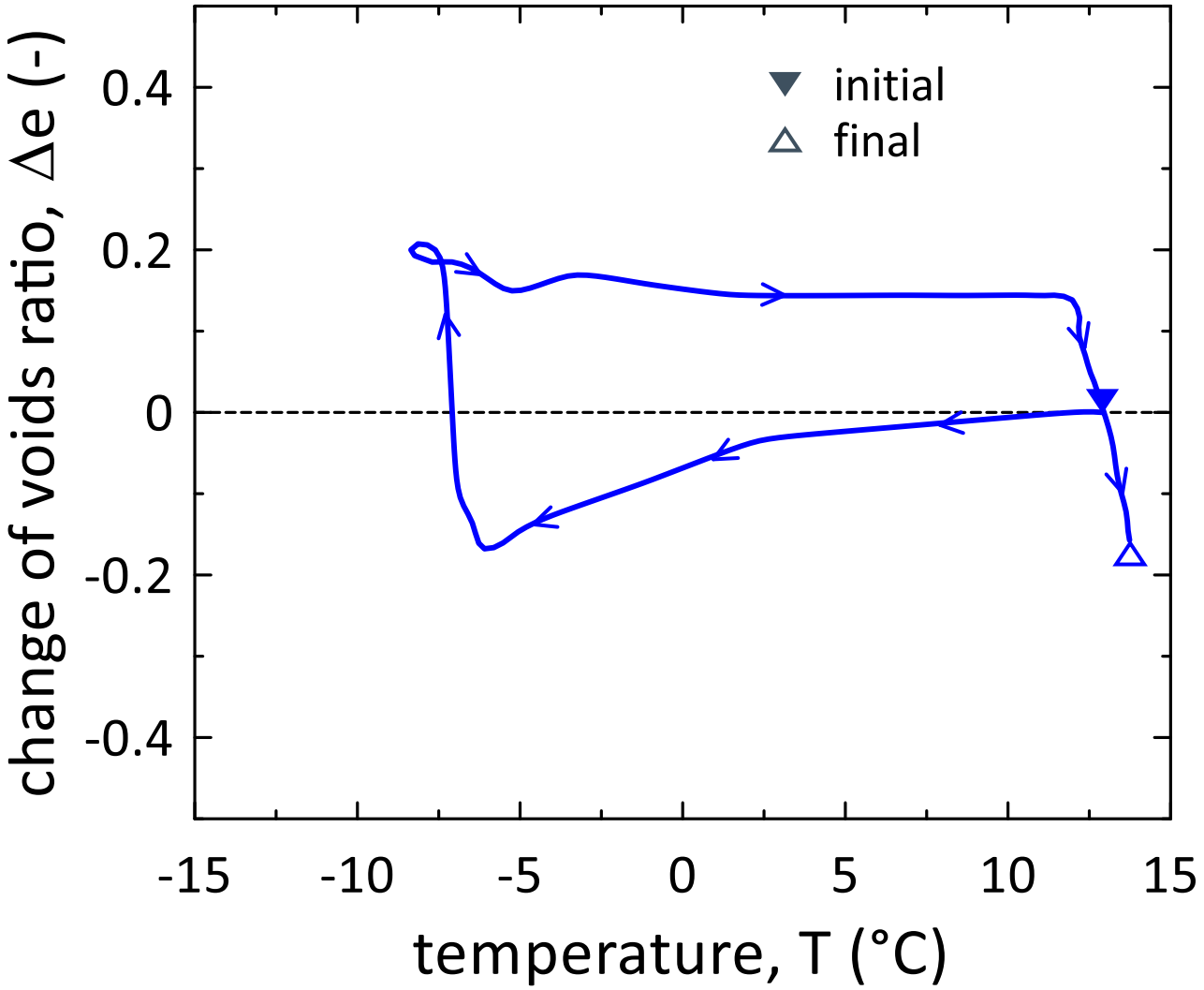


initial w/c ≈ 32%

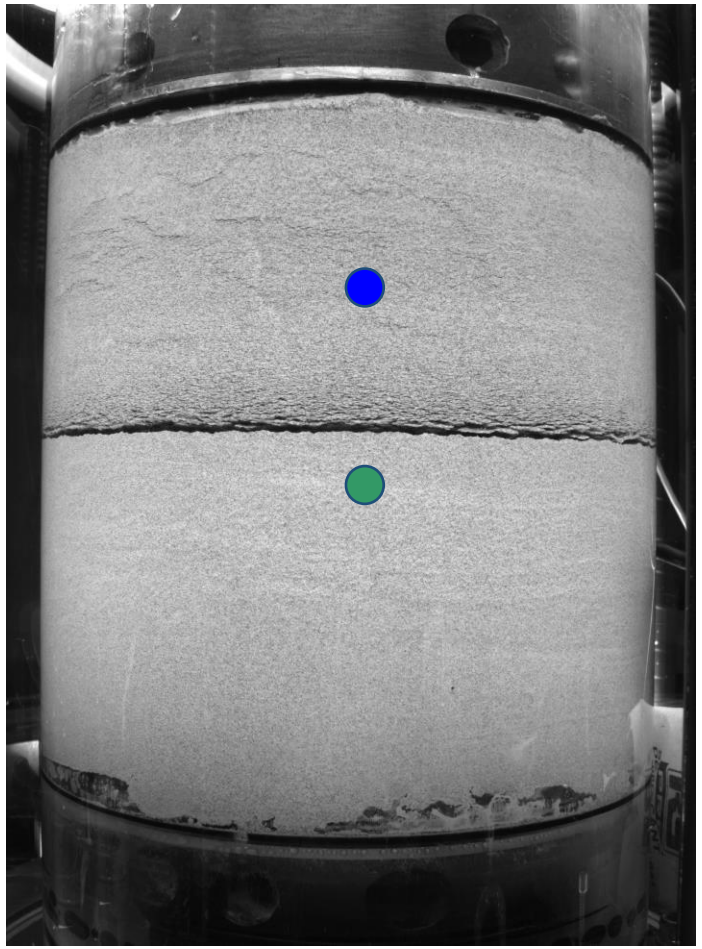
final w/c ≈ 24%

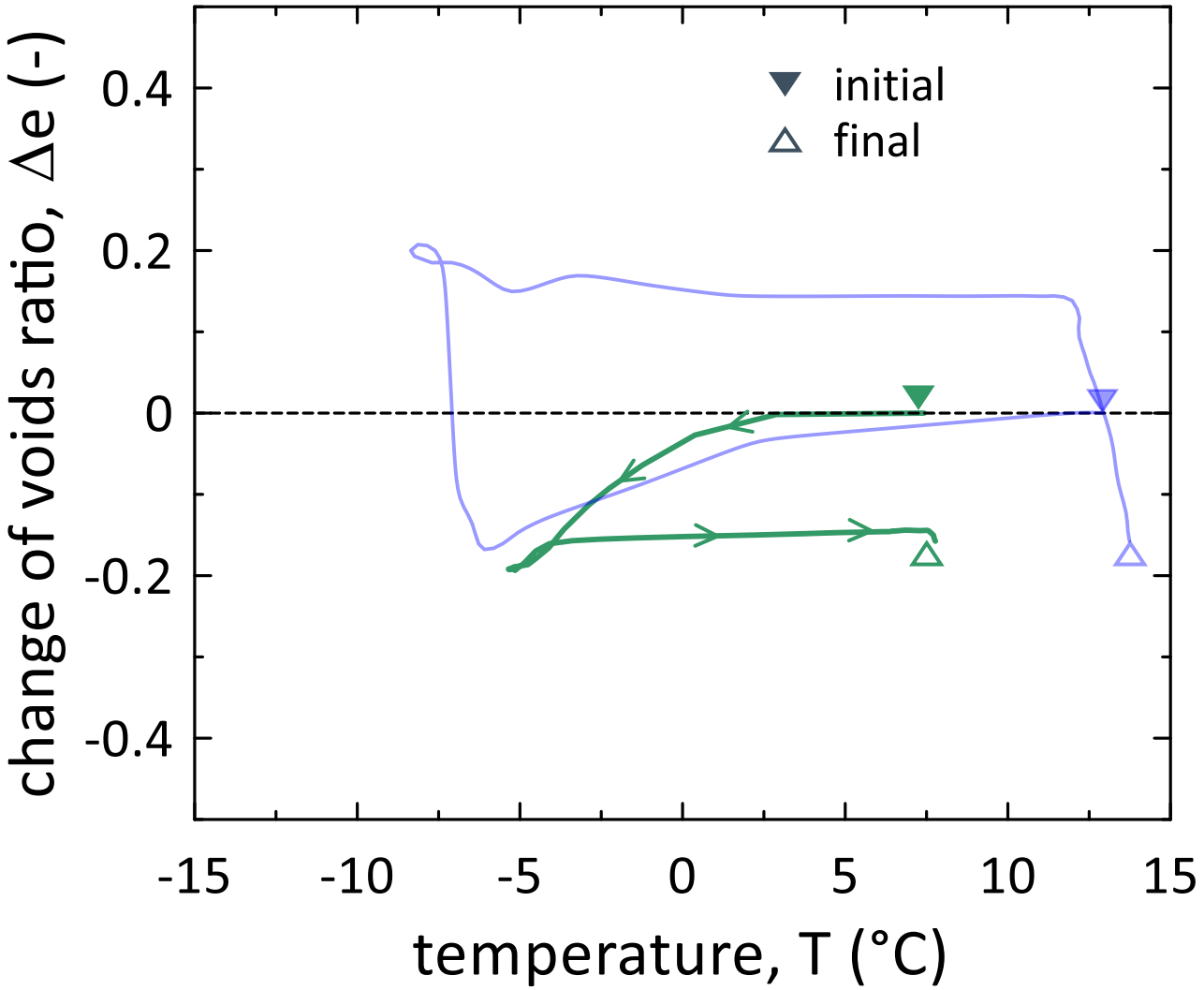
FREEZING/THAWING



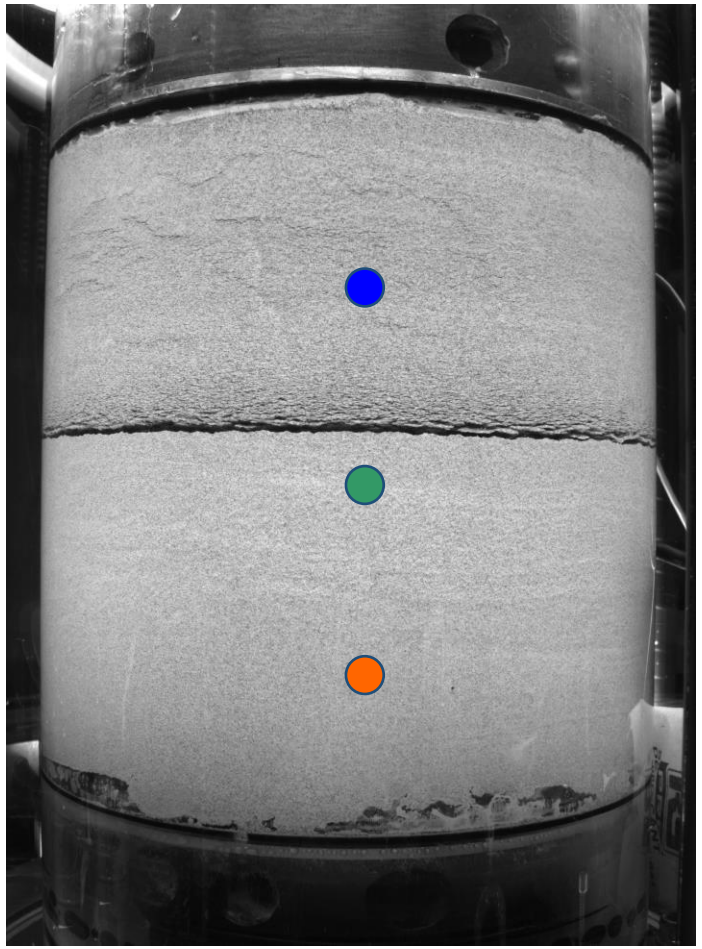


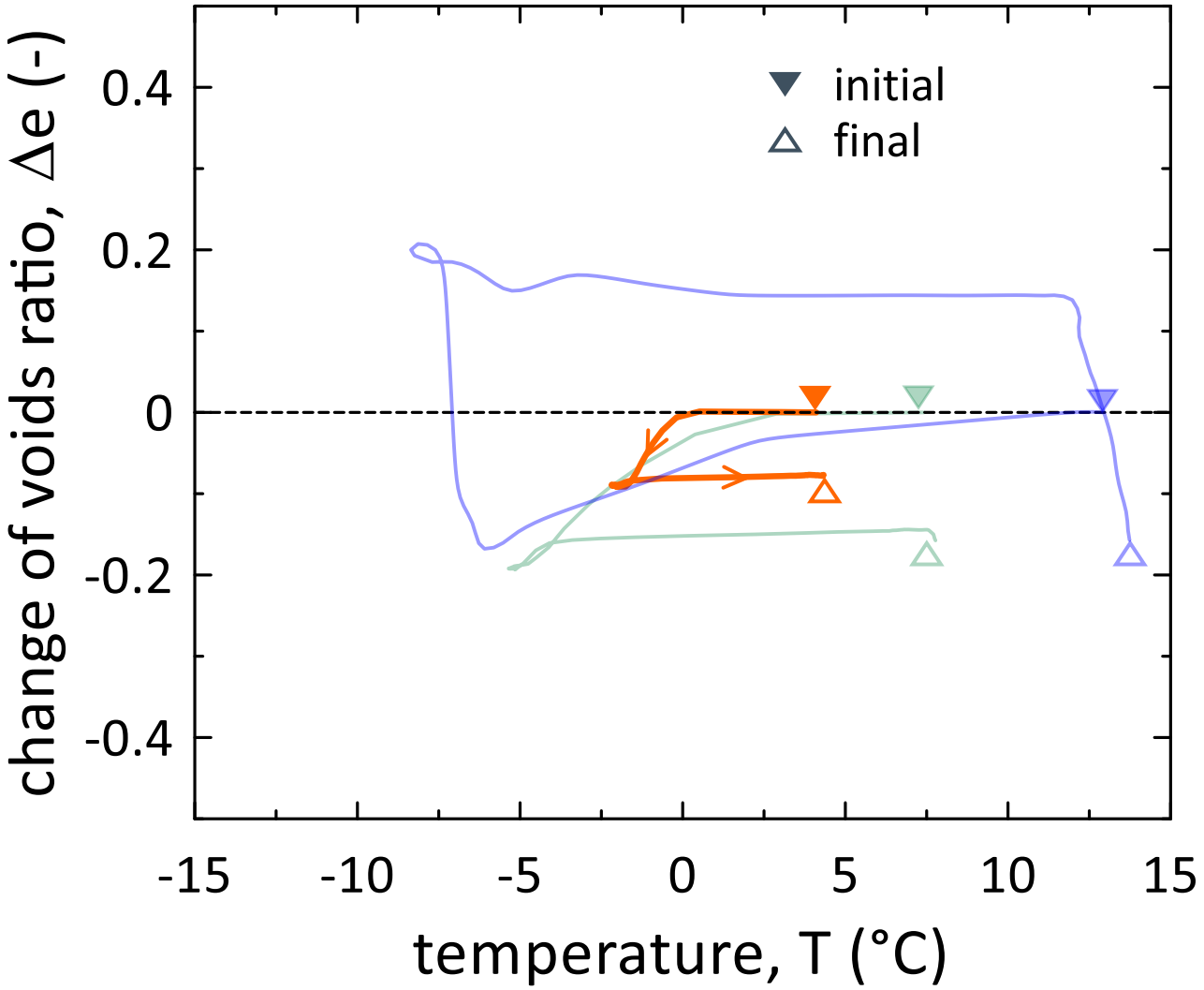
FREEZING/THAWING





FREEZING/THAWING



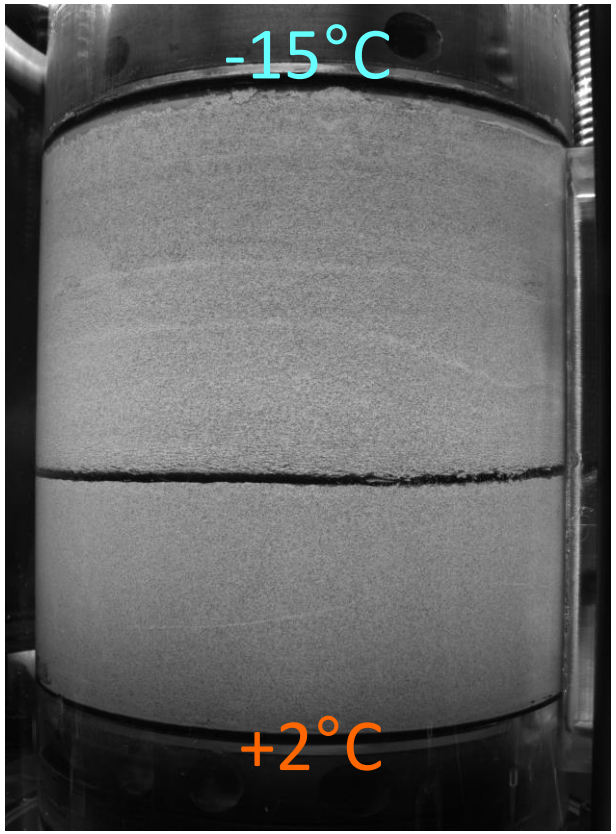


ICE LENSING ON FREEZING

thermal BC

100 kPa

100 kPa

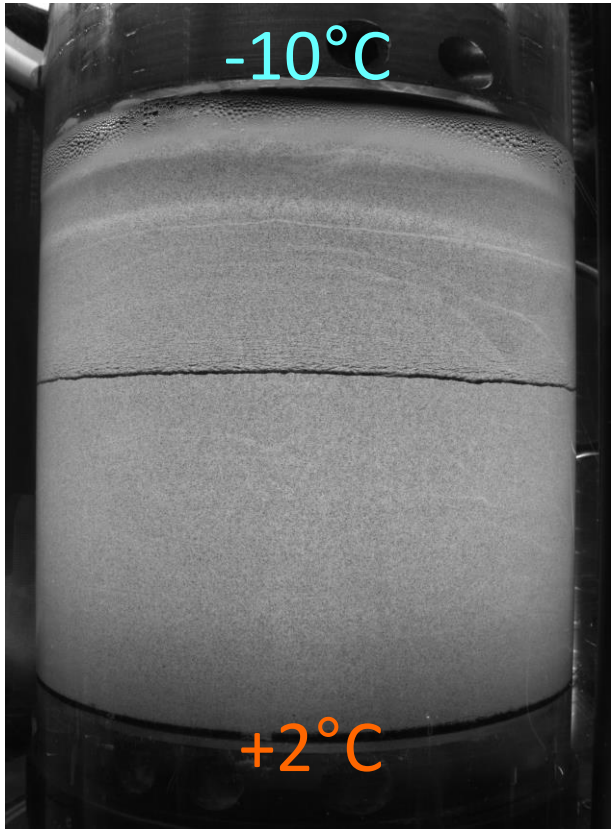


ICE LENSING ON FREEZING

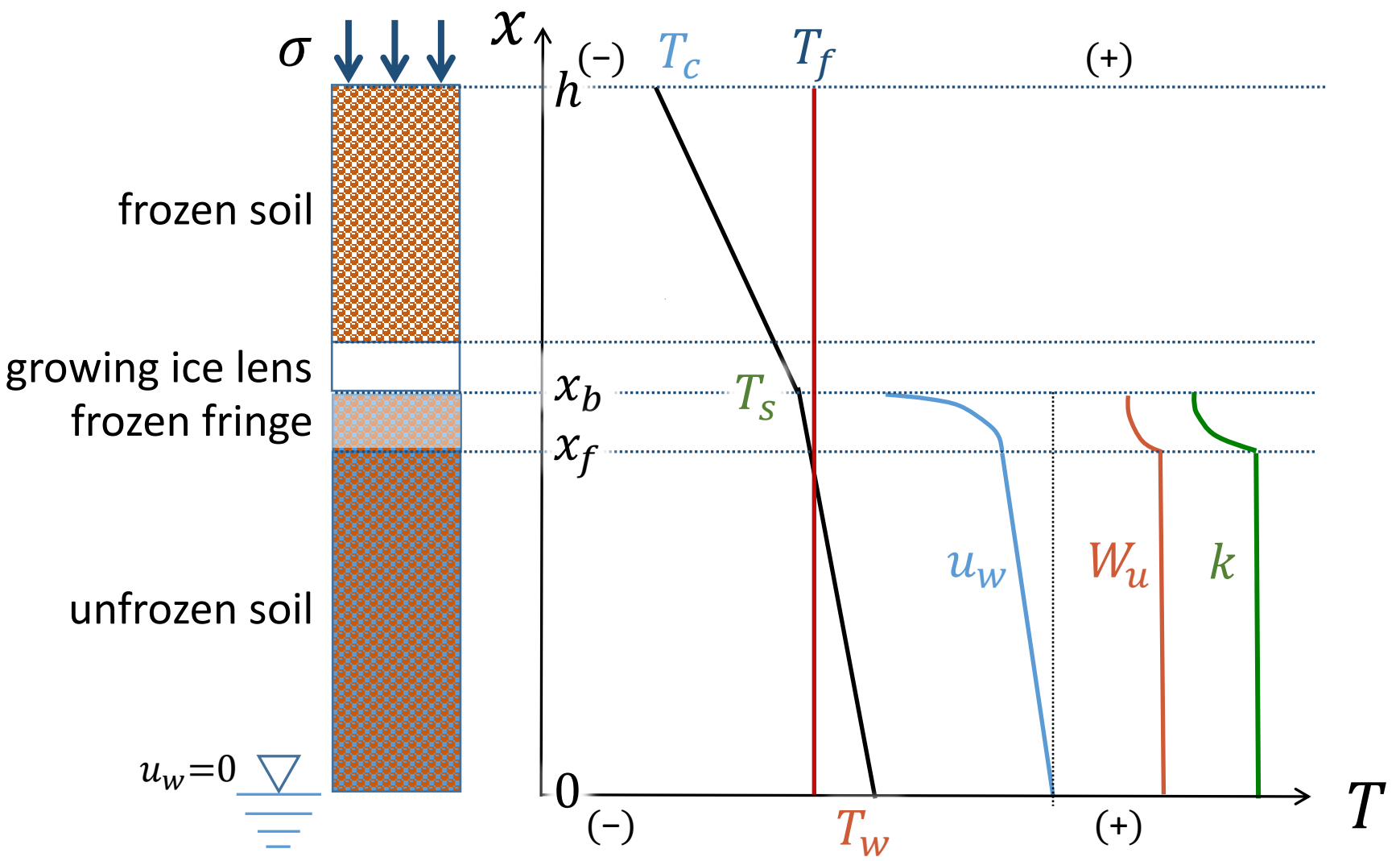
mechanical BC

100 kPa

200 kPa



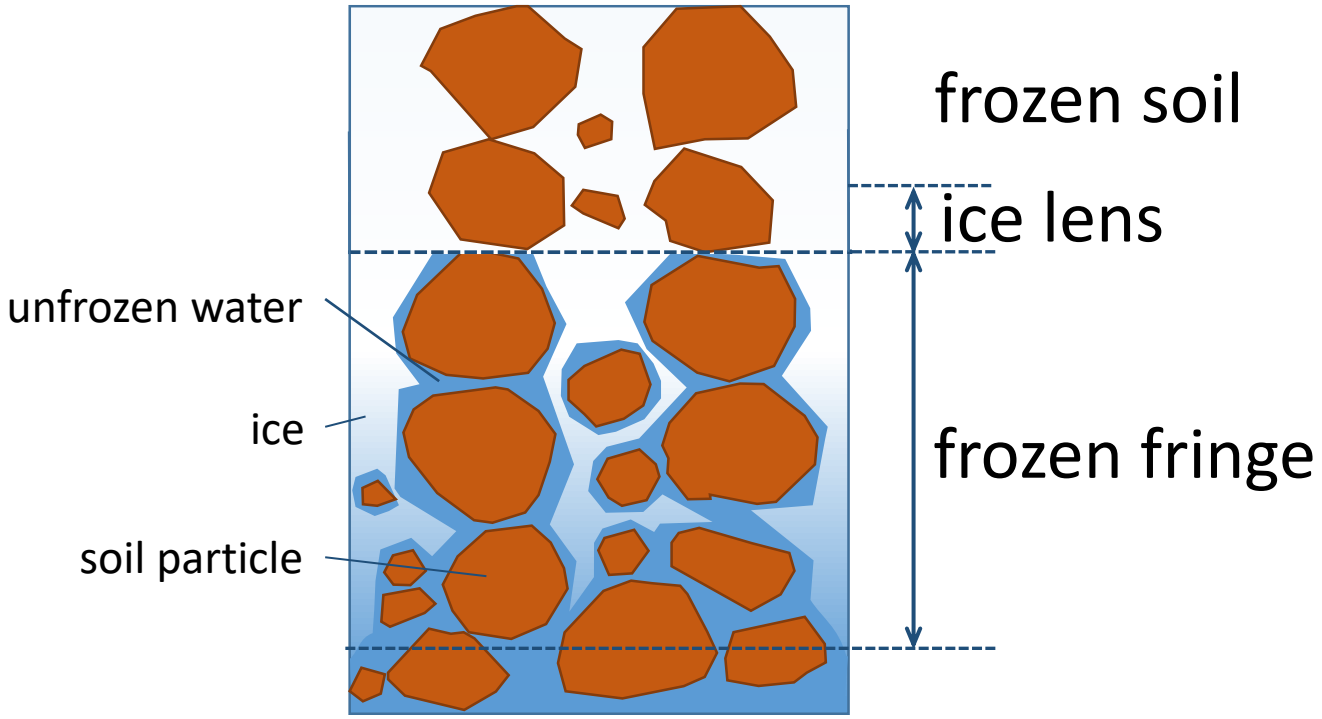
FROST HEAVE SUSCEPTIBILITY



$$\frac{u_w}{\rho_w} - \frac{u_i}{\rho_i} = L\, ln\left(\frac{T}{T_0}\right)$$

Daichao Sheng *et al.* (1995)

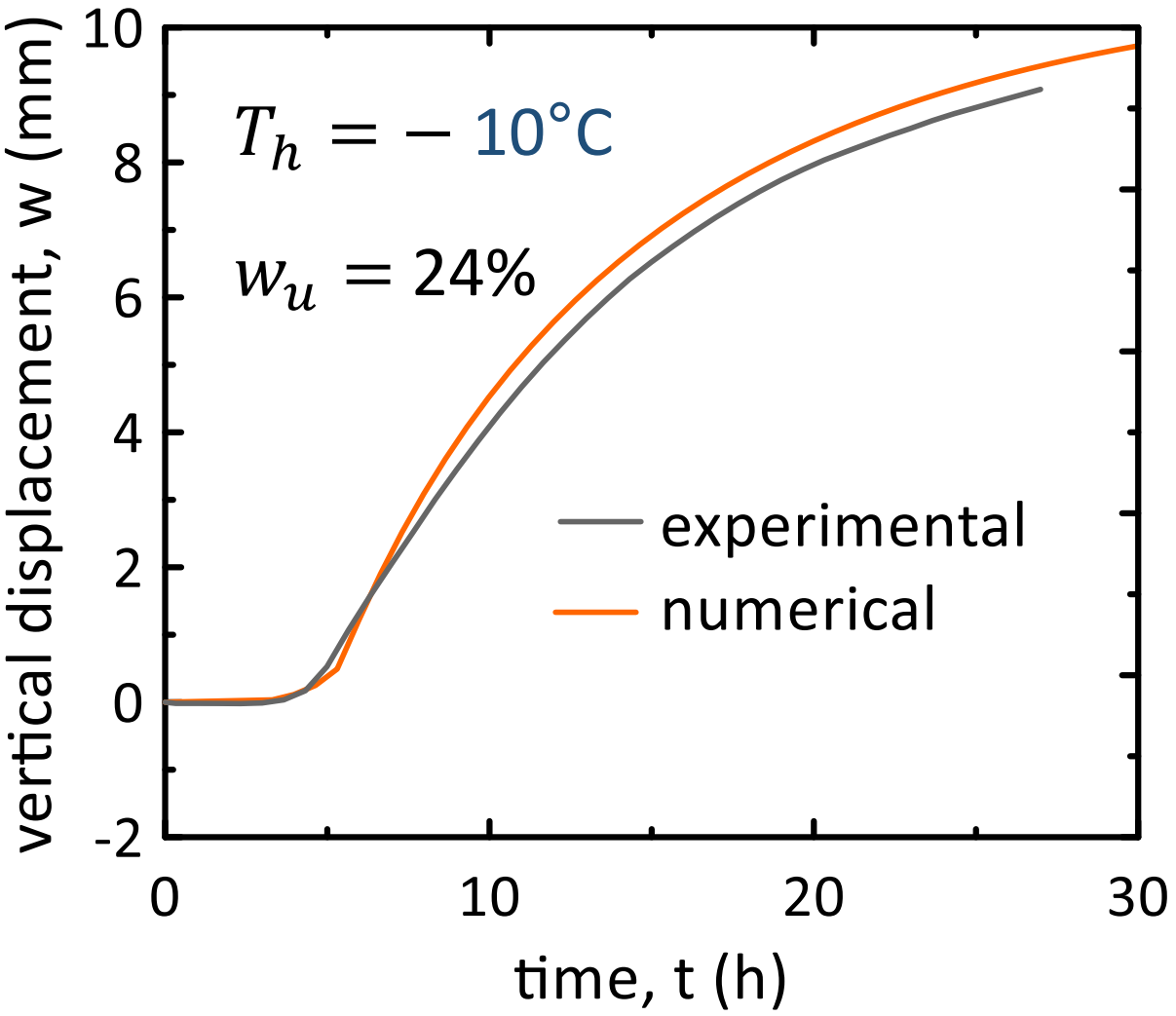
ICE LENS INITIATION

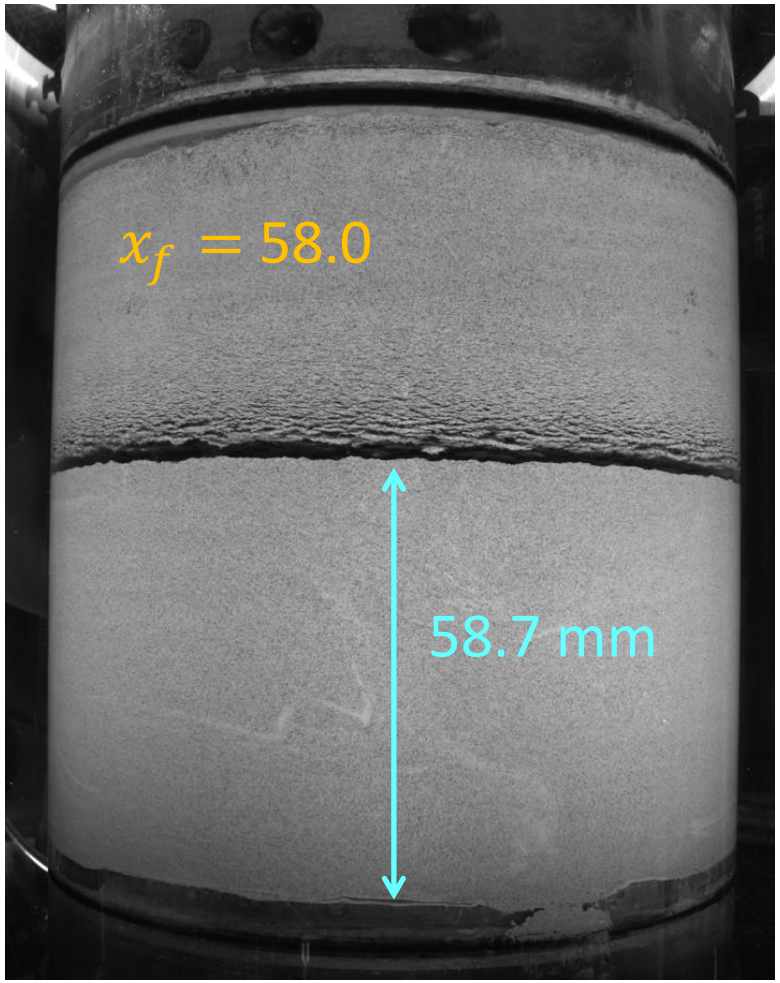


$$\sigma' = \sigma - u_n$$

$$u_n = \frac{n - I}{n} u_w + \frac{I}{n} u_i$$

ICE LENSING


$T_h = -10°C$
$w_u = 24\%$
experimental
numerical
vertical displacement, w (mm)
time, t (h)
10
8
6
4
2
0
-2
0
10
20
30


$x_f = 58.0$
58.7 mm

WHAT'S NEXT?

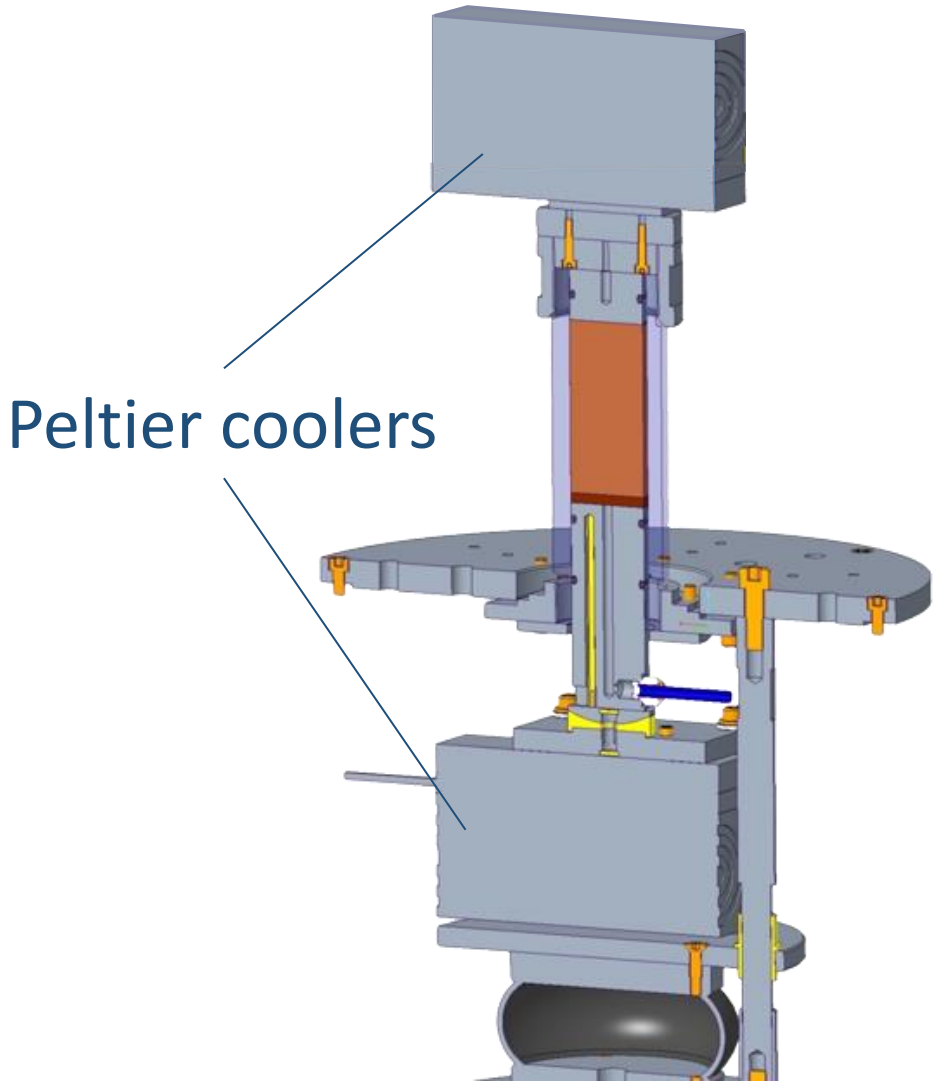
Pico RP2040 based
I2C wireless data acquisition

measurement of suction

TE MS5837-02BA

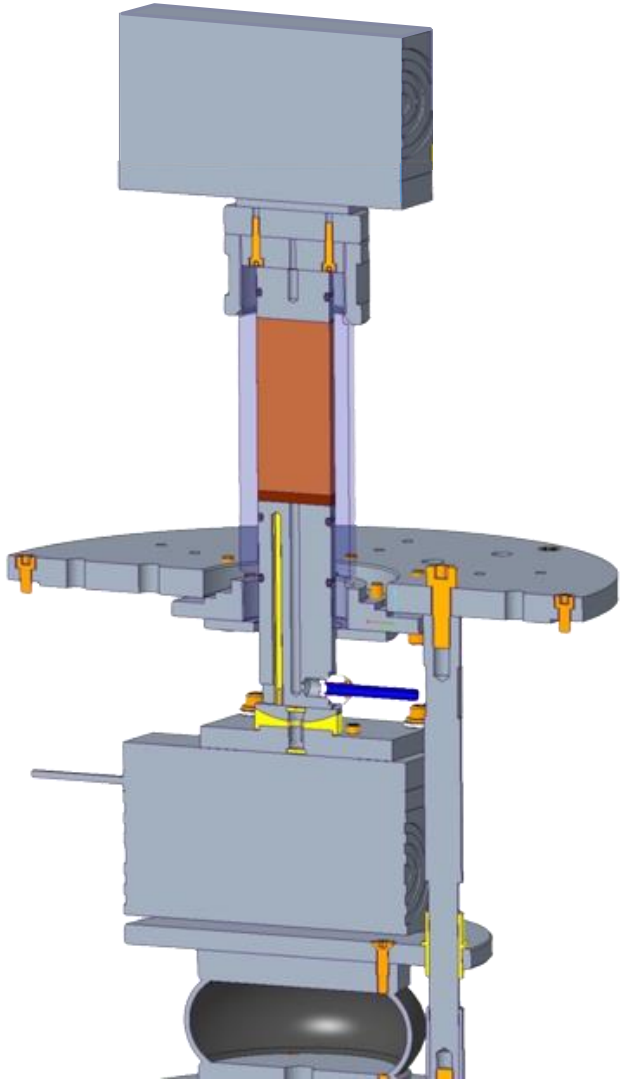
3.3×3.3×2.75 mm

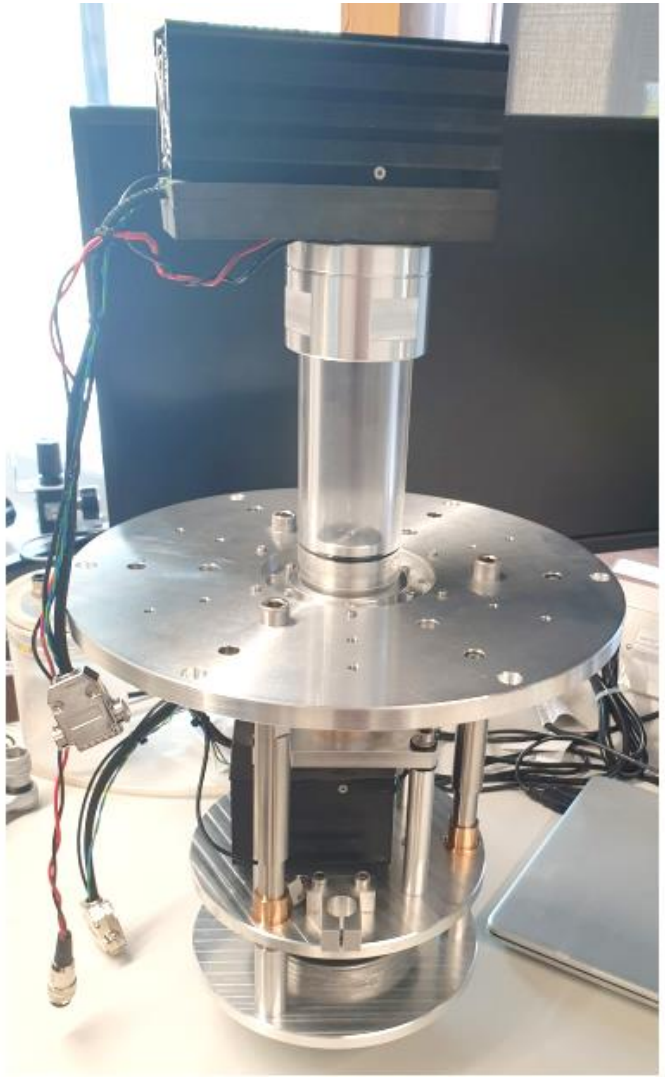
WHAT'S NEXT?



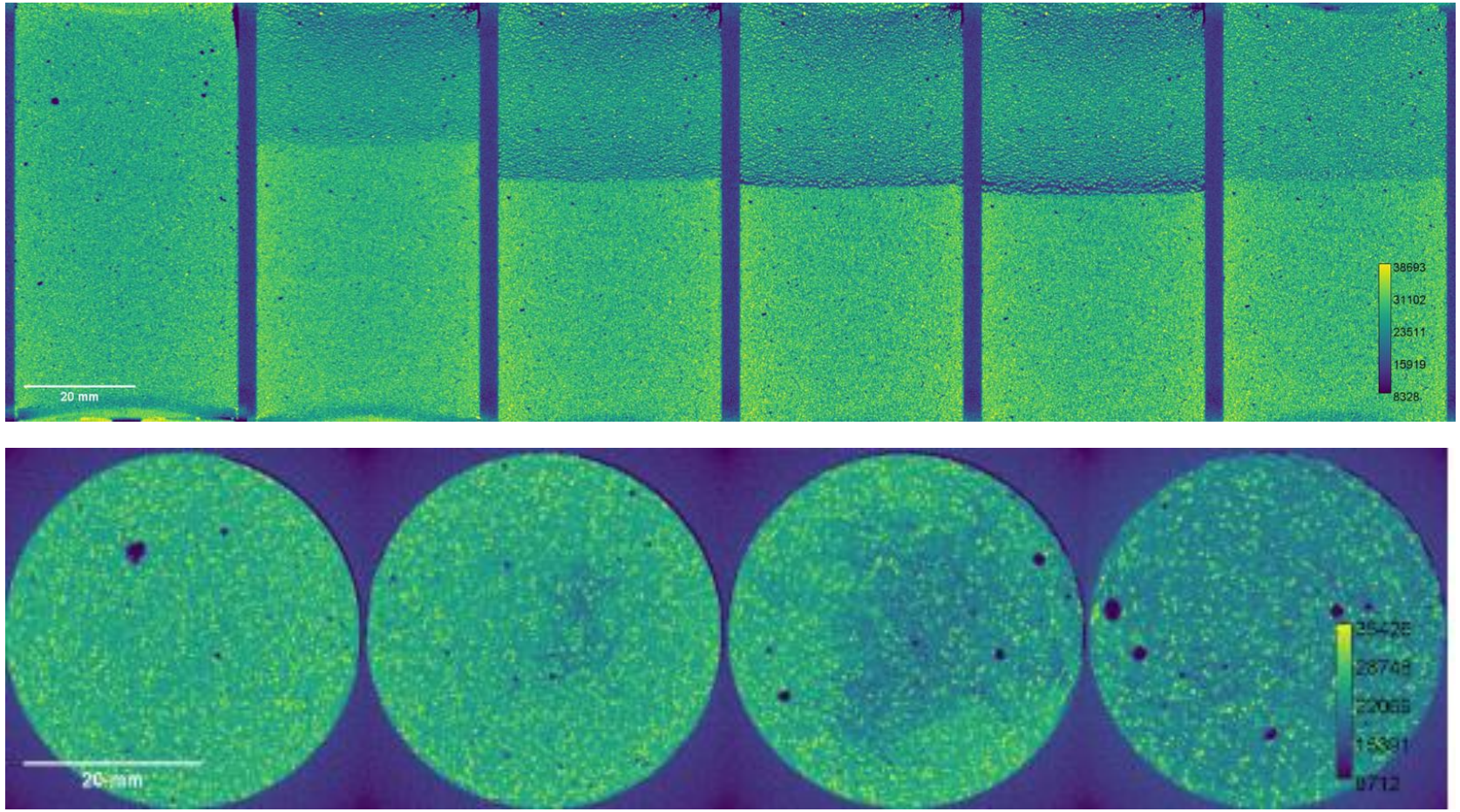
miniature X-Ray transparent FHA

WHAT'S NEXT?



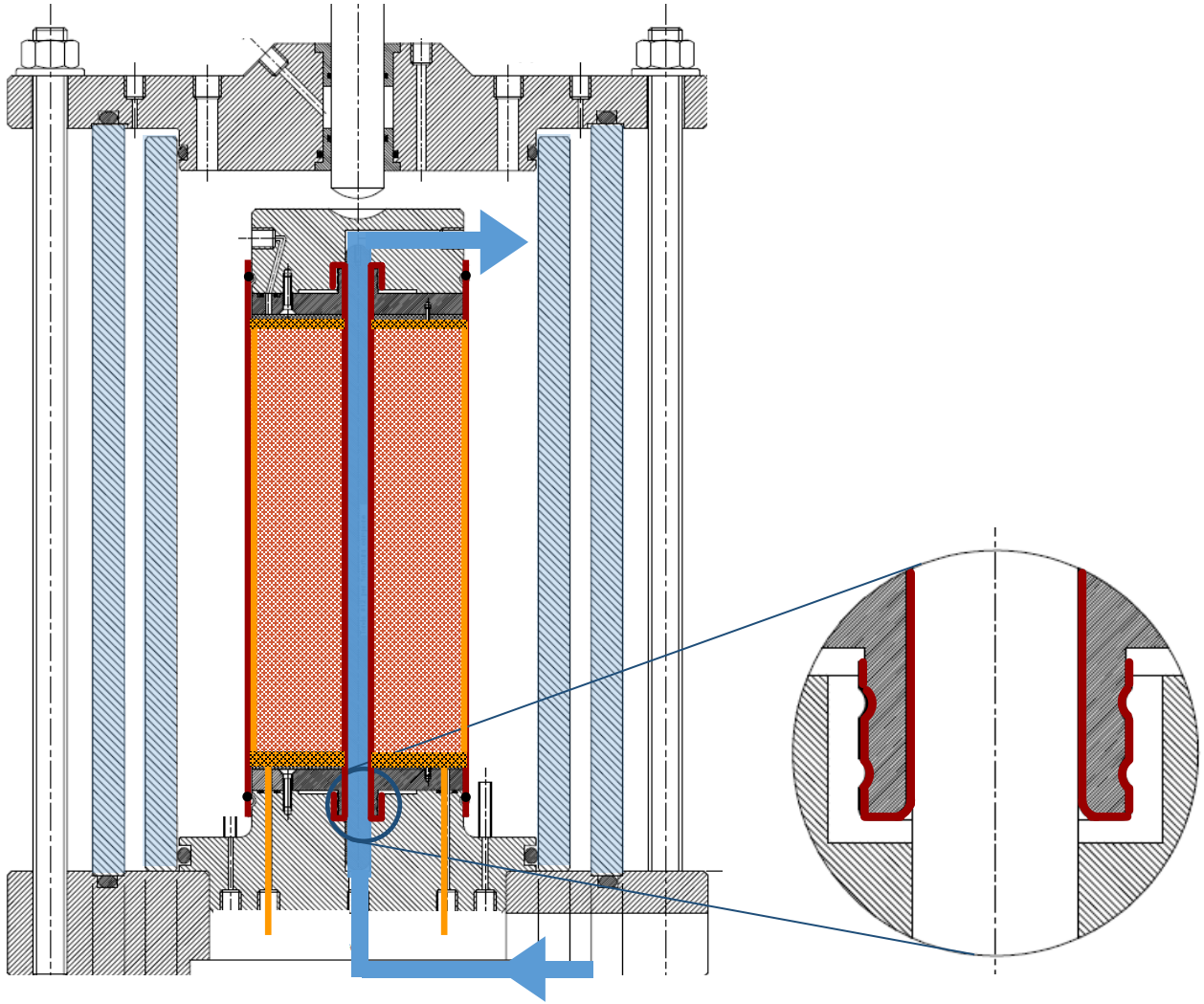


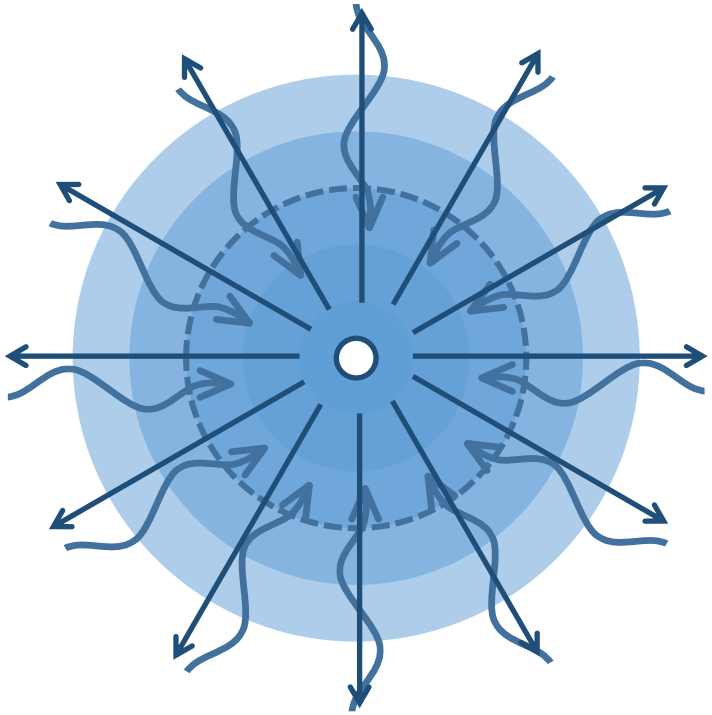
WHAT'S NEXT?



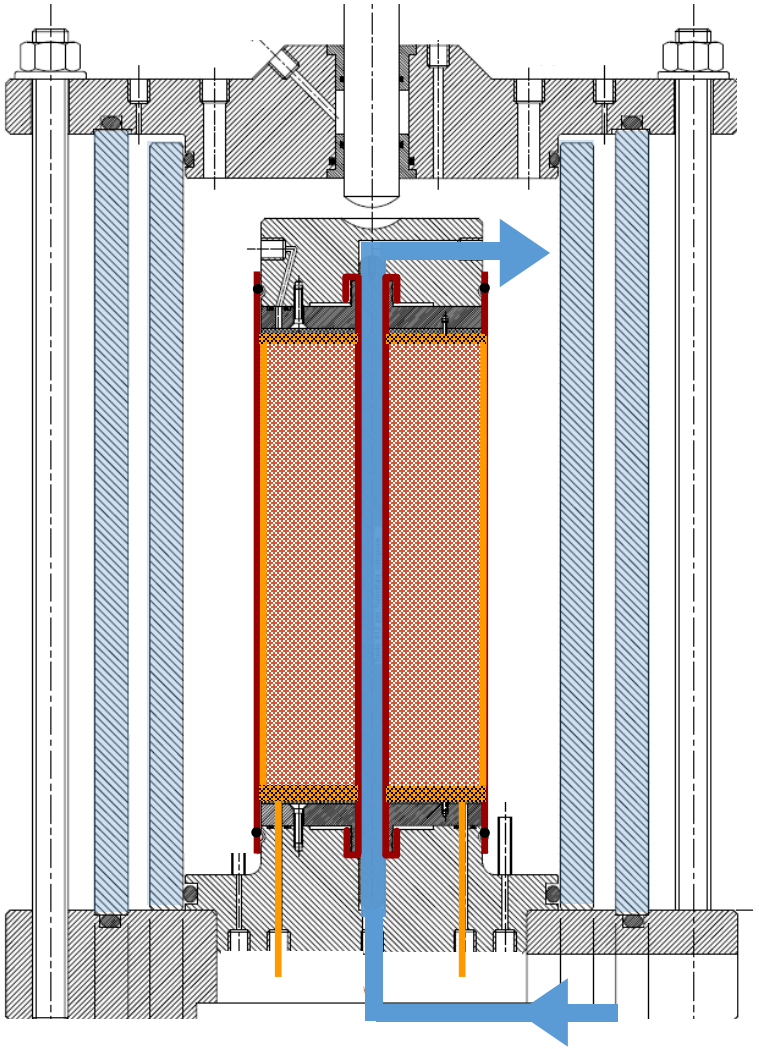
Tom Mlady MSc (2023)
Cino Viggiani, Giulia Guida

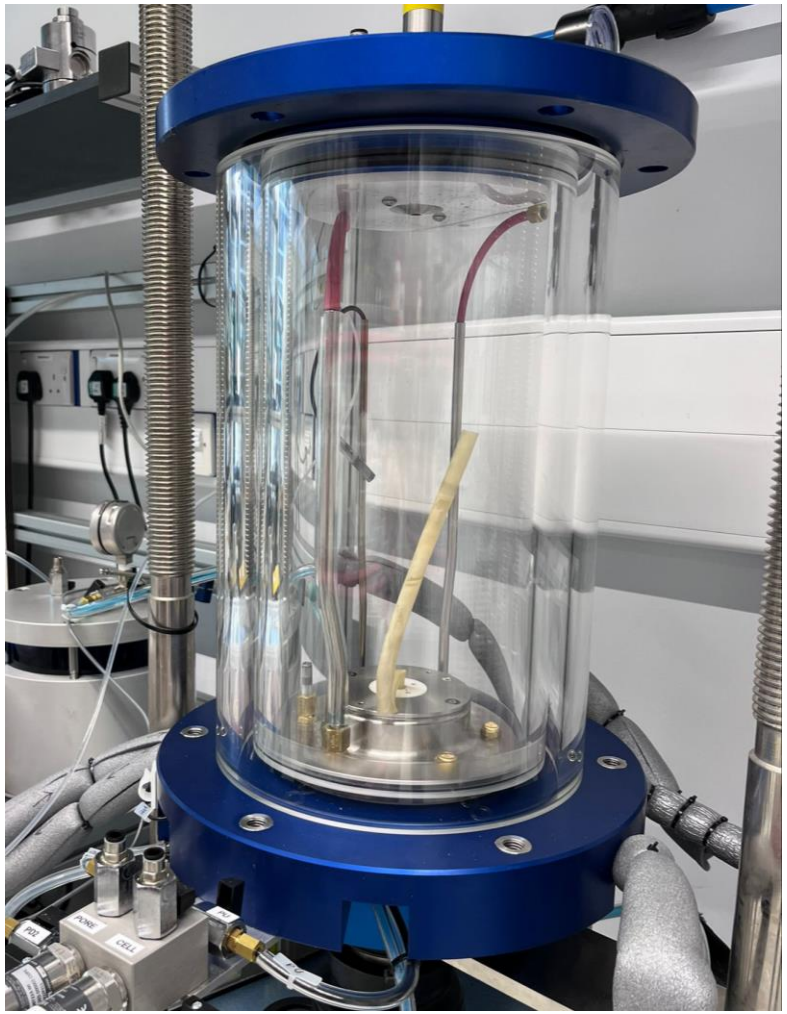
WHAT'S NEXT? THM-TX





WHAT'S NEXT? THM-TX





WHAT'S NEXT? THM-TX

true 3D imaging system

originally developed @ UWA

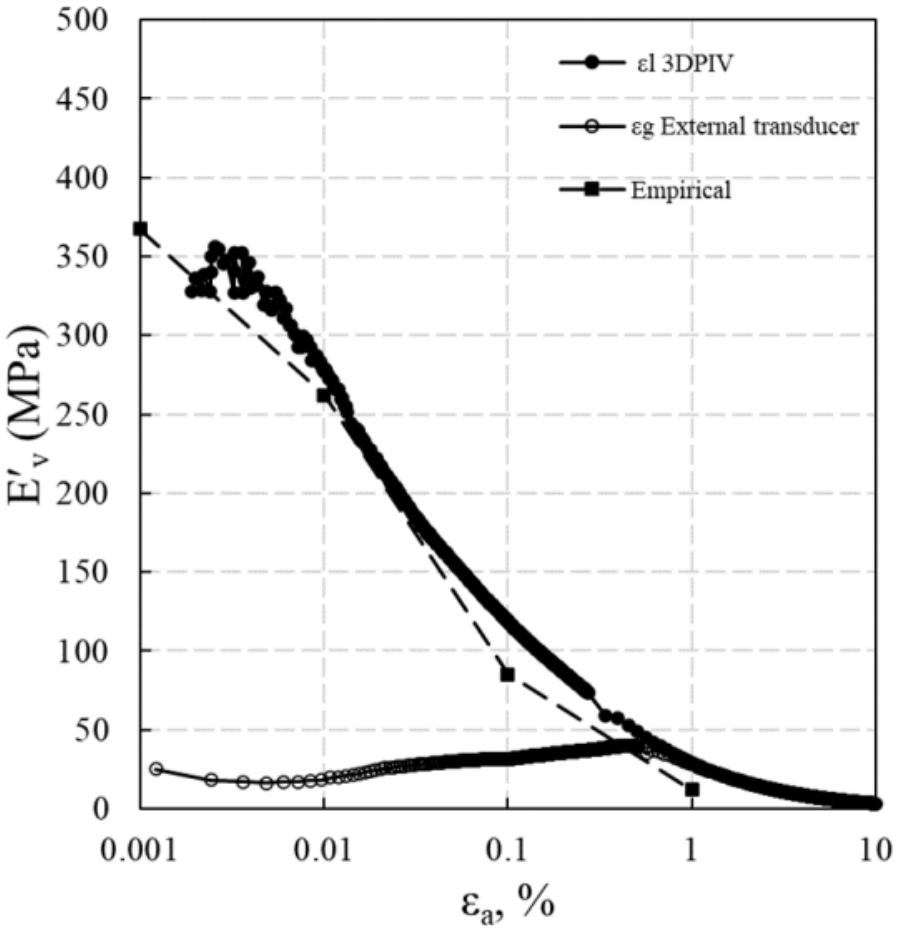
Raspberry Pi Zero W and HQ camera modules

UDP controlled acquisition via Python scripts

PIV-driven - stereophotogrammetry

all codes available on GitHub

displacements resolved to μm precision
comparable with internal local gauges



Hilario Greggi MSc (2023)

CONCLUSIONS

relevance	underground construction - AGF climate change induced seasonal freezing and thawing
monitoring	construction effects/ control processes collect evidence
analysis	data reduction modelling
THM coupling	volume expansion on freezing driven by mass transfer under temperature gradients
equipment	thermal & hydraulic boundary conditions full field measurements of deformations by PIV

[…] Many of his research interests were motivated by his consulting activities wherein the state of the art fell short of explaining performance. […]

Milton Harr (1998)