COMITÉ FRANÇAIS DE MÉCANIQUE
DES SOLS ET DE GÉOTECHNIQUE

LA CONGÉLATION _
ARTIFICIAL FREEZING OF SOILS, *IN CIVIL ENGINEERING*

Phénomènes physiques à l'œuvre lors de la congélation et Risques associés

BOUYGUES TRAVAUX PUBLICS

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Estimation des paramètres par essais en laboratoire.

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Thermal Parameters

Usual parameters of Soil Characterization for Artificial ground freezing (AGF) are ususally sufficient to estimate thermal parameters.

- Water content
- Bulk Density/Dry Density

Quartz content should be measured as it has a significant impact on thermal conductivity

- XRF (X-Ray fluorescence spectroscopy)

In our experience, Thermal parameters derived from correlations are sufficient for AGF Design and fit properly with in-situ observation during works

To get an exact fit of numerical model with in-situ observation these parameters can be retro-fitted (more on that later)

Johansen (1975)

$$k_{sat} = \left(k_q^q k_0^{1-q}\right)^{1-n} k_i^{n-n_u} k_w^{n_u}$$

k_q : thermal conductivity of quartz (7.7 W.m^{-1}.°C^{-1})
k_0 : thermal conductivity of solid content (2-3 W.m^{-1}.°C^{-1})
k_i : thermal conductivity of ice (2.21 W.m^{-1}.°C^{-1} at 0°C)
k_w : thermal conductivity of water (0.56 W.m^{-1}.°C^{-1} at 0°C)
n : porosity
n_u : porosity unfrozen

$$c_{sat} = \rho_d\left(c_s + c_w w_u + c_i(1 - w_u)\right)$$

ρ_d : dry density
c_s : heat capacity of solid part (0.7-0.9 kJ.kg^{-1}.°C^{-1})
c_w : heat capacity of water (4.22 kJ.kg^{-1}.°C^{-1} at 0°C)
c_i : heat capacity of ice (2.09 kJ.kg^{-1}.°C^{-1} at 0°C)
w_u : unfrozen water content

$$L = \rho_d L_w \frac{w - w_u}{100}$$

ρ_d : dry density
L_w : Latent heat of fusion for water (334 kJ.kg^{-1})
w : water content
w_u : unfrozen water content

Hydraulic parameters

Water flow can have a significant impact on ice development.
Maximum flow speed to close 1m space between freeze pipes :

- Brine : 5m/day
- Liquid Nitrogen : 15-20m/day

In sensitive contexts, flow speed should be measured/estimated prior to operations:

- Using tracing test (fluorescein, ..)
- Based on hydrogeological modeling, considering dam effect from adjacent structures

Flow speed can have an impact on ice development rate and should be considered in design :

- Delays to get watertightness
- Dissymetry of frozen body

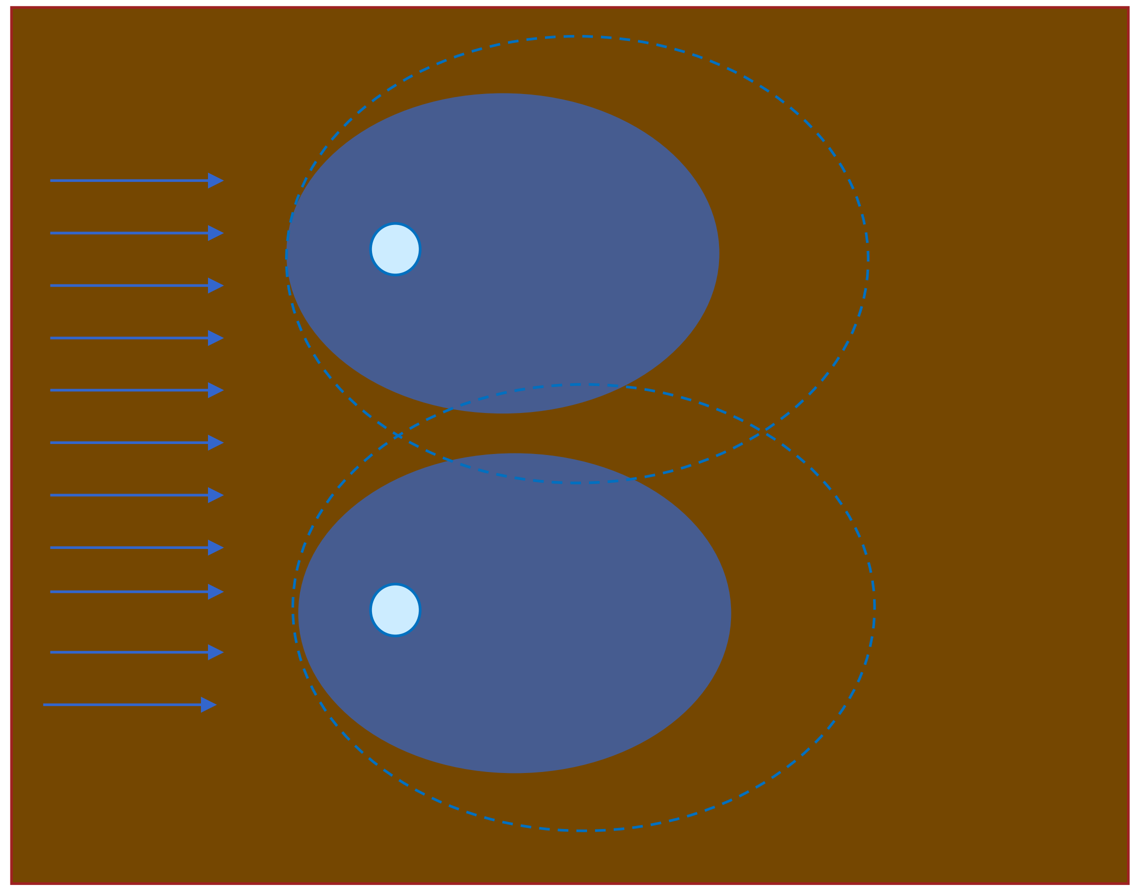
- Redistribution of water gradients
- Increase of flow speed in openings

Validation of design in coupled hydrothermal FEM
Modification of freezing operations to freeze permeable ground units first (fractured rock, gravel..)

Sanger and Sayles (1979)

$$uc = \frac{k_f}{4\ S\ ln\left(\frac{S}{4\ r_0}\right)} \frac{V_s}{V_0} \quad \text{(m/day)}$$

r_0 (m) pipe diameter
k_f (W/(m . °C)) thermal conductivity of soil
S (m) pipe spacing
V_s (°C) abs. of refrigerant temperature
V_0 (°C) abs. of soil initial temperature



Mechanical parameters - Creep

Freezing the pore water in the soil results in an increase in bulk resistance in the short term

Creep is a time dependent deformation at constant load:

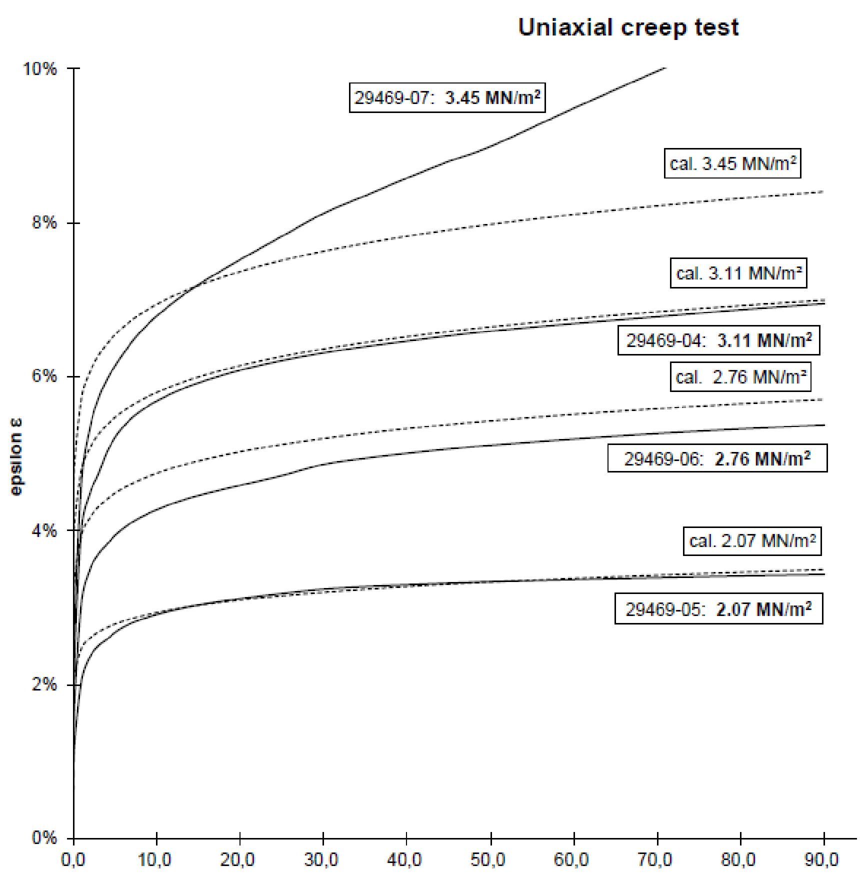
- Temperature dependent (Usually -10°C for mechanical behavior)

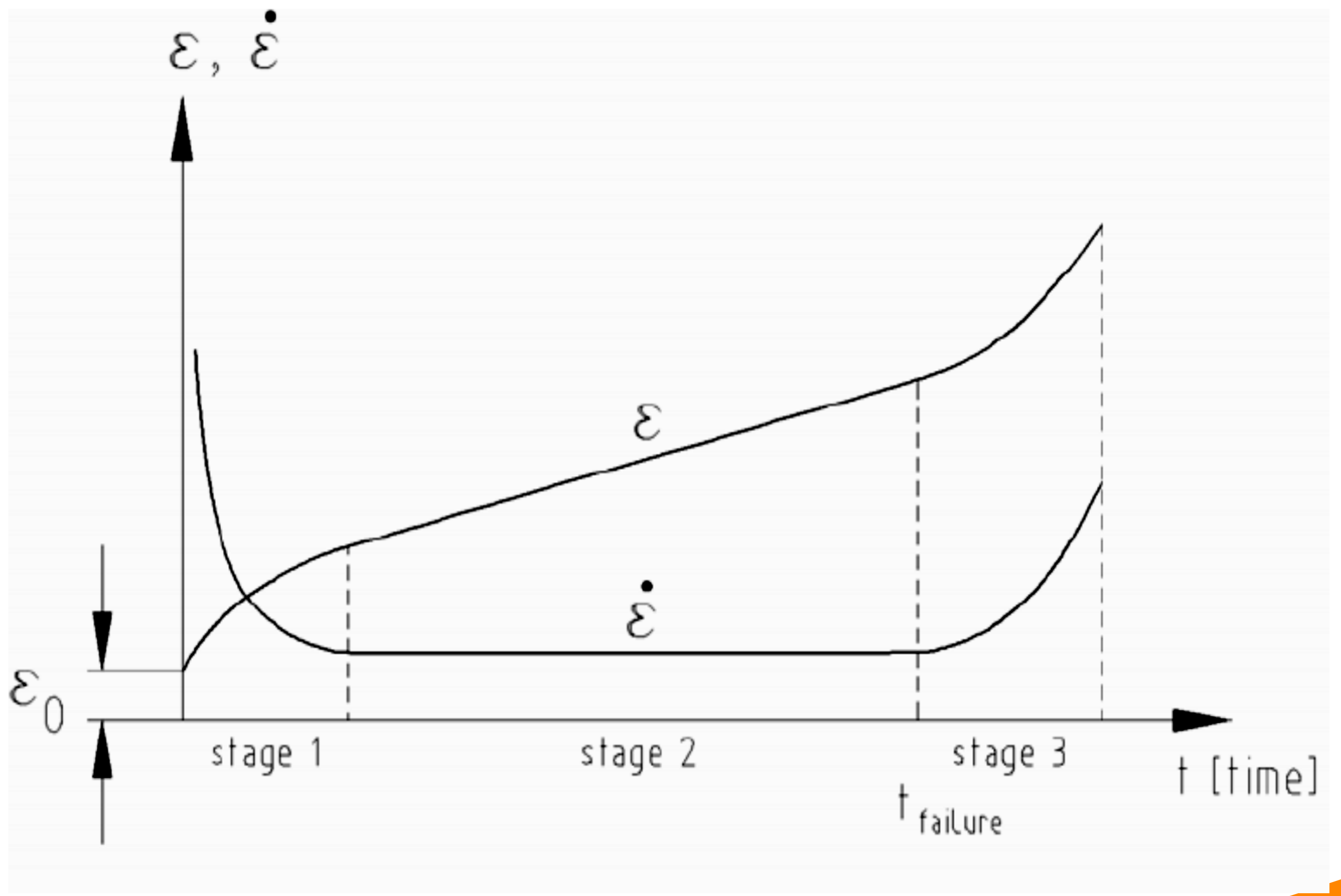
Uniaxial Creep test to characterize creep law :

$$\varepsilon = \frac{\sigma}{E} + \varepsilon_k \left(\frac{\sigma}{\sigma_k}\right)^k + \dot{\varepsilon}_c \left(\frac{\sigma}{\sigma_c}\right)^c t \qquad\qquad \varepsilon = \frac{\sigma_1}{E_0} + A\sigma_1^B t^c$$

- The « French » approach to calculate σ(t, ε):
  - Time t: Duration of frozen soil mobilization (unsupported)
    - i.e. excavation phase (24-48h)
  - Deformation ε: Failure strain is independent of stress and time

- The « German » approach to calculate σ(t, ε, $\dot{\varepsilon}$) (Orth 1986-88):
  - Stage 3 should be avoided.
  - $\dot{\varepsilon}$ min => beginning of stage 2 => ε





Frost Heave

Two physical phenomena should be considered :

- Volume increase of pore water +9%

  With n=0.4 : $\Delta V \approx 3.6\%$
- Cryogenic succion

  Due to contact forces at the surface of the grains (Van der Waals) freezing point of water is decreased and is at an unstable physical state (Clausius-Clapeyron equation)

  To counteract the unstability succion is created toward the freezing fringe

  Water flows toward the freezing fringe and ice lenses are created.

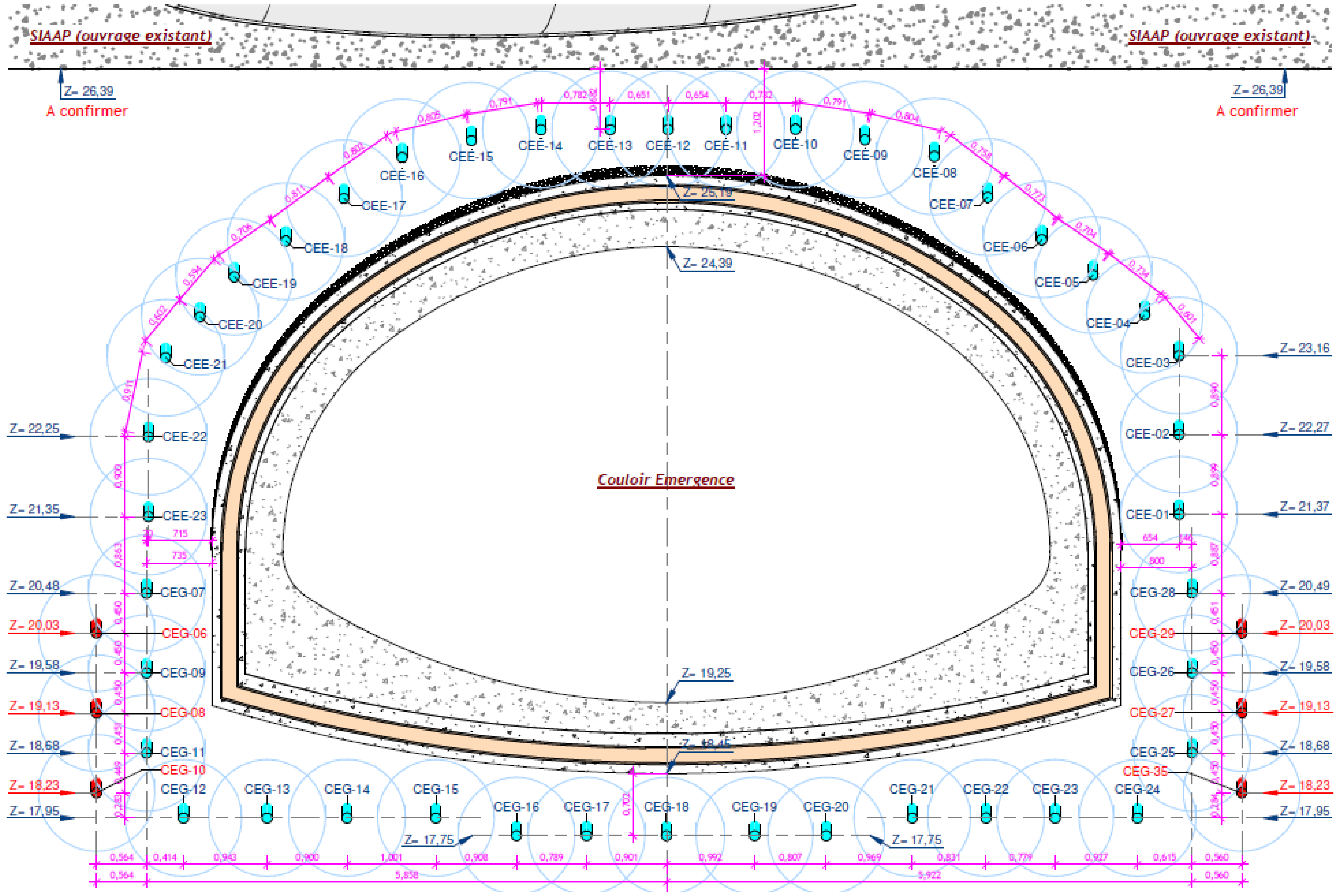
This phenomenon was described empirically by Konrad and Morgenstern (1981) using the segregation potential (SP)

- SP is accessible using frost Heave test (ASTM 5918)
- SP value can be corrected to account for vertical stress (Konrad and Morgenstern)

Cryogenic succion is supposed to decrease exponentially with stress according to empirical study by Konrad and Morgenstern.

However if water is available, -even under large stresses-, cryogenic succion can exist

- Permeable/Fractured ground unit closeby,
- Drainage along Tunnel segments/diaphragm wall..



$$\dot{\varepsilon} = SP\ grad(T)\Big|_{0°C}$$

Konrad and Morgenstern (1981)

$$SP(\sigma) = SP_0 e^{-a\sigma}$$

Frost Heave

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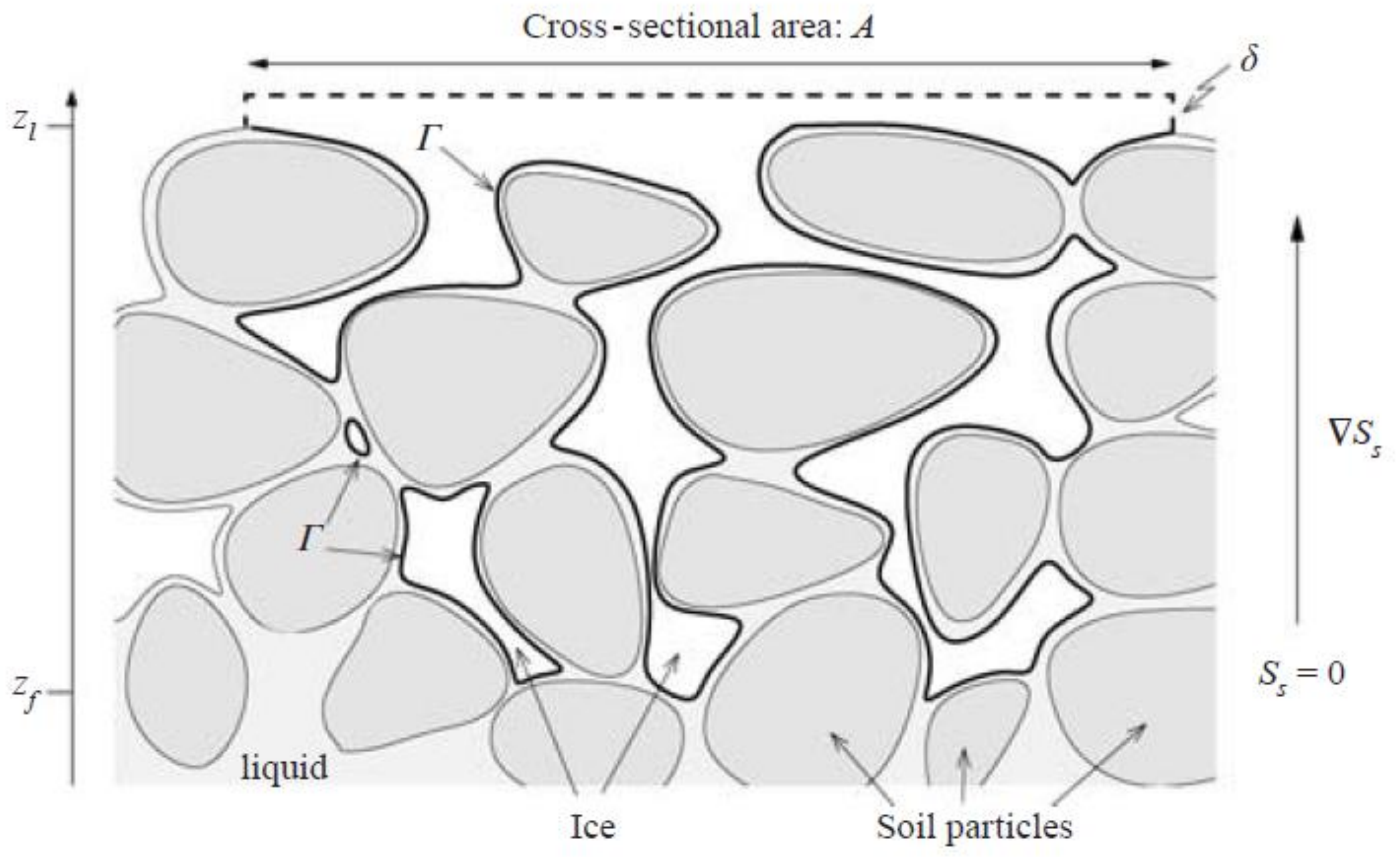

$$\frac{p_i}{\rho_i} - \frac{p_w}{\rho_w} = -L\ \ln\left(\frac{T}{T_f}\right)$$

Clausius-Clapeyron

$$\dot{\varepsilon} = SP\ grad(T)\Big|_{0°C}$$

Konrad and Morgenstern (1981)

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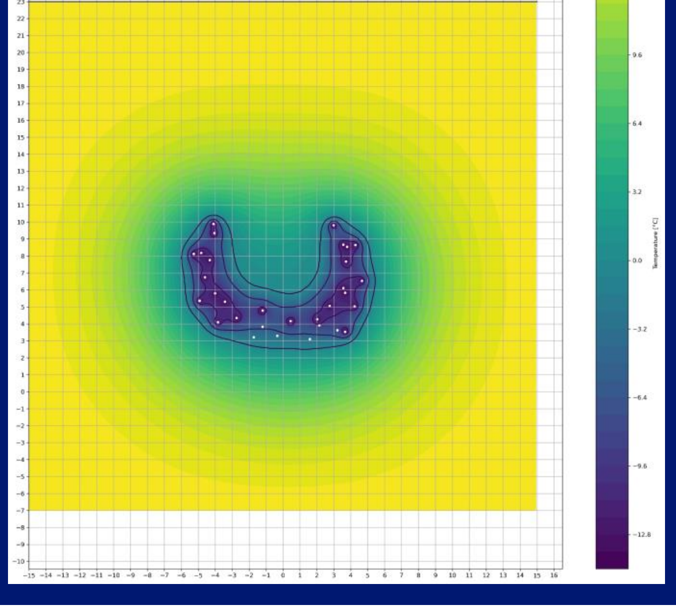
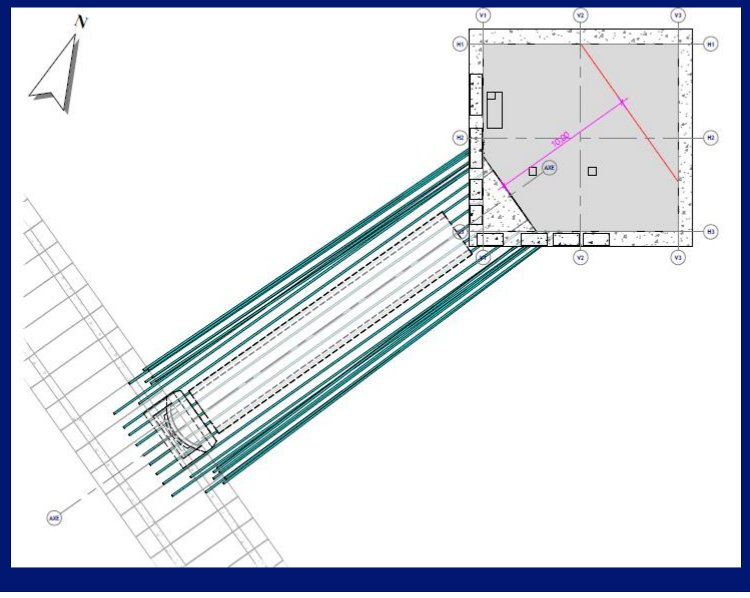




27m cross passage between a shaft and tunnel (at ~30m depth)

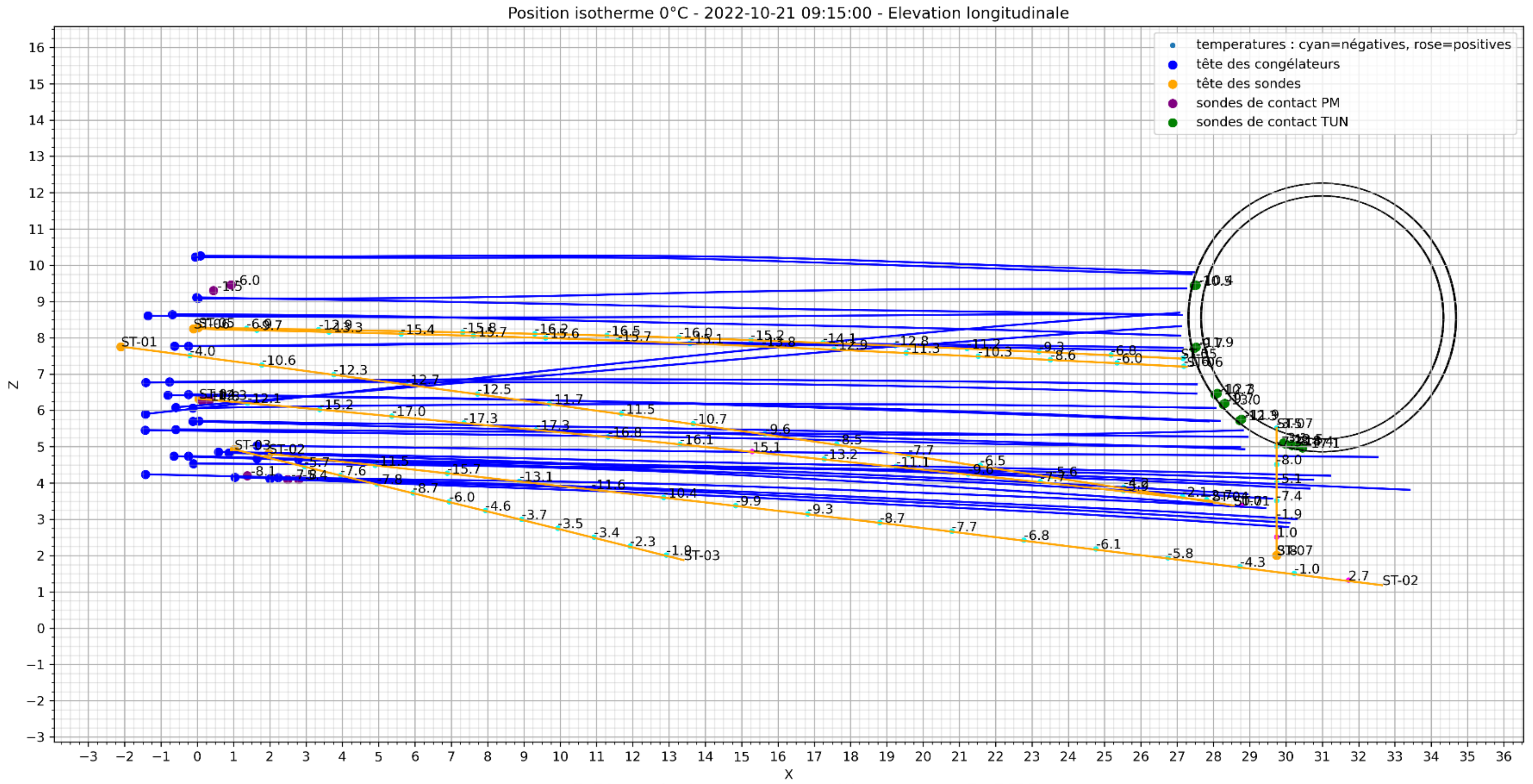
- Calcaires de Saint-Ouen in upper part : grouted
- Sables de Beauchamp (silty-clay) in lower part : frozen

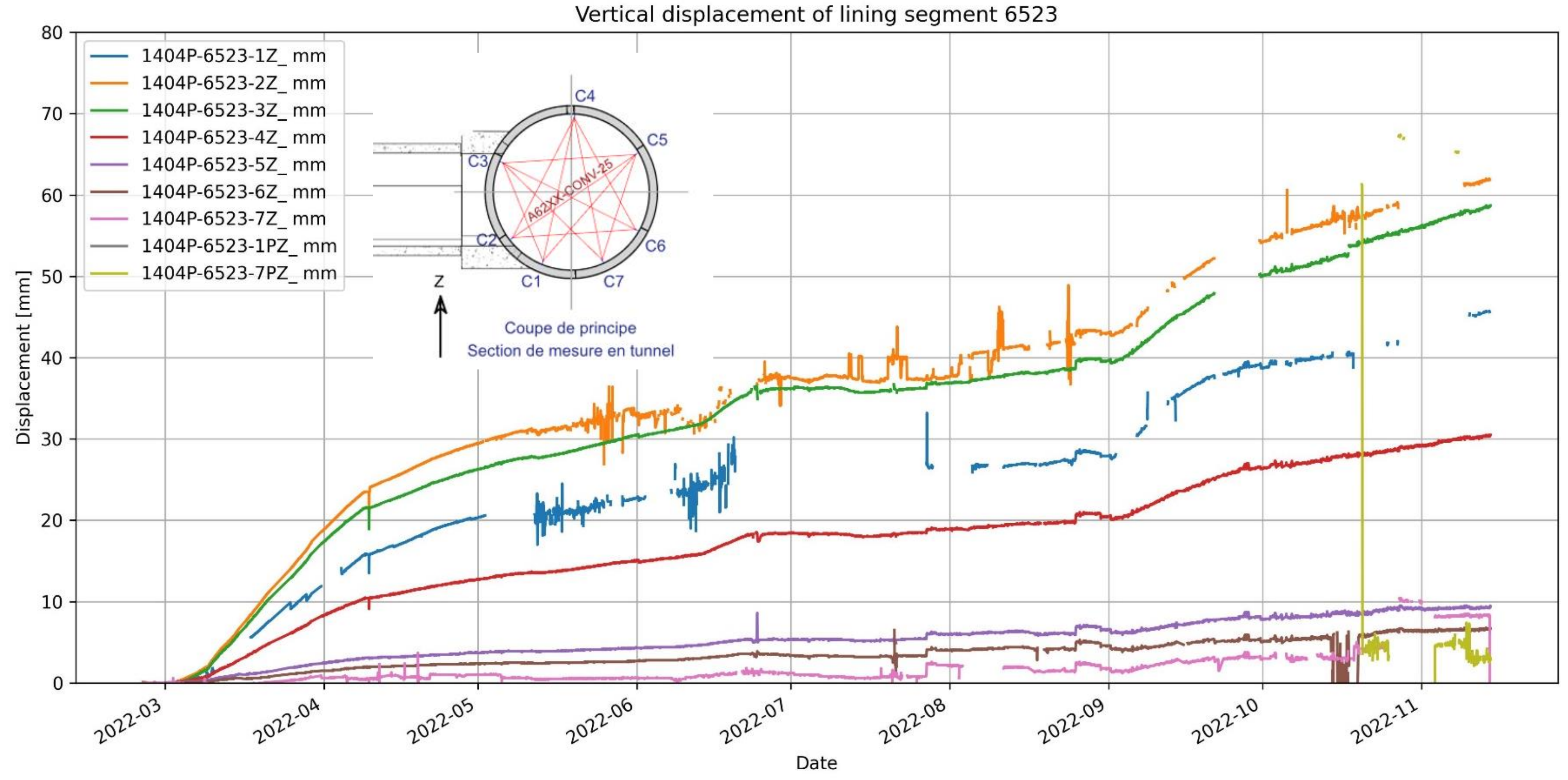
According to Laboratory test (Frost heave test) cryogenic succion was negligible.

- Deformations were observed and related with the increase of the 0°C isotherm:
- As the volume defined by isotherm 0°C increased deformations were observed
- Increase in brine Temperature and deactivation of selected freeze pipes
- “Stabilization” of isotherm 0°C position led to “stabilization” of displacements
- Regression of isotherm 0°C led to stabilization of displacements
- Once isotherm 0°C developed further than historical max value displacement increased at initial rate.

Displacements being correlated with isotherm 0°C position :

- Retro-analysis of temperature distribution and correlation with tunnel displacements
- Volume increase ratio 2.5-2.7% could explain the history of deformations.

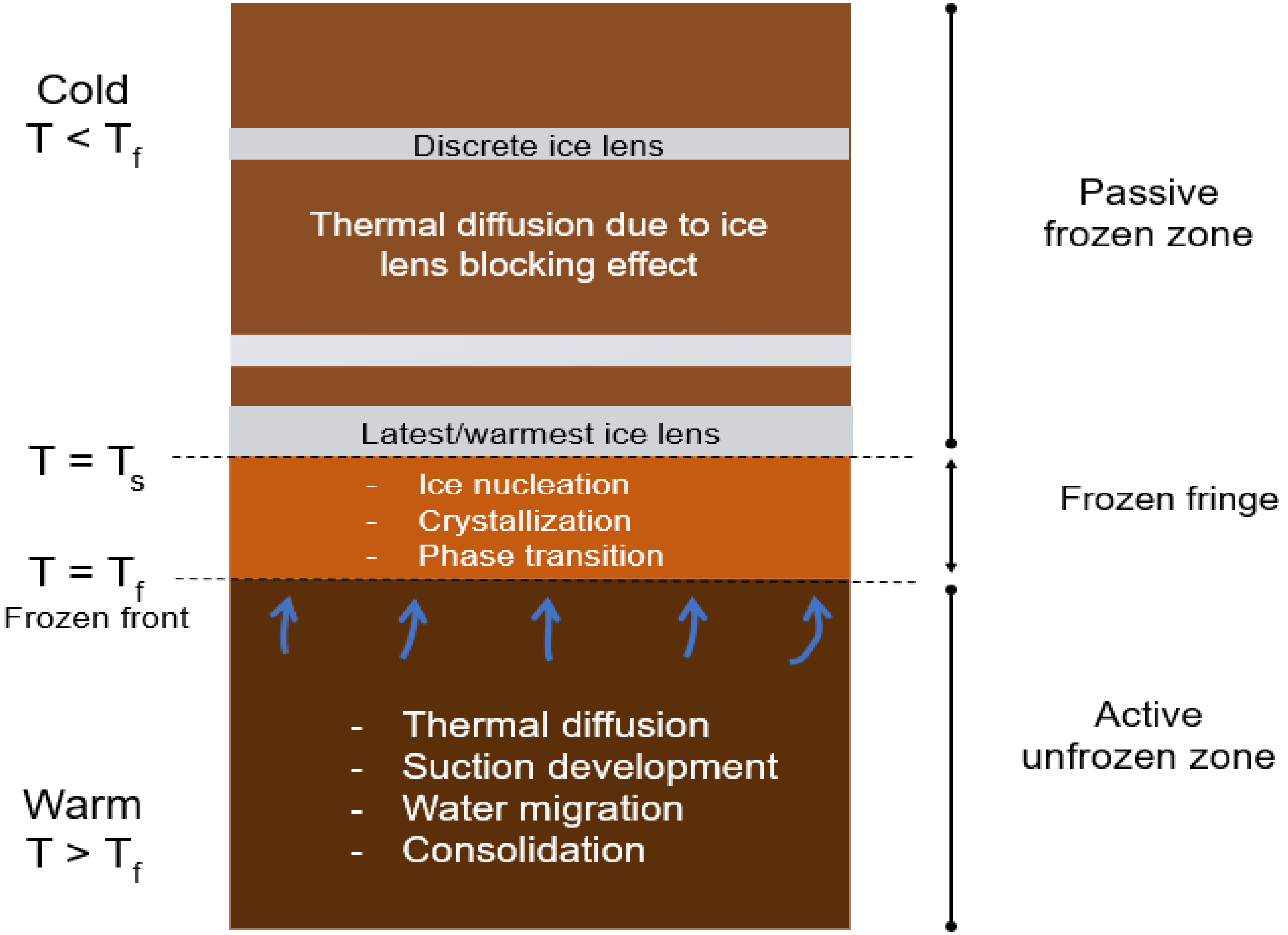




<u>Lesson learned so far :</u>

Increase of volume due to phase change should be taken into account in design even under large stresses

Processes governing fine-grained soil freezing



(Joudieh 2023)

Summary of a frozen soil profile and the processes that govern freezing

Factors influencing frost heave

Factors influencing soil freezing

Condition	Factor
Site conditions	• Soil type, grain size, • Water content, water availability, • **Applied load, Overburden pressure** • Soil temperature, temperature gradient
Project settings and choices	• Freezing temperature • Distance from the injection axis, • Thickness of soil layer(s) above tunnel, • Thickness of the frozen soil

Factors influenced by overburden pressure

Factor	Reference
Water content and Water migration	Penner and Ueda 1977; Loch and Kay 1978; Ming et al. 2016; Lu et al. 2021
Suction in the frozen fringe	Konrad and Morgenstern 1982; Ji et al. 2022
Segregation temperature	Konrad 1980; Azmatch 2013; Ji et al. 2022
Thickness of the frozen fringe	Konrad and Morgenstern 1982; Xia et al. 2005; Ji et al. 2022

Effect of overburden pressure external on water intake

Effect of overburden pressure on water intake

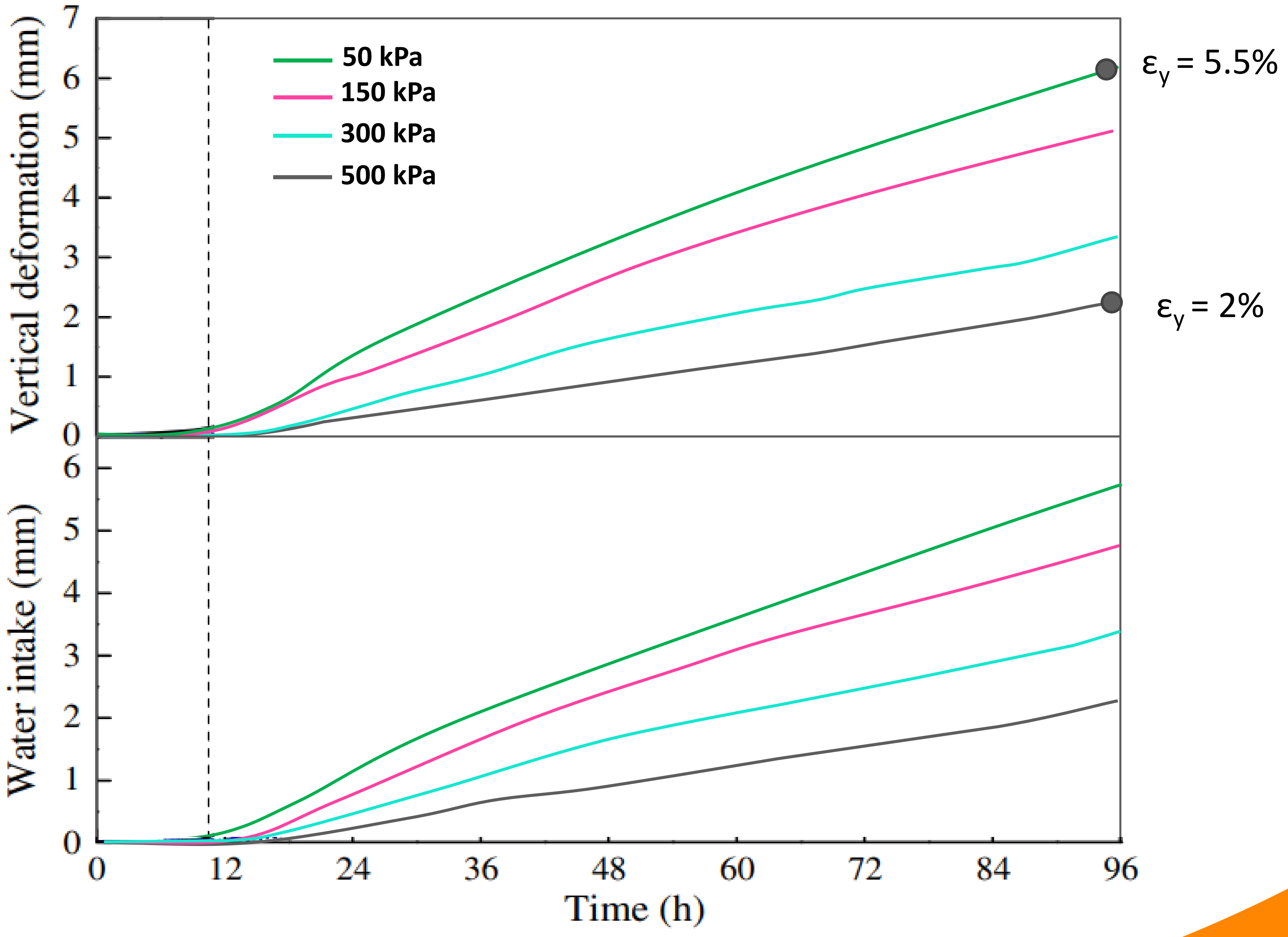
Saturated silty clay:

H = 11 cm, D = 10 cm,
w =22.3%, ρ_d = 1.75 g/cm^3
T_{top} = -2 °C, T_{bottom} = +2 °C, freezing time = 96 hours

- As stress ↗ time to absorb water ↗ → heave ↘
- Water absorption starts when the advance rate of the freezing front < critical value

External water intake ↘ as stress ↗ → heave ↘

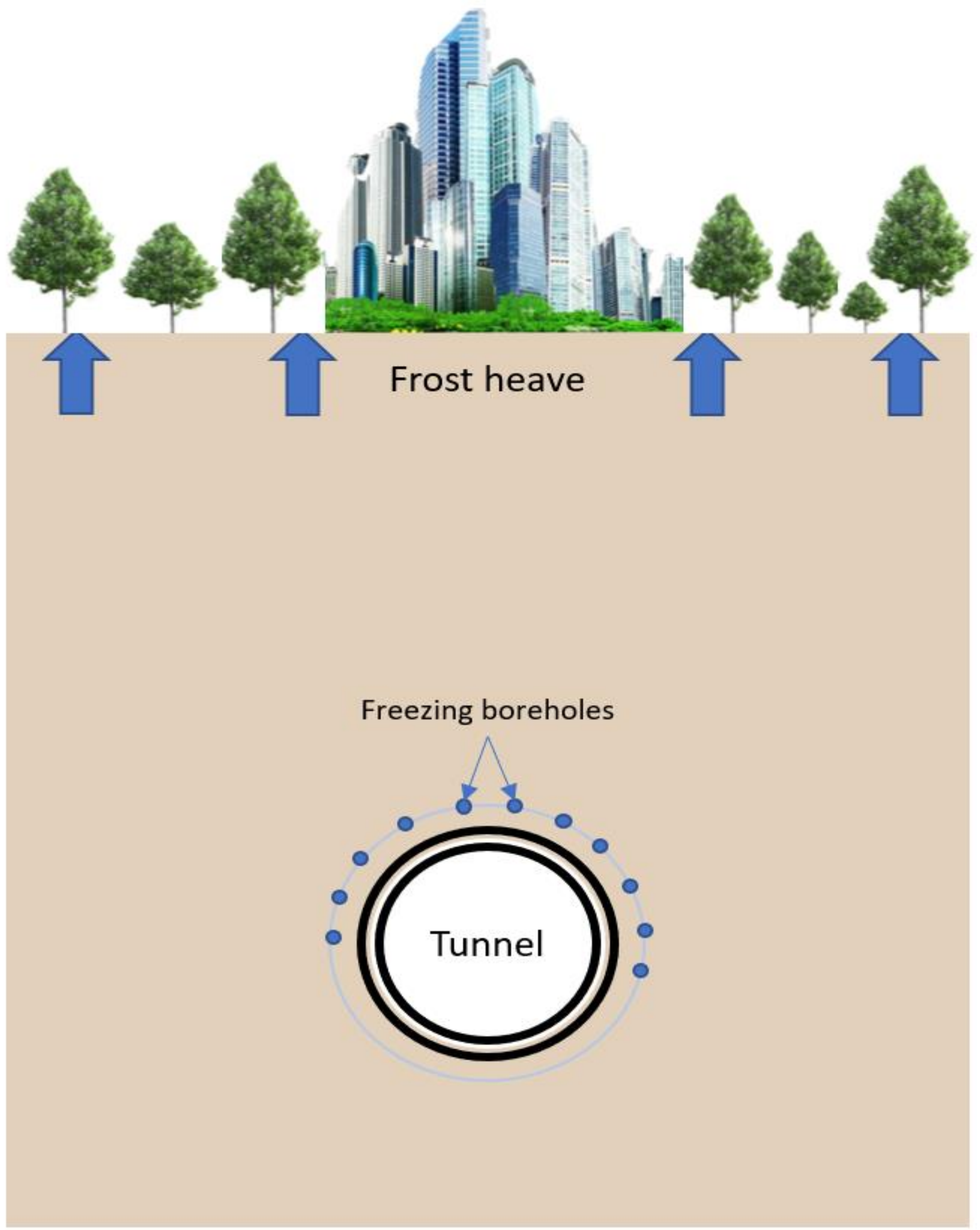
(Penner and Ueda 1977; Loch and Kay 1978; Ming et al. 2016; Lu et al. 2021)

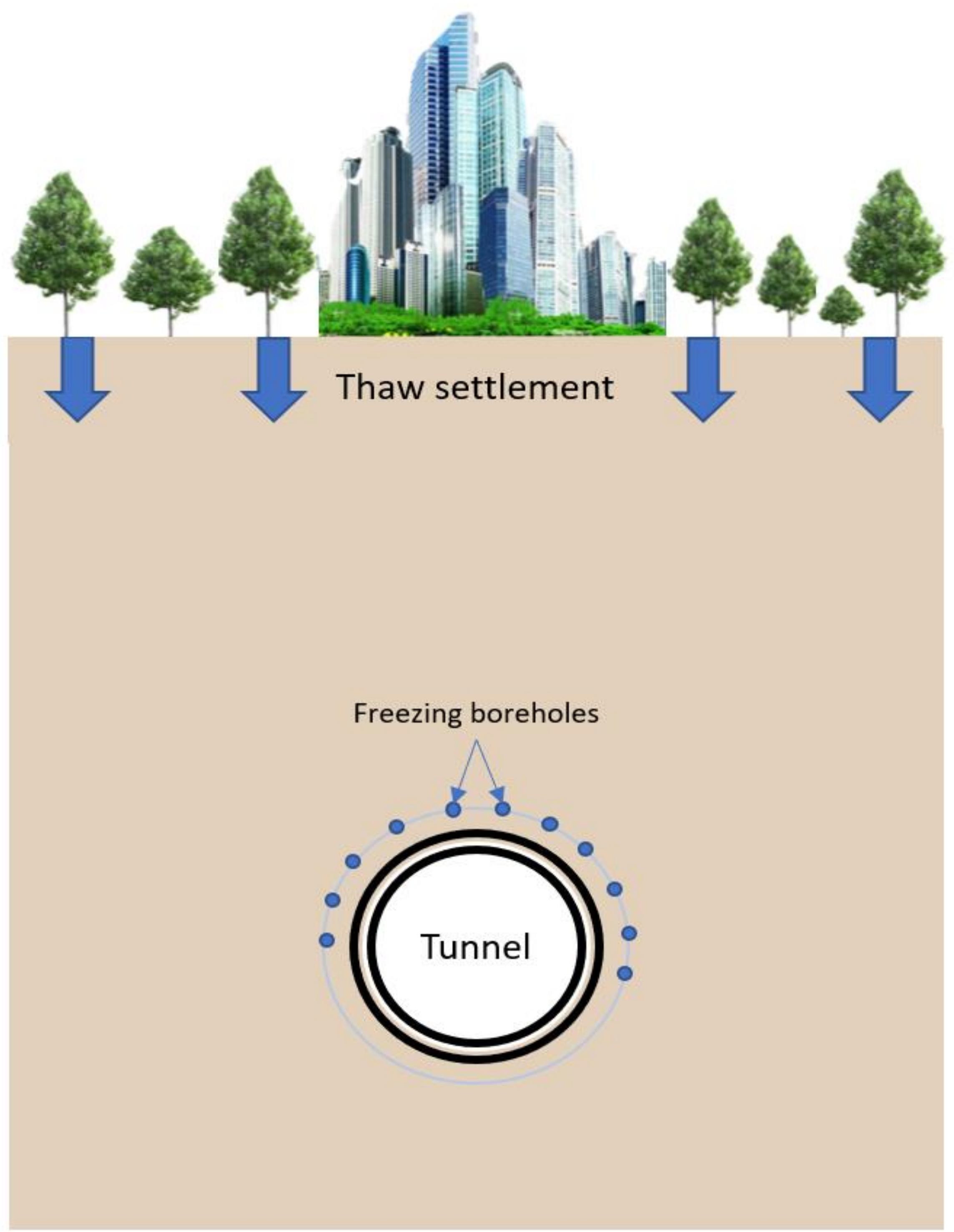


Variations of the vertical deformations and water intakes of the saturated silty clay soil samples under different applied pressures (Zhang et al. 2017)

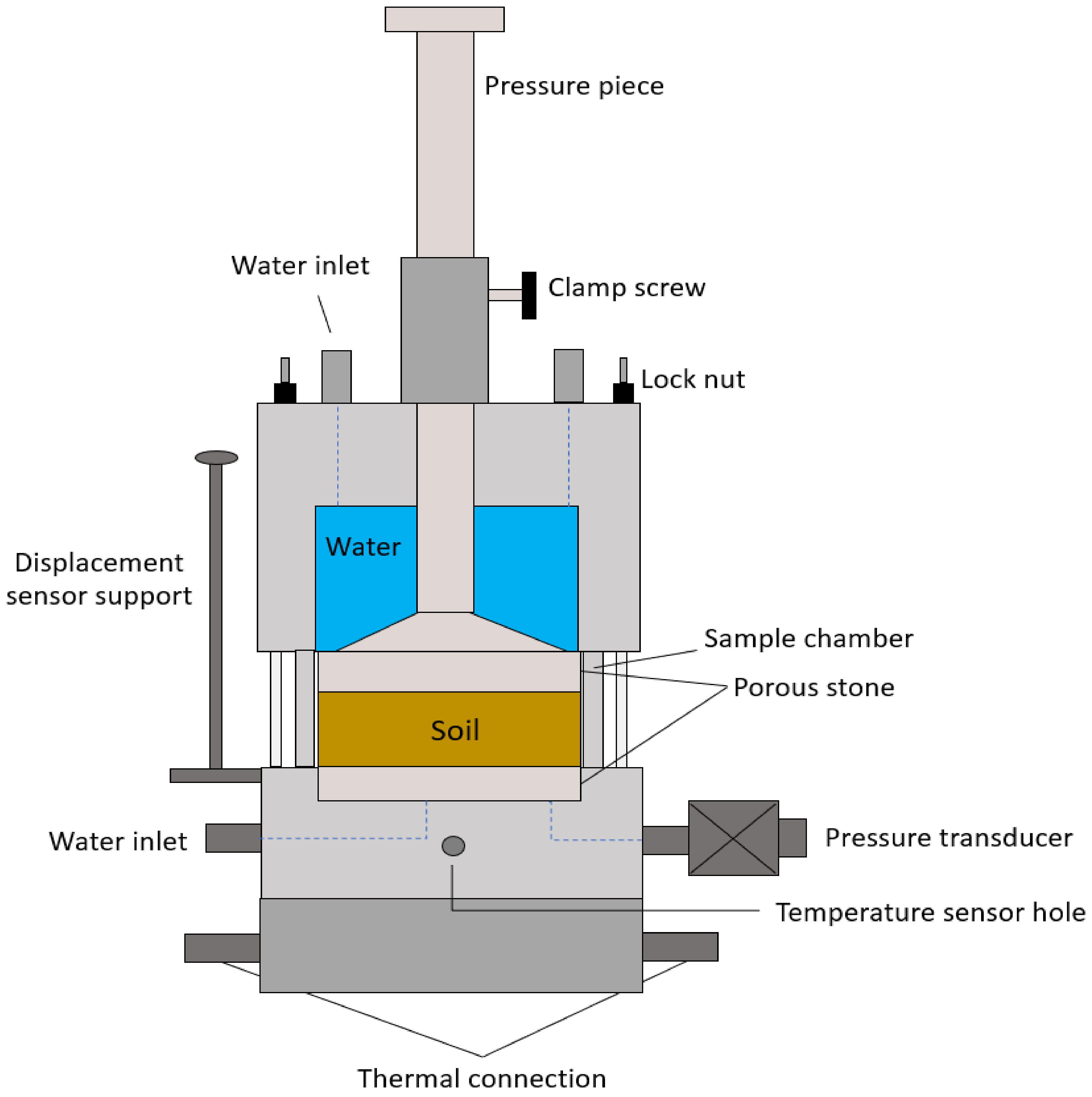
Effect of overburden pressure?

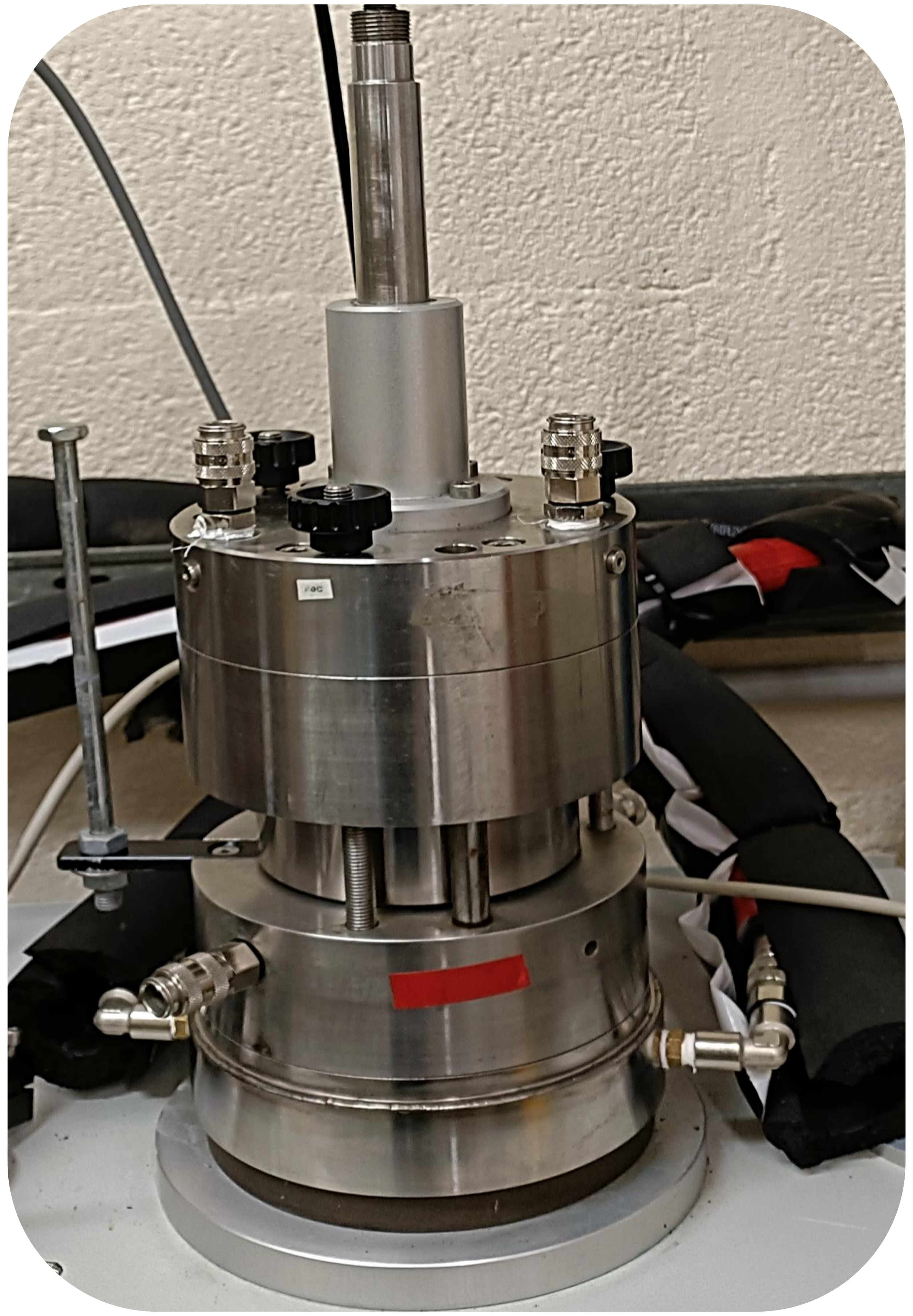
- Develop and ameliorate an experimental setup
- Establish a test procedure
- Carry on tests to understand the behavior of soil during both freezing and thawing under different temperature conditions and applied pressures
- Use the acquired data to develop a model capable of predicting the F-T behavior of soil under applied pressure





Modified temperature-controlled oedometer





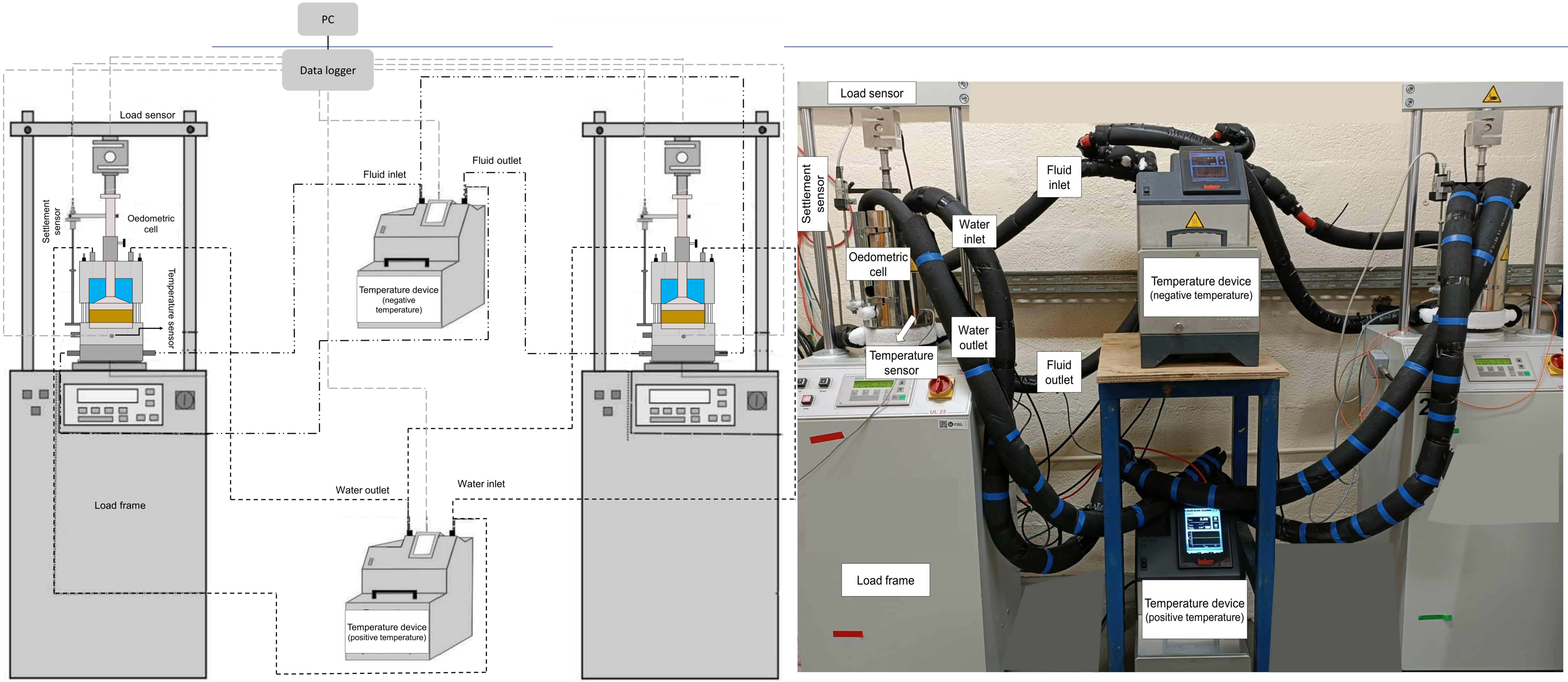
Sample size

- Surface area of 40 cm^2
- Diameter of 71.4 mm
- Height of 20 or 40 mm

Technical Specifications

- Temperature: - 40 -> + 90 ^{o}C
- Maximum axial stress up to 5000 kPa

Modified temperature-controlled oedometer

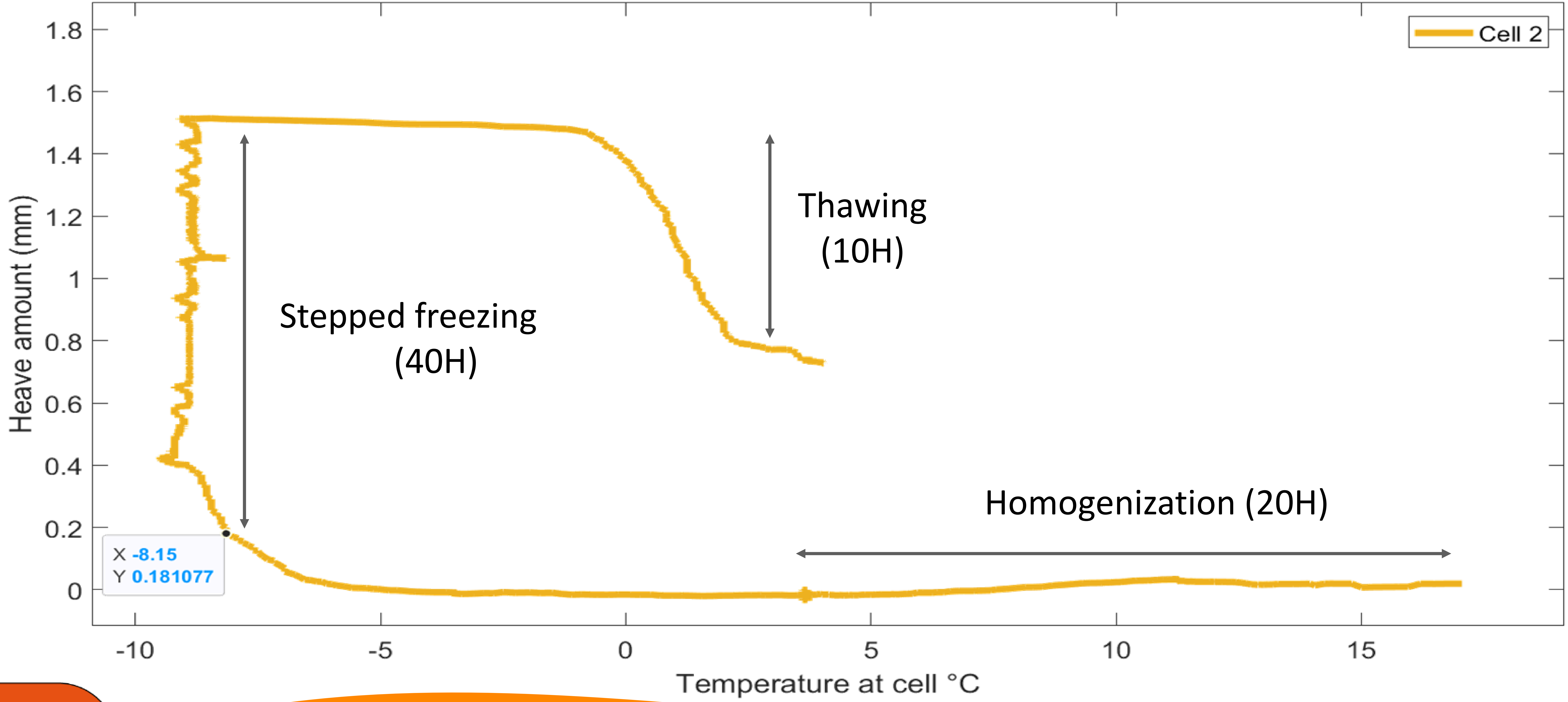


Schematic diagram and photograph of the modified TC oedometric system

Modified temperature-controlled oedometer

Repeatability

Silty soil: H = 2 cm, water content = 17.2%, dry density = 1.75 Mg/m^3



Modified temperature-controlled oedometer
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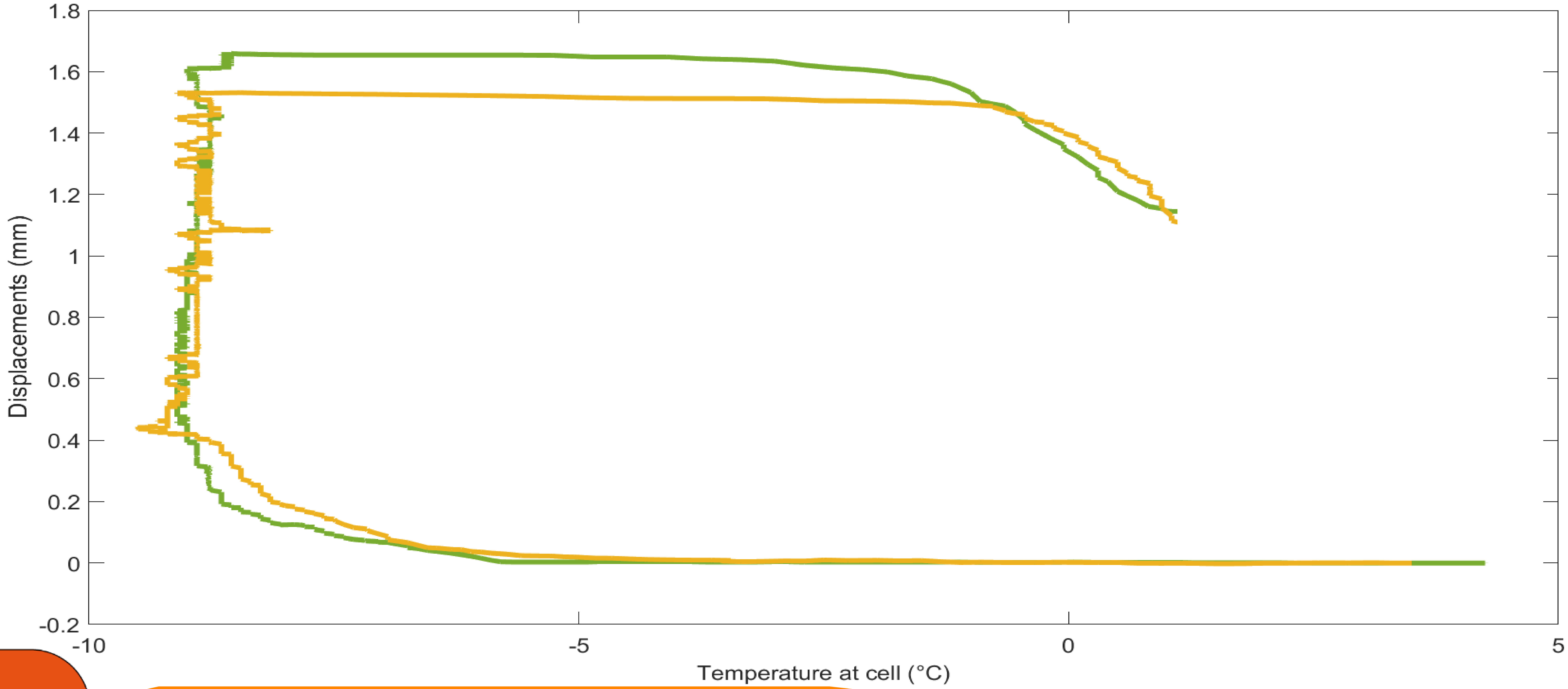
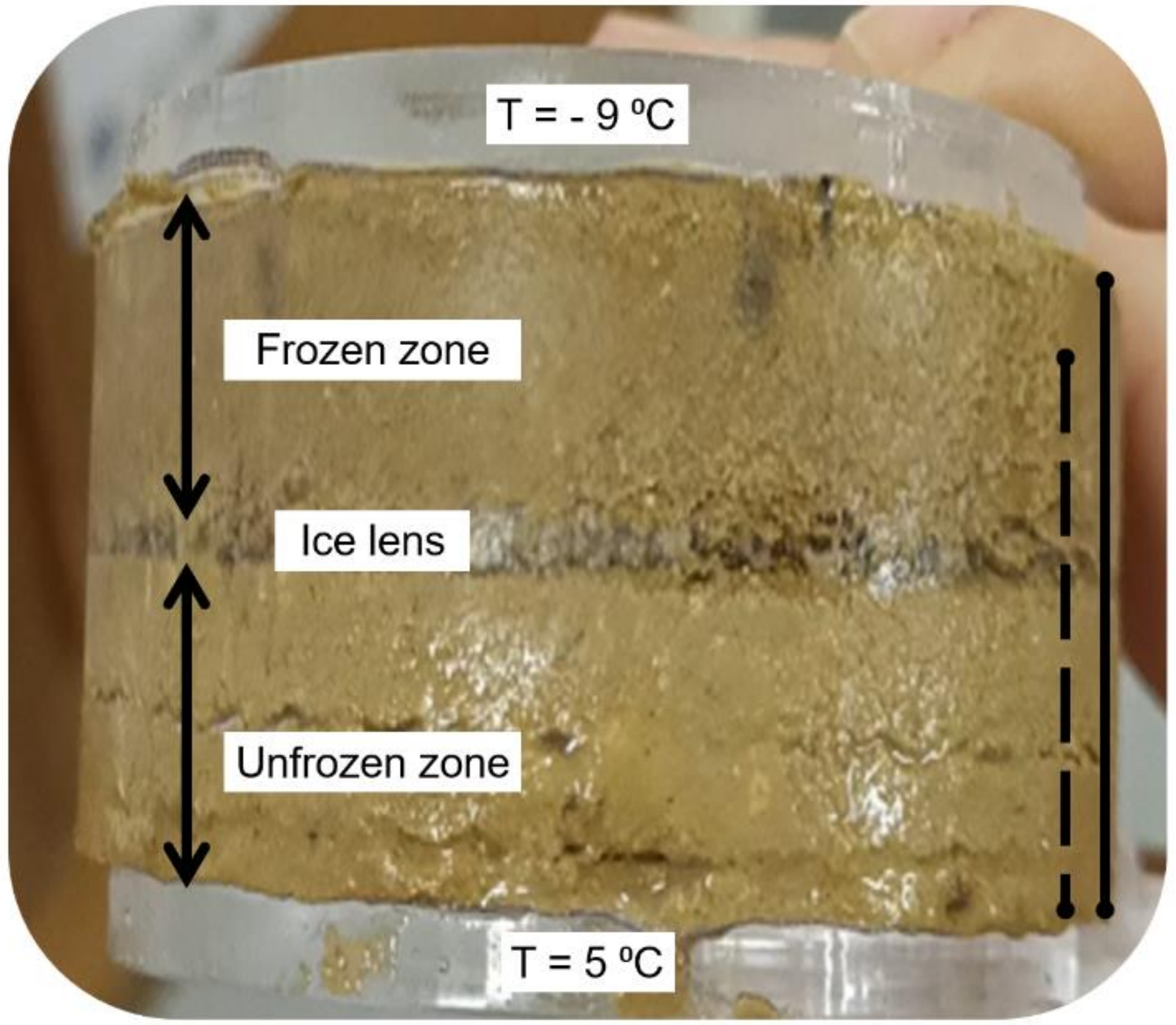


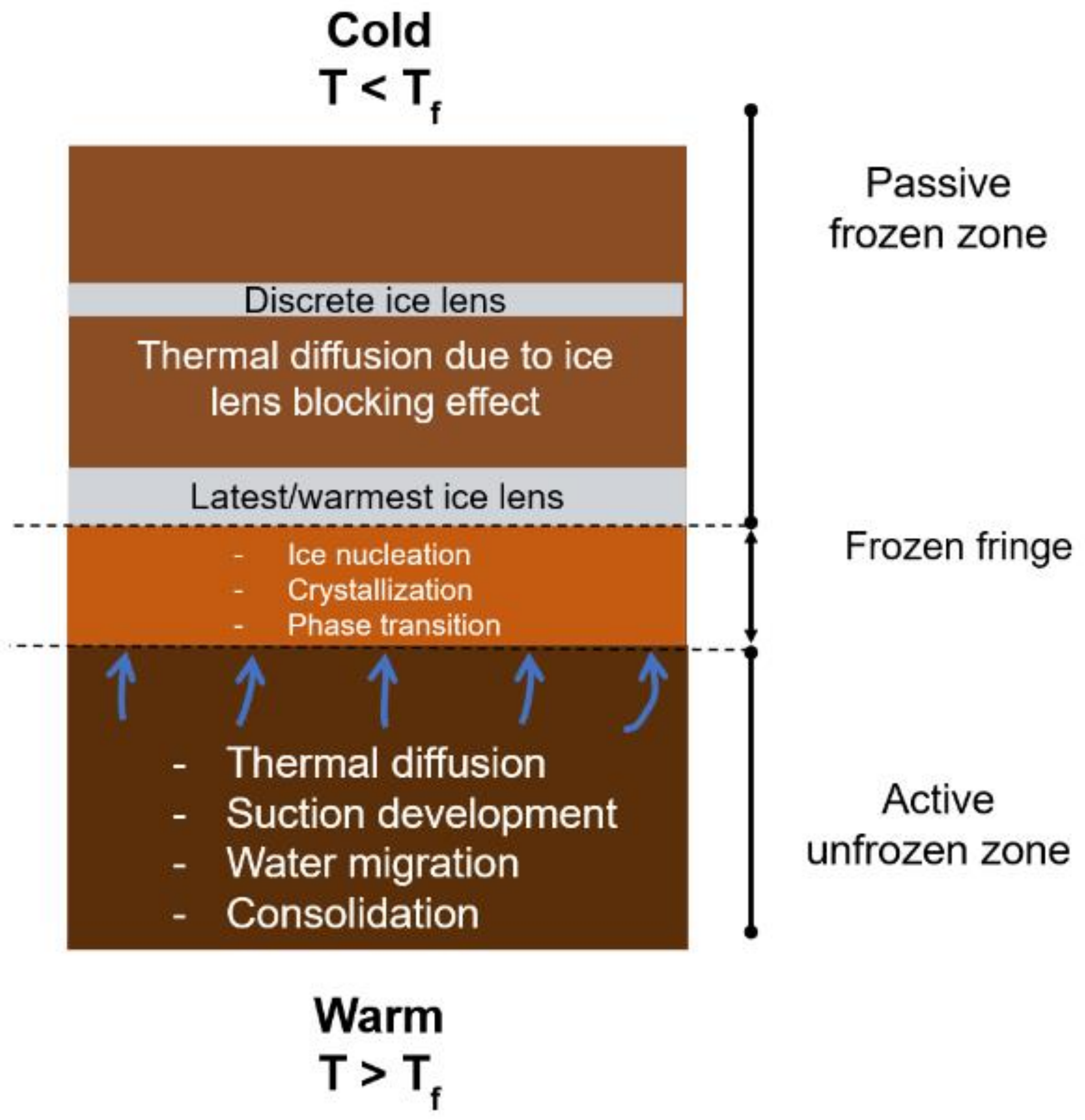
Modified temperature-controlled oedometer

Silty soil: H = 4 cm, water content = 17.2%, dry density = 1.75 Mg/m^3

6 months of a heavy experimental plan to:

- Develop a prototype: a miniature heave test
- Check the repeatability of the results using LP
- Check saturation inside the TC oedometer
- Validate the experimental protocol





$\%W_{Initial} = 17.2$ ➡ $\%W_{Frozen} = 29.4$ ➡ + 12.3 %

Freeze-thaw tests on silty sand under applied pressures

Test protocol

1. Sample preparation → **2. Sample saturation + temperature homogenization** → **3. Load application** → **4. Freezing** → **5. Thawing**

1. Sample preparation

Retained value:

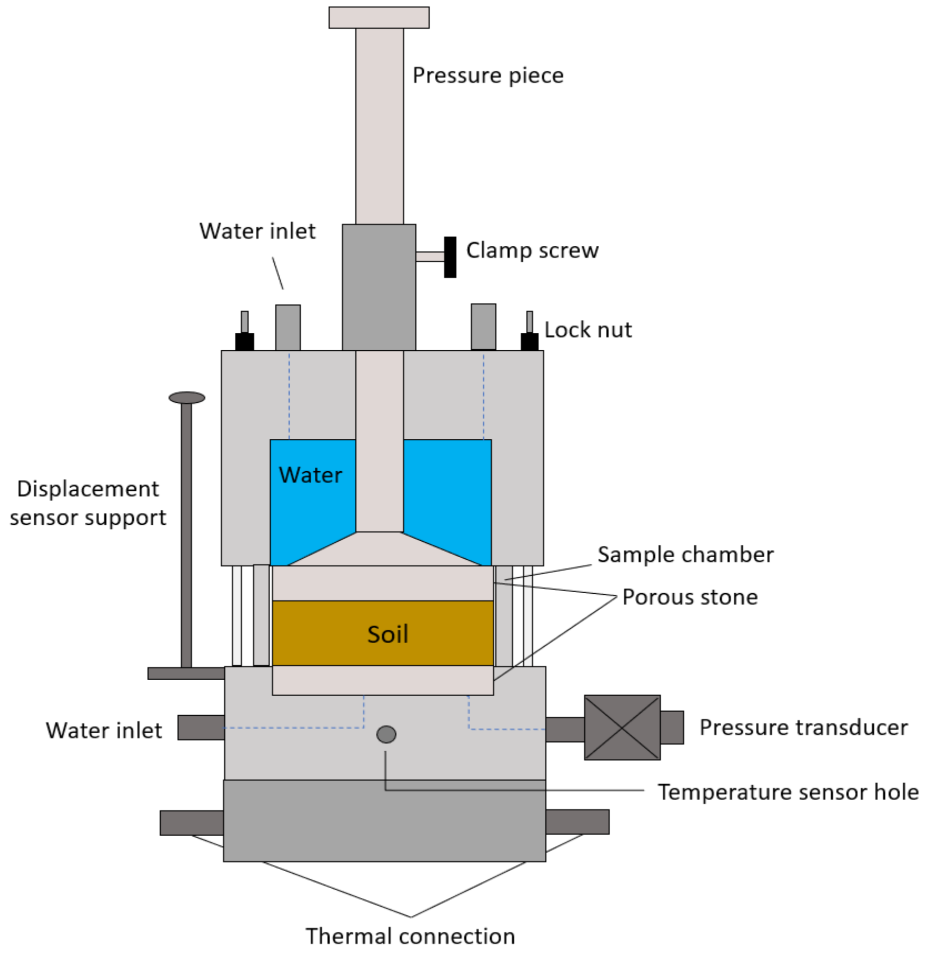
H = 2 cm
D = 7.1 cm
Water content = 16.5 %
Dry density= 1.7 Mg/m^3

2. Sample saturation + temperature homogenization

Applied pressure = 100 kPa for 10 mins to ensure contact
Applied pressure = 10 kPa
T_{cell} = + 4 ~ 5 ^oC
Saturation time = 65 hours

3. Load application

Stepped loading of 24 hours each

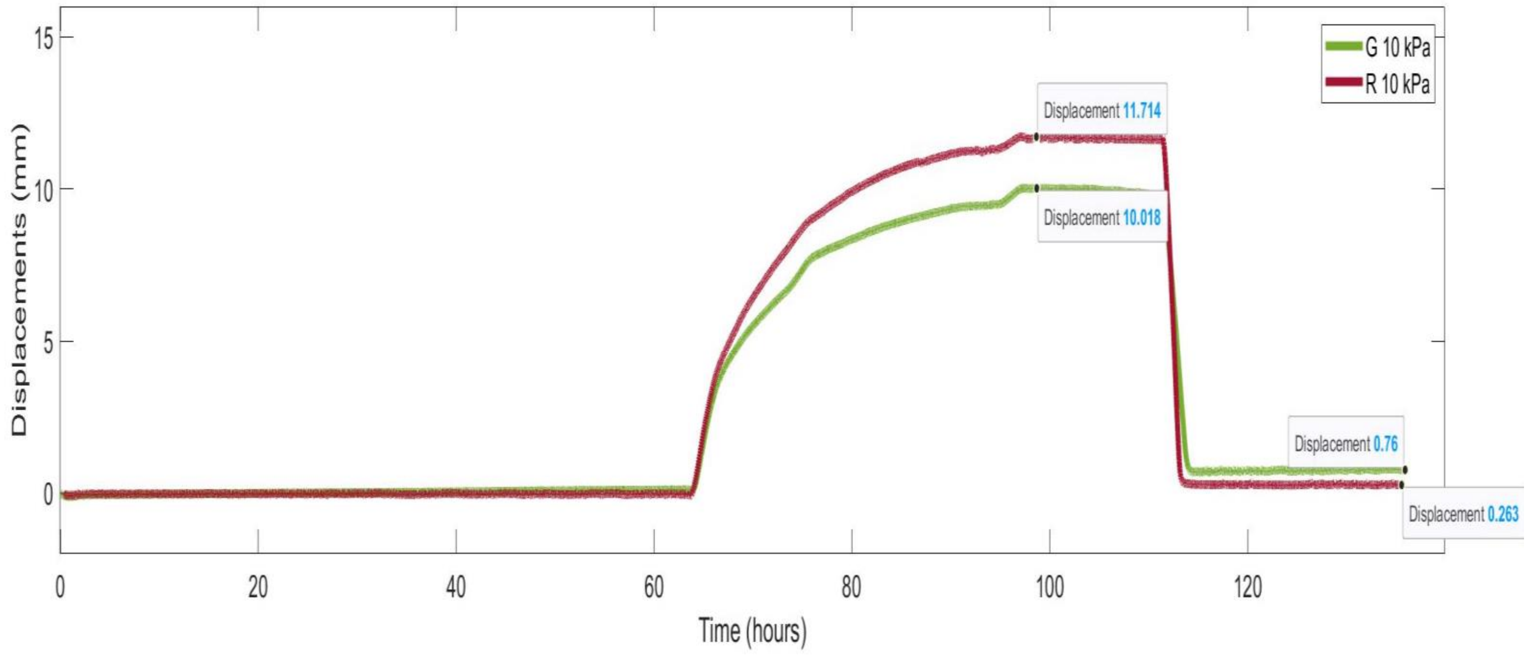


4. Freezing

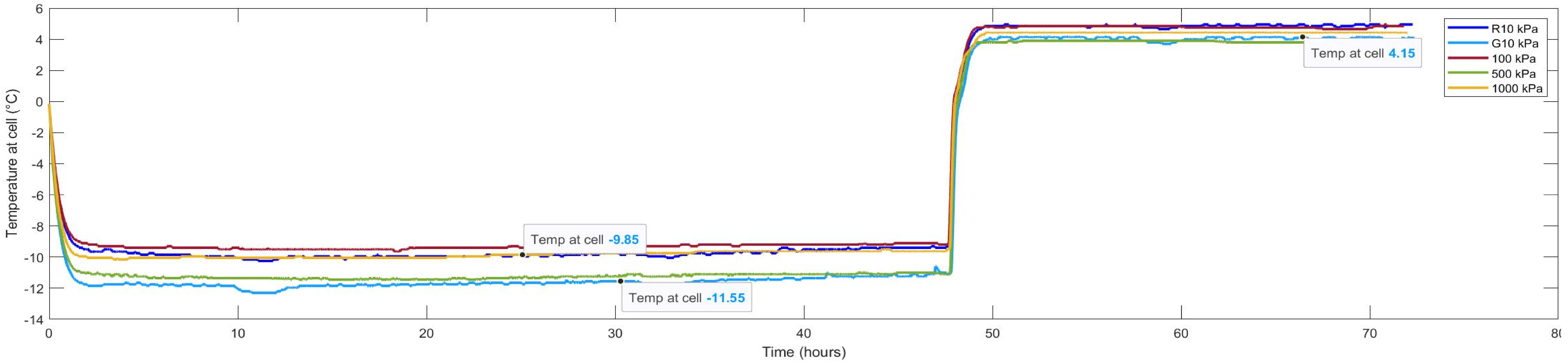
For 48 hours

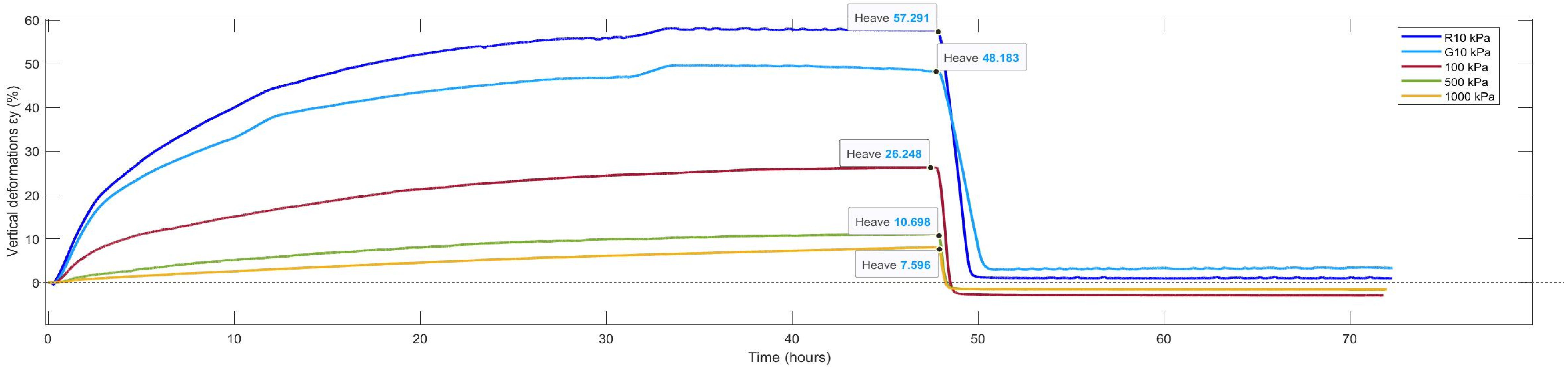
5. Thawing

For 24 hours

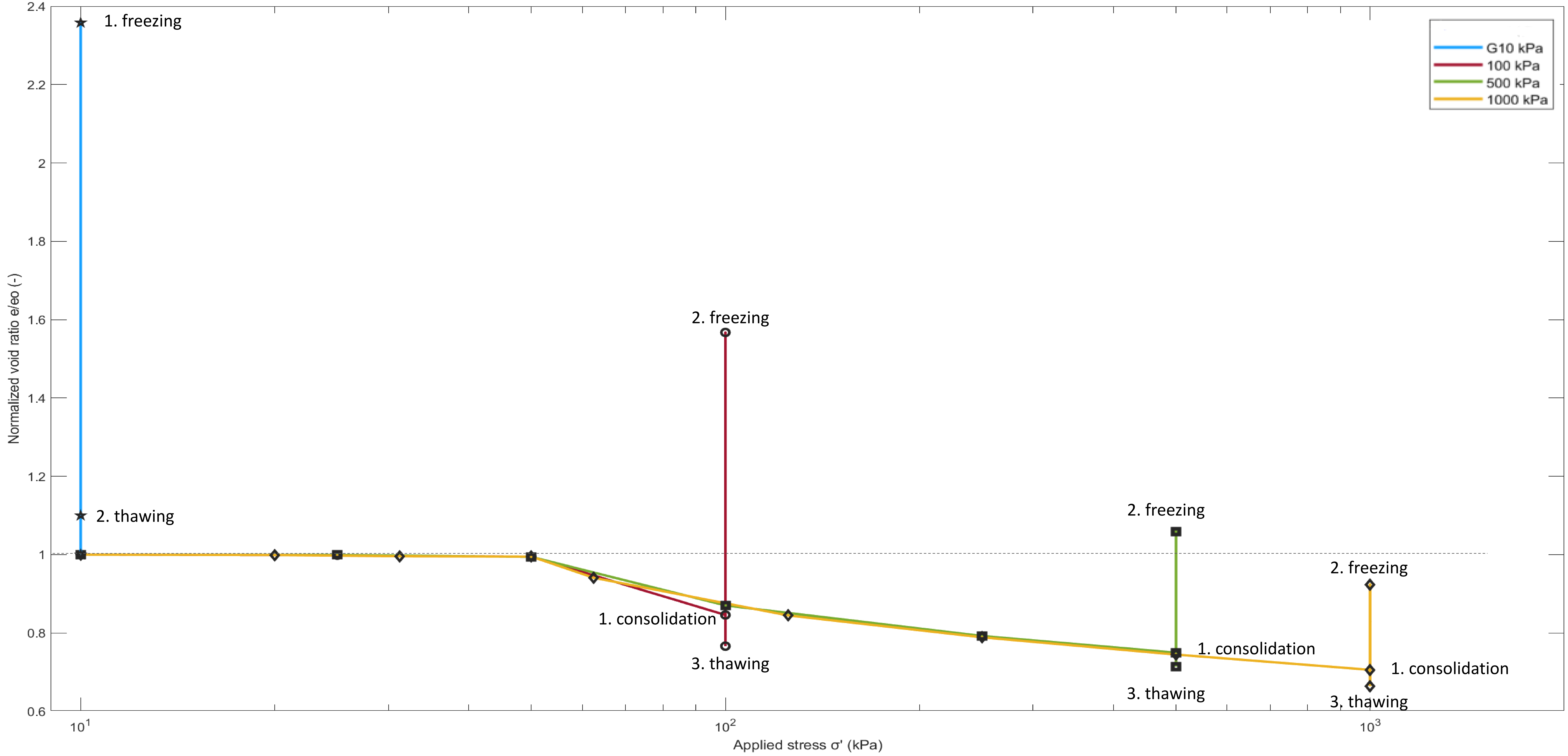


Freeze-thaw tests on silty sand under applied pressures





Freeze-thaw tests on silty sand under applied pressures



Conclusions

- AGF = ft (Soil type, grain size, water content, water availability, **applied load**…)
- Overburden pressure affects water content, water migration, suction in the frozen fringe segregation temperature, the thickness of the frozen fringe, permeability (partially frozen soil)
- Heave ↘ as applied pressure ↗
- Further research on higher applied pressure is in perspective

Thank You

Questions?

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