NTNU
Norwegian University of Science and Technology

Constitutive modeling of frozen soils

PoreLab Kick-off Meeting

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Overview

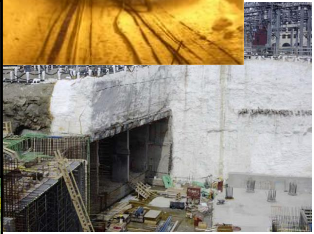
- Background
- Main features in the behavior of frozen soils
- Elasto-plastic model
- Elasto-viscoplastic model
- Results

Background

- Challenges in the arctic
  - Coastal erosion
  - Settlements
  - Thawing permafrost
- Challenges in the subpolar and temperate zones
  - Seasonal frost

Background (cont.)

- Artificial ground freezing

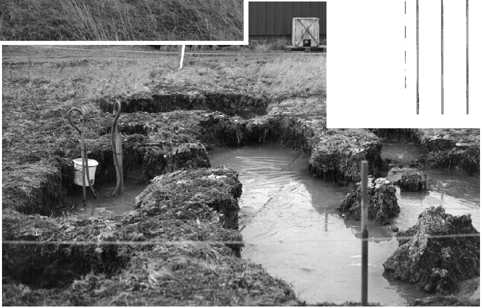


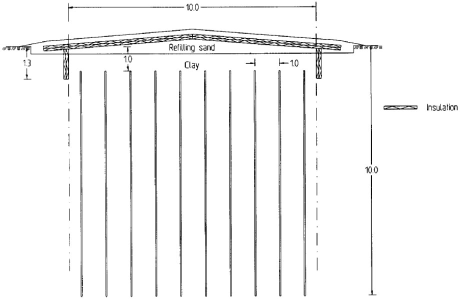
Frozen soil testing at NTNU

- New 20MPa triaxial cell (GDS)
- -30°C to + 65°C
- Up to 250 kN of axial load
- Accurate high pressure volume controllers
- Local displacement transducers

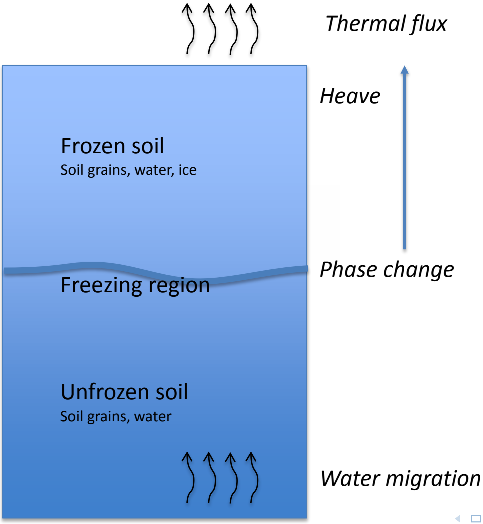
Example

- Heat storage and (over)extraction





The physical system of 1D ground freezing



Modelling of frozen soils

- Total stress models
  - Pure mechanical
  - Parameters given for one temperature -> change in temp. -> change in parameters
- Effective stress models
  - For THM modelling
  - Ice as fluid or solid?

Saturated frozen soils

$$s_w + s_i = 1$$

Ice content

Poor ice soils:

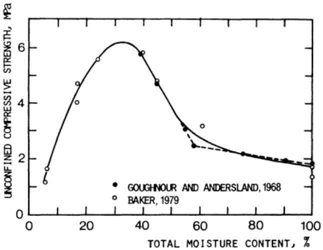
→ Binding effects on grains
→ Ice cementation

An increase in ice content results in an increase in strength

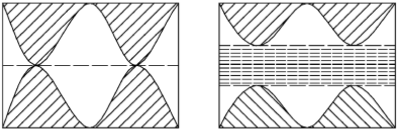
Ice rich soils:

→ Decreases grains contact

An increase in ice content results in a decrease in strength



Effect of total moisture on strength of frozen soil
(adopted from Baker 1979)



Schematic of ice increasing in an ice rich soil body
(Li et al. 2002)

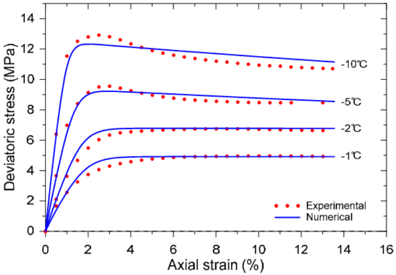
Temperature

Decreasing temperature results in:

→ An increase in elastic modulus

→ An increase in strength

In other word: Change of behavior from plastic type to a brittle type



Stress-strain curves at different temperatures (Xu 2014)

Confining pressure

Low pressure: (Region I)

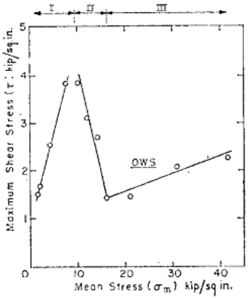
- → Confining pressure makes the solid phase (soil and ice) more compact
- → Strength increases with confining pressure

High pressure: (Region 2)

- → Ice in the sample begins to be crushed
- → Pressure melting occurs
- → Strength decreases with confining pressure

Higher pressure: (Region 3)

- → Ice content tends to zero
- → Strength increases with confining pressure



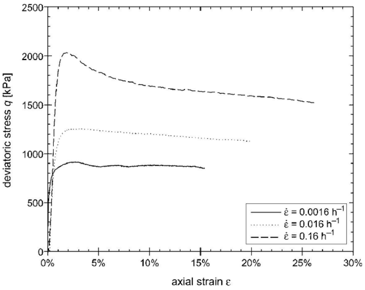
Relation between strength and confining pressure
(Chamberlin et al. 1972)

Strain rate

Increasing strain rate results in:

→ An increase in strength

→ More brittle behavior



Stress-strain curves at different strain rates (Arenson et al. 2004)

Cryogenic suction

- ✓ Clausius-Clapeyron Equation:

$$\text{Suction} = f\,(\text{Temperature})$$

- ✓ Freezing Characteristic Function:

$$\text{Ice content} = f\,(\text{Suction})$$

⇨ **Studying the effect of suction could be sufficient for capturing the effects of ice content and temperature**

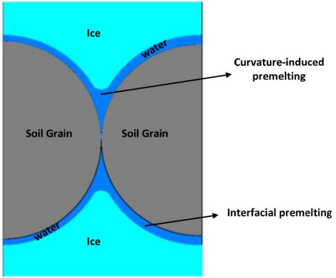
Pre-melting Dynamic (Weelaufer and Worster 2006)

Curvature-induced pre-melting mechanism

- Result of surface tension
- Acts very similar to capillary suction
- Bonding the grains together

Interfacial pre-melting mechanism

- Result of disjoining pressure
- Acts as a repelling force between ice and grains
- Tends to widen the gap by sucking in more water



Combination of these mechanisms controls the behavior against ice content and temperature variations.

Elastoplatic Model

Frozen soil could be explained by

- Solid phase (consists of soil particles and ice)
- Water phase

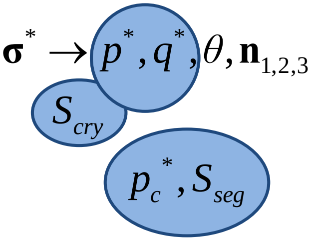
The behavior will be explained in two stress-state variables framework:

Solid phase stress: $\boldsymbol{\sigma}^* = \boldsymbol{\sigma} - s_w p_w \mathbf{I}$

Cryogenic suction: $S_{cry} = p_w - p_i = -\rho_i l \ln \frac{T}{T_0}$

Fundamentals of elasto[visco]plasticity

- Stresses and State variables (**σ**, **κ**)
- Elastic, d**σ** = **D** · d**ε**^{e}
- Yield surface(s), $F \leq 0$ [or reference surface(s)]
- Flow rule d**ε**$^{(v)p}$ = dλ·$\partial Q/\partial$**σ** <-> Potential surface(s), Q
- Hardening rules, **h** (d**κ**/dλ)



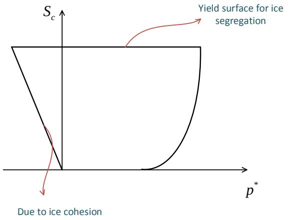
$$F_1\left(p^*, q, S_{cry}, p_c^*, s_w\right)$$

$$F_2\left(S_{cry}, S_{seg}\right)$$

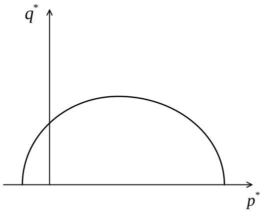
$$h_1\left(p_c^*, \frac{\partial Q}{\partial p^*}\right)$$

$$h_2\left(S_{cry}, S_{seg}, s_w\right)$$

Elastoplastic model (cont.)

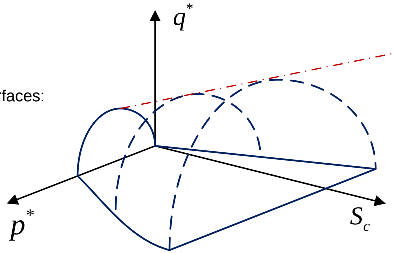


Yield surfaces in $S_{cry} - p^*$ space



Yield surface in p^* - q space

Complete yield surfaces:

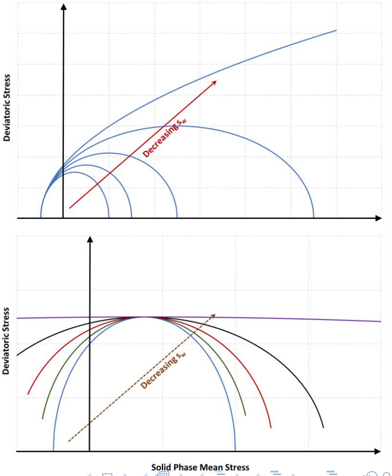


(cont.)

- **By freezing, the material goes from a porous material to a non-porous material**
- **Yield and plastic potential should be saturation dependent**

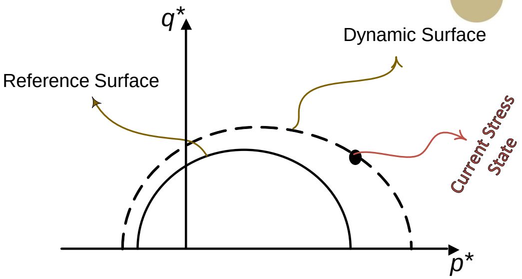
$$F_1 = \left(p^* + k_t S\right)\left[\left(p^* + k_t S\right)s_w^m - \left(p_y^* + k_t S\right)\right] + \left(\frac{q^*}{M}\right)^2$$

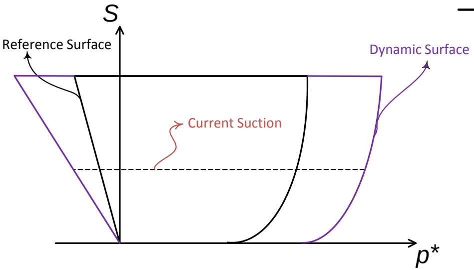
$$Q_1 = s_w^{\gamma}\left[p^* - \frac{p_y^* - k_t S}{2}\right]^2 + \left(\frac{q^*}{M}\right)^2$$



Elasto-viscoplastic model

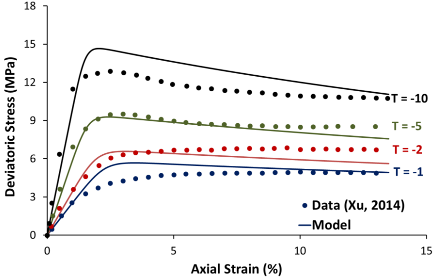
Over-stress method

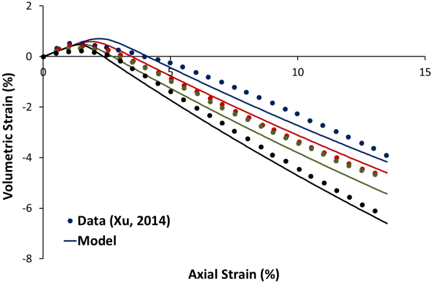




Model Results

Model Results: Triaxial tests under different temperatures

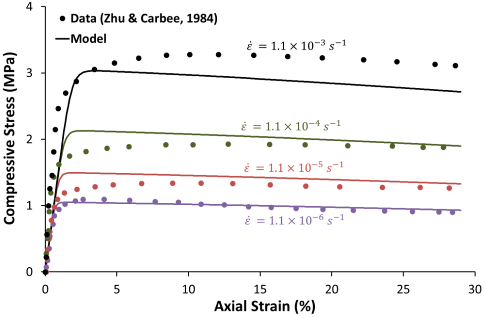




Confining pressure: 1 MPa

Strain rate: Constant

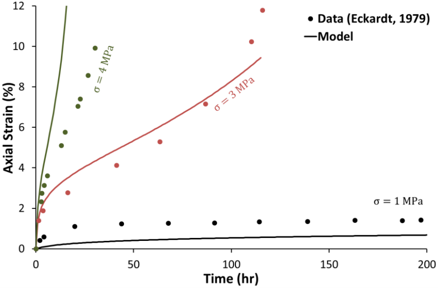
Model Results: Compression tests at different strain rates



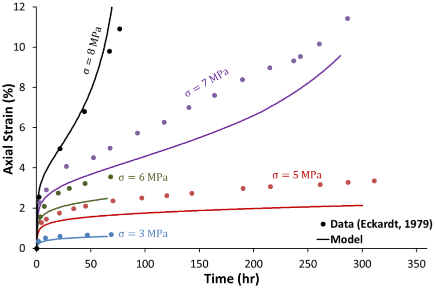
Confining pressure: 1 MPa

Temperature: -3 C

Model Results: Creep tests at different temperatures and stress level



Temperature = -5 °C



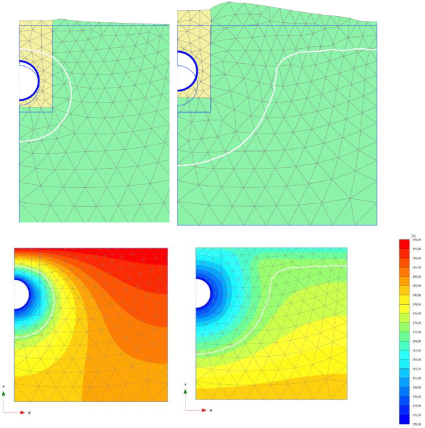
Temperature = -15 ° C

Boundary Value Problems

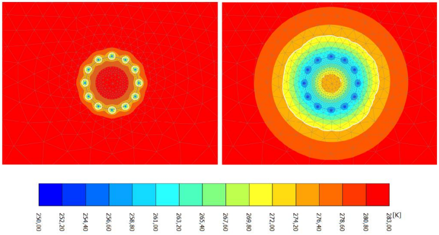
BWPs

Artificial ground freezing, surface heave

30 days 210 days



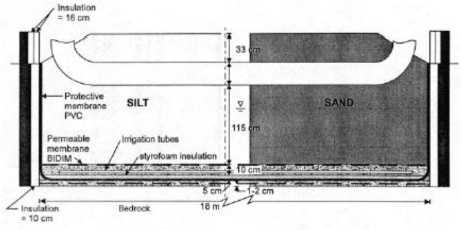
Manuel Aukenthaler, TUD and PLAXIS



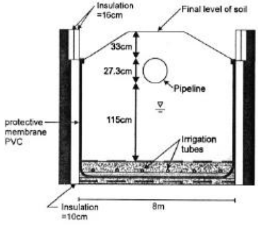
Artificial ground freezing, temperature distribution

10 days 180 days

BWP – Caen experiment

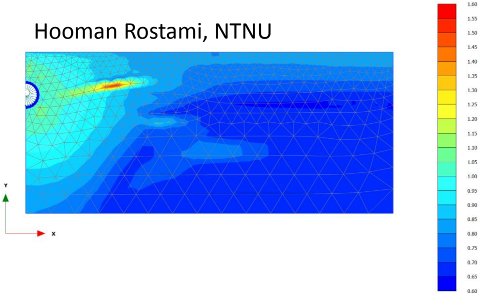


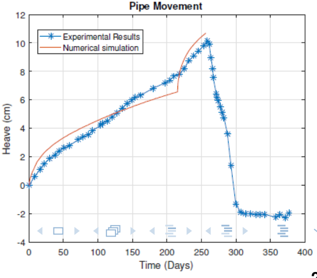
The longitudinal section



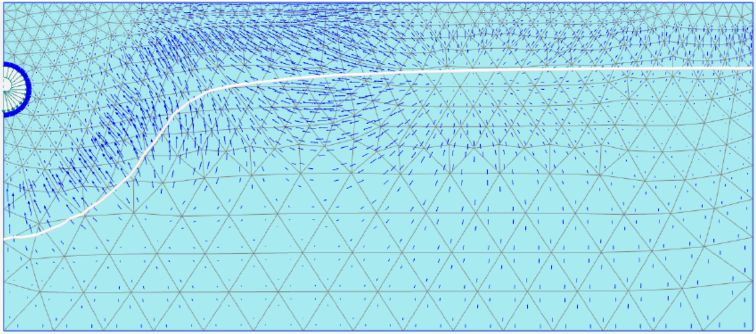
The transverse section

Hooman Rostami, NTNU



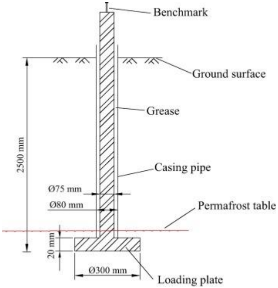


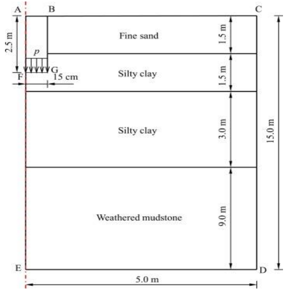
BWP – Caen experiment – cont.



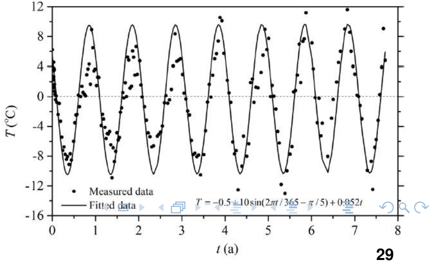
EVP- Plate loading experiment

subjected to seasonal temperature variation (Zhang et al., 2014)





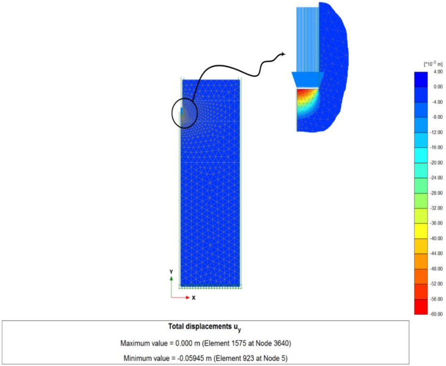
Ground surface Temperature variation



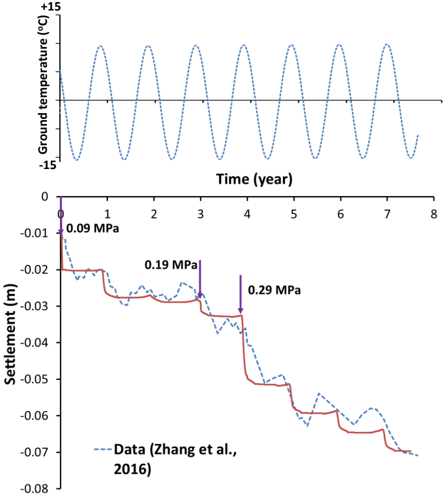
Loading steps during 8 years of simulations

Loading Step (Years)	Load (MPa)
0-3	0.09
3-4	0.19
4-8	0.29

Cont.



[*10^-3 m]
4.00
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
-24.00
-28.00
-32.00
-36.00
-40.00
-44.00
-48.00
-52.00
-56.00
-60.00
Y
X
Total displacements u_y
Maximum value = 0.000 m (Element 1575 at Node 3640)
Minimum value = -0.05945 m (Element 923 at Node 5)



+15
Ground temperature (°C)
-15
Time (year)
0
1
2
3
4
5
6
7
8
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
Settlement (m)
0.09 MPa
0.19 MPa
0.29 MPa
Data (Zhang et al., 2016)