“Modelling av leire med fokus på anisotropi og kryp”

“Modeling of soft clay with focus on anisotropy and creep”

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Outline

• Background
• Fundamental aspects of soft clay behavior
  – Understanding soil
  – Getting the parameters
  – Modeling
• Modeling principles
• Model examples
Background
The purpose of this subtask under the GeoFuture project is to develop an effective stress soil models that can simulate the characteristic behavior of soft clays.

A significant portion of the challenges in geotechnical engineering practice in Scandinavia relates to the behavior of such clays and appropriate models are essential for reliable analyses of bearing capacity, settlements of and displacements around foundations and embankments, deep excavations, soil-structure interaction in general as well as slope stability.

Important aspects of clay behavior include time/rate dependency, anisotropy in strength and stiffness and structuration/destructuration.

Hence, appropriate design of structures on natural clays demands proper understanding of the behavior as well as sufficiently good models that may simulate the important behavior of natural clays.
Examples on recent norwegian R&D on this topic (PhD @NTNU.UiO)

Fundamental aspects of soft clay behavior

- Creep
- Anisotropy
  - Strength
  - Stiffness
  - Yield stress
- Structure and destructuration
- Unloading/reloading cycles – small strain
- Degradation during cyclic loading
- ALL ARE LINKED!
Creep

• What is creep?
  – General Definition: “the continuous permanent deformation of a body or substance as a result of stress or heat.”
  – Soil perspective: “time-dependent strain that develop at a rate controlled by the viscous resistance of the soil structure.”
Creep in soils

- Compression of saturated soil consists of two successive phases, namely the *primary* and *secondary* consolidation phases.
Creep

• Fundamental question: does creep always act?
  – Yes!
  – Consequence: “Easy” to include in calculation and “difficult” to isolate from lab (what is real in-situ?)
  – How to proceed then?
Historical resume on creep during “primary consolidation”

- Ladd et al. (1977) summerized the practices and the view on creep during primary consolidation of clays.
- There exist two independent views (hypotheses) on creep during primary consolidation of clays.
  - **Hypothesis A**: Creep acts after primary consolidation (acts during secondary consolidation only)
  - **Hypothesis B**: Creep acts during both primary and secondary consolidation
Two creep Hypotheses

- Implications in strain-time relationship for a given stress increment

**Hypothesis A** => In-situ EOP strain = Lab. EOP strain

**Hypothesis B** => In-situ EOP strain > Lab. EOP strain
Two creep Hypotheses

- Implications in stress-strain relationships

**Hypothesis A** => In-situ EOP $p'_c = \text{Lab. EOP } p'_c$

**Hypothesis B** => In-situ EOP $p'_c < \text{Lab. EOP } p'_c$
Creep behaviour of soil

✓ Hypothesis B

Laboratory tests supporting hypothesis B (after Konovalov & Bezvolev (2005))

In-situ and EOP laboratory tests that support hypothesis B (after Kabbaj et al., 1988)
Laboratory study of creep

- Creep can be studied in all types of soil tests as it manifests itself along with all soil behavior
- Incremental oedometer test – the standard
- Loads applied incrementally with sequence 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 700 kPa and 1200 kPa
- Time between load increments is 24 hr
- Deformation under each load increment is measured

Schematic drawing of the 20 cm² oedometer cell (www.ngi.no)
“1D” Creep – (24h) incremental oedometer test

• Advantages:
  – Gives first estimate of creep/consolidation parameters and the “vertical” pre-consolidation stress directly

• Disadvantages
  – Time consuming compared to CRS tests
  – Only average settlement parameters for large stress increments
  – Ideally back calculation with mathematical model is needed (FEA)
Current Norwegian engineering practice

• Using low OCR (if material has not been subjected to preloading an OCR of 1.0? is often used)

• Ignoring creep

• Adding creep after consolidation? (Hyp. A!)

• Advanced: Janbu’s time resistance concept

• What about the selected pre-consolidation stress? IMPORTANT!!!

• What about sample quality?
Sample quality

Compression curves for Väsbys clay at a depth of 4.0 – 4.3 m (after Leroueil and Kabbaj, 1987)
Janbu’s time resistance concept

• Increment in time divided by the increment in strain (Cause/Effect).
1D equation

\[
\frac{dt}{d\varepsilon_{v}^{vp}}(t) = r_s \cdot (t - \tau) + R_{ref} = r_s \cdot t
\]

\[
\frac{d\varepsilon_{v}^{vp}}{dt} = \frac{1}{r_s \cdot t} \Rightarrow \Delta \varepsilon_{v}^{vp} = \frac{1}{r_s} \ln \frac{t}{\tau}
\]

\[
\frac{dp_{ref}^{eq}}{d\varepsilon_{v}^{vp}} = \frac{p_{ref}^{eq}}{\zeta} \Rightarrow \Delta \varepsilon_{v}^{vp} = \zeta \cdot \ln \left( \frac{p_{ref}^{eq}}{p^{eq}} \right)
\]

\[
\frac{d\varepsilon_{v}^{vp}}{dt} = \frac{1}{R_{ref}} \cdot \left( \frac{p^{eq}}{p_{ref}^{eq}} \right)^{r_s \cdot \zeta} = \frac{\mu^{*}}{\tau} \cdot \left( \frac{p^{eq}}{p_{ref}^{eq}} \right)^{\frac{\lambda^{*} - \kappa^{*}}{\mu^{*}}}
\]

\[p_{ref}^{eq} \text{ is important for creep rate! Initial value is the pre-consolidation stress!}\]
Ignoring creep?

A case of SSC and SS model giving the same final settlement.

Illustration of dependence of OCR on the corresponding reference time ($\tau$).
Anisotropy

• First:
  – Undrained Triaxial Compression versus Undrained Triaxial Extension and Direct Simple Shear (Bjerrum 1973)

• Second:
  – Preconsolidation stress from Oedometer test versus isotropic consolidation test test (Feng 1991)

• Third:
  – “Stress/strain induced anisotropy” – Changes in macroscopic yield surface (Wheeler 2003)
Undrained shear strength

- Used as basis for the NGI-ADP model
Pre-consolidation stress and "cap" yield surface

- Experiments from literature on finding cap surface – yield points in $p'$ – $q$ space
Stress/strain induced anisotropy
Destructuration

![Graph showing void ratio vs. effective stress for different states and samples.](image)

- Undisturbed sample
- In situ state
- Reconstituted at wL
- Predicted ICL
- SCL

Burland (1990)

Christensen (1985)
Unloading/reloading

• -> Cyclic behavior
Modeling principles

• Elasticity
• **Elasto-plasticity**
  – Isotropic hardening
  – Kinematic hardening
  – Nested yield surfaces
• **Elasto-visco-plasticity**
• Total stress based
• **Effective stress based**
Hardening rules

- Isotropic hardening
  - Increase in size
  - Decrease in size

- Kinematic hardening
  - Rotation
  - Position
Creep - Yield surface becomes reference surface

- Option 1 – extending by volume strain (ACM)
- Option 2 – extending by plastic multiplier directly

\[
\frac{d\lambda}{dt} = \dot{\lambda} = \frac{1}{r_s \cdot \tau^*} \cdot \left( \frac{p^{eq}}{p_{ref}^{eq}} \right)_{\tau^*}
\]

Calibrated for oedometer
Anisotropy and creep – The n-SAC model

• A non-associated creep model for structured anisotropic clay

• Non-associated because:
  – prediction of the strain behavior under various stress paths, based on experimental evidence from e.g. Feng (1991)

\[
p_{\text{eq}} = p' + \frac{3}{2} \left\{ \frac{\sigma_d - p' \beta_d}{\left( M^2 - \frac{3}{2} \beta_d^T \beta_d \right) p'} \right\} \left\{ \sigma_d - p' \beta_d \right\}
\]

\[
Q = p' + \frac{3}{2} \left\{ \frac{\sigma_d - p' \alpha_d}{\left( M_f^2 - \frac{3}{2} \alpha_d^T \alpha_d \right) p'} \right\} \left\{ \sigma_d - p' \alpha_d \right\} - p_{\text{eq}} = 0
\]

where \( p' = \) mean stress; \( \sigma_d = \) deviatoric stress vector; \( \beta_d = \) deviatoric rotational vector; \( M = \) Lode angle dependent peak of the reference curve of in \( p'-q \) space

where \( M_f \) is the Lode angle dependent critical state line in \( p'-q \) space; \( \alpha_d \) is the deviatoric rotational vector.
Motivation for time resistance concept

- **DSS**
- **TRIAX**
- **Drammen clay**

\[ \frac{d\epsilon}{dt} = 6.39 \times 10^{-8} \text{ s}^{-1} \]
\[ \frac{d\epsilon}{dt} = 9.72 \times 10^{-5} \text{ s}^{-1} \]
How to use/Parameters for analyses

- Two models - SSC and n-SAC
- Three analysis cases - SSC1, SSC2 and n-SAC

<table>
<thead>
<tr>
<th>Model</th>
<th>v</th>
<th>$K_0^{NC}$</th>
<th>$E_{ref} / p_{ref}$</th>
<th>${E_{oed}^{ref}}<em>i / p</em>{ref}$</th>
<th>$r_{smin}$</th>
<th>$r_{si}$</th>
<th>$\omega$</th>
<th>$\phi_p$</th>
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<td>SSC1</td>
<td>0.15</td>
<td>0.54</td>
<td>200</td>
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<td>-</td>
<td>267</td>
<td>-</td>
<td>-</td>
<td>35°</td>
</tr>
<tr>
<td>SSC2</td>
<td>0.15</td>
<td>0.54</td>
<td>200</td>
<td>6.0</td>
<td>-</td>
<td>233</td>
<td>-</td>
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<tr>
<td>n-SAC</td>
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<td>0.5</td>
<td>200</td>
<td>13.0</td>
<td>200</td>
<td>625</td>
<td>0.3</td>
<td>25°</td>
<td>35°</td>
</tr>
</tbody>
</table>

$k_v = k_h = 5e-5$ m/day; $\gamma' = 10$ kN/m$^3$, $K_0 = 0.54$, OCR = 1.36

$$\kappa = \frac{3(1 - 2v)}{E_{ref}}$$

$$\lambda = \frac{1}{\{E_{oed}^{ref}\}_i}$$

$$\mu^* = \frac{1}{r_s}$$
Oedometer simulations

\[ R = \frac{\Delta \tau}{\Delta \varepsilon} \text{ (days)} \]

Vertical stress, \( \sigma \) [kPa]

\[ E_{oed} = \frac{\Delta \sigma}{\Delta \varepsilon} \text{ [kPa]} \]
Example: settlement problem

- SSC1 - Point A
- SSC2 - Point A
- n-SAC - Point A

Graph showing settlement over time for different scenarios.
Profiles

Horizontal displacements [m]

Vertical displacements [m]

SSC1
SSC2
n-SAC
Issues

- Softening – Regularization needed?
- Tension cracks (piles, walls etc.)
- Small strain stiffness
- Unloading/reloading (cyclic behavior)
Mesh dependency due to softening

Shadings of “structure”
Effect of stiffness

\[ \sigma_{xy'} = \begin{cases} \sigma_{v0}' = 105 \text{ kPa} \\ \frac{d\sigma}{dt} = \frac{1}{3 \times 10^5 \text{ s}} \end{cases} \]

25.7 days. Looks more like perfectly plastic behavior!
Solution? non-local strain

Mesh independent results

Shadings of shear strain

(Grimstad et al. 2010)
Cyclic ADP model

- Coupling of several NGI-ADP models (lwan type model)
- Becomes like nested yield surfaces
Testing in PLAXIS

- Foundation with vertical load
Results at one stress point (1/2)
Results at one stress point (2/2)

\[ \frac{(\sigma'_yy - \sigma'_xx)}{2} \text{ [kPa]} \]

\[ \sigma'_xy \text{ [kPa]} \]

\[ \varepsilon_{yy} [-] \]

\[ \gamma_{xy} [-] \]

\[ \frac{(\sigma'_yy - \sigma'_xx)}{2} \text{ [kPa]} \]
Crack changes damping! (cyclic model)
Conclusions

• Creep/rate and anisotropy are important if we want to fully understand soil behaviors.
• Sample quality is crucial and deserves more attention as it forms the basis for numerical modeling.
• With increased sample quality and testing procedure, the soil models also needs to be improved.
• Models should ideally cover all aspects from static undrained to cyclic/dynamic undrained loading with consolidation and drained situations – Is this possible?
• We have some model tools. However, not mature enough?
• The “huge gap” between state-of-the-art and state-of-the-practice must be closed or at least narrowed down!