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

Frozen soil
Soil grains, water, ice

Freezing region

Unfrozen soil
Soil grains, water

Water migration

Thermal flux

Heave

Phase change
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

Ice rich soils:
- Decreases grains contact

An increase in ice content results in an increase in strength

An increase in ice content results in a decrease in strength

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

Effect of total moisture on strength of frozen soil (adopted from Baker 1979)
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 1)
→ 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.
Elastoplastic Model

Frozen soil could be explained by

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

- Solid phase stress:
  \[ \sigma^* = \sigma - s_w p_w I \]

- 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 ($\sigma$, $\kappa$)
- Elastic, $d\sigma = D \cdot d\varepsilon^e$
- Yield surface(s), $F \leq 0$ [or reference surface(s)]
- Flow rule $d\varepsilon^{(v)p} = d\lambda \cdot \partial Q / \partial \sigma \leftrightarrow$ Potential surface(s), $Q$
- Hardening rules, $h$ ($d\kappa/d\lambda$)

\[ F_1\left(p^*, q, S_{\text{cry}}, p_c^*, s_w\right) \]
\[ F_2\left(S_{\text{cry}}, S_{\text{seg}}\right) \]
\[ h_1\left(p_c^*, \frac{\partial Q}{\partial p^*}\right) \]
\[ h_2\left(S_{\text{cry}}, S_{\text{seg}}, s_w\right) \]
Elastoplastic model (cont.)

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

Yield surface for ice segregation

Due to ice cohesion

Yield surface in $p^* - q$ space

Complete yield surfaces:

Elastoplastic model (cont.)
(cont.)

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

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

\[
Q_i = s_w^p \left[ p^* - \frac{p_y^* - k_i S}{2} \right]^2 + \left(\frac{q^*}{M}\right)^2
\]
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

Artificial ground freezing, temperature distribution
10 days 180 days

Manuel Aukenthaler, TUD and PLAXIS

Artificial ground freezing, temperature distribution
10 days 180 days
BWP – Caen experiment

Hooman Rostami, NTNU
BWP – Caen experiment – cont.
EVP- Plate loading experiment subjected to seasonal temperature variation (Zhang et al., 2014)

Loading steps during 8 years of simulations

<table>
<thead>
<tr>
<th>Loading Step (Years)</th>
<th>Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3</td>
<td>0.09</td>
</tr>
<tr>
<td>3-4</td>
<td>0.19</td>
</tr>
<tr>
<td>4-8</td>
<td>0.29</td>
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</tbody>
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Ground surface Temperature variation
Cont.

Ground temperature (°C)
-15 +15

Total displacements $u_y$
Maximum value = 0.000 m (Element 1575 at Node 3640)
Minimum value = -0.05945 m (Element 923 at Node 5)

Settlement (m)

Data (Zhang et al., 2016)