Back calculation of embankments with OCR determined from prediction of initial strain rate rather than from OCR determined from disturbed samples in oedometer tests under unknown (different than the in-situ) stress condition, with a simple creep model

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Outline

• Background
• Modelling creep
  – Time resistance concept
  – Soft Soil Creep Model (the “simple” model) in PLAXIS
  – Alternative extensions from 1D to 3D
• Implications of parameter selection
  – Creep ratio
  – Over Consolidation Ratio
• The MIT-MDPW test embankment
  – The case
  – Previous back calculations
  – Back calculation with OCR based on initial creep rate estimate
• Conclusions and recommendations
Background

- Expected new stress state to cross $p_c'$ (24h)
- Expected new stress state below $p_c'$ (24h)

NC clay
(OCR$_{t=24h} = 1.4 - 1.8$)
Time resistance concept

- Described by in e.g. Janbu (1969)
- Used for 1D strain in KRYKON, Svanø & Emdal (1986)

\[ R = \frac{\tilde{t}}{\tilde{t}r} \]

"Pure creep"

\[
\begin{align*}
    r_s &= \frac{d}{dt} \left( \frac{\partial t}{\partial \varepsilon} \right) = \frac{dR}{dt} = \frac{1}{\mu^*} \\
    \frac{d\varepsilon}{dt} &= \frac{\mu^*}{t} \\
    \Delta \varepsilon (\Delta t = t - \tau) &= \mu^* \cdot \ln \left( \frac{t}{\tau} \right)
\end{align*}
\]
Extending model to 3D

• Option 1: Volumetric strain always develops according to the equation below. The plastic multiplier is calculated by dividing with the differentiate of the plastic potential function with respect to the mean stress. (e.g. SSC, PLAXIS)

\[
\varepsilon_v^p = \frac{\mu^*}{\tau} \cdot \left( \frac{p_{eq}^\text{eq}}{p_0^\text{eq}} \right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} = \frac{\mu^*}{\tau} \cdot OCR^\frac{\mu^*}{\lambda^* - \kappa^*}
\]

• Option 2: The equation above is valid for 1D strain condition, i.e. it is given by the plastic multiplier and the plastic potential for this condition. (e.g. n-SAC, Grimstad et al. 2010)
Example: SSC model - The effect of the $\mu^*/(\lambda^*-\kappa^*)$ ratio on OCR (creep rate)

$$\dot{\varepsilon}_v = \mu^* \cdot \left( \frac{p_{eq}^{\text{eq}}}{p_0^{\text{eq}}} \right)^{\frac{\lambda^*-\kappa^*}{\mu^*}} = \frac{\mu^*}{\tau} \cdot \text{OCR}^{\frac{\mu^*}{\lambda^*-\kappa^*}}$$

Specifying lower OCR
The effect of the $\mu^*/(\lambda^*-\kappa^*)$ ratio on OCR (creep rate)

$$\frac{\mu^*}{\lambda^*-\kappa^*} = \frac{1}{r_s \cdot \zeta}$$

$OCR_t = \left(\frac{t}{\tau}\right)^{\frac{\mu^*}{\lambda^*-\kappa^*}}$

$t_{age} = \tau \cdot OCR_t \cdot \frac{\mu^*}{\lambda^*-\kappa^*}$

<table>
<thead>
<tr>
<th>$r_s \cdot \zeta$</th>
<th>$OCR_t$</th>
<th>$\tau = 1$ day</th>
<th>$t = 10^4$ years</th>
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<tbody>
<tr>
<td>0.010</td>
<td>1.163</td>
<td>6.79E+08 years</td>
<td></td>
</tr>
<tr>
<td>0.015</td>
<td>1.254</td>
<td>1.08E+05 years</td>
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<td>0.020</td>
<td>1.353</td>
<td>1.36E+03 years</td>
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<td>0.025</td>
<td>1.459</td>
<td>98.9 years</td>
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<td>0.030</td>
<td>1.574</td>
<td>17.2 years</td>
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<tr>
<td>0.035</td>
<td>1.697</td>
<td>4.93 years</td>
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<td>0.040</td>
<td>1.830</td>
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<td>0.050</td>
<td>2.129</td>
<td>0.520 years</td>
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<tr>
<td>0.070</td>
<td>2.880</td>
<td>0.116 years</td>
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</table>

$\lambda^*$ decreasing with stress

$\mu^*$ decreasing with time

"Recommended" range (PLAXIS manual)

~0.04 - 0.07
The oedometer test…

- Can we rely on OCR from IL oedometer tests?
  1) Sample disturbance, temperature? (we all know this)
  2) Stress condition?
     - Start at some unknown isotropic stress condition and consolidates to 12.5 kPa of vertical stress
     - Loads further along a line different from $K_0^{NC}$ line (i.e. stress path hits the reference pre-consolidation at different place than it would in-situ!)
       → Do we need to simulate the oedometer test rather than interpret OCR from it?
       → Should we measure horizontal stress in the oedometer?
  3) Consolidation (is the effective stress constant for most of the 24h?, e.g. clays with low permeability)
  4) Extrapolation… (should model OCR and reality OCR be the same?)
Simulated oedometer with SSC
What about $K_0$?

- Is the in-situ $K_0$ affected by creep (NC clay)?
  - Model says: very limited influence, i.e. $K_0 \approx K_0^{NC}$

- Has the material been unloaded (OC clay)?
  - Model says: yes, but creep will try to make $K_0 \approx K_0^{NC}$ if the model is not changing its plastic potential, since the volumetric strain should be equal to the vertical strain

- Should we then set $K_0 \approx K_0^{NC}$ for models like SSC?
OCR and $K_0$

- The $K_0$ value does not change significantly in a 1D creep case due to the increase in OCR. Since 1D creep requires $d\varepsilon_1^{vp} = d\varepsilon_v^{vp}$, then the stress state is fixed to one point at the potential surface.
- In PLAXIS if one specify a OCR (due to creep alone), the suggested initial horizontal stress generated (suggested $K_0$) is based on the assumption of unloading. Remember to change this back to a value close to the real $K_0^{NC}$.
Stress increment in the field

- No need to fit the whole lab curve…
  - What is the experienced stress change?
  - For most of the soil it is little change (around $p'_c$ or less)

\[
\frac{H}{H_0} = \ln(\sigma') - \frac{\sigma'_0}{p'_{c_{24h}}}
\]

Accept wrong OCR – Fit at large stress change, well above $p'_c$

Accept that initial creep rate is too big

In most cases: Fit for the actual stress change in the region around $p'_c$, higher $\lambda^*$ gives lower OCR for same $\mu^*$
The MIT–MDPW embankment

- Latest paper looking at back calculating this is from 2012 (Fatahi et al.)
Vertical Stresses; $\sigma'_{v0}$, $\sigma'_p$ and $\sigma_v$ (kPa)

Profile 2: $\sigma'_p$

Profile 1: $\sigma'_p$

POP = 120

Elevation [m]

Sand

Table:

<table>
<thead>
<tr>
<th>Program</th>
<th>Oed.(1 day)</th>
<th>Oed.(EOP)</th>
<th>CRS</th>
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<tr>
<td>1966</td>
<td>△</td>
<td>△</td>
<td></td>
</tr>
<tr>
<td>1977</td>
<td>●</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>1980</td>
<td>●</td>
<td>○</td>
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</table>

BBC 1

BBC 2
The trial embankment
Alternative models
Oedometer simulations

Vertical effective stress, $\sigma'$ [kPa]

Vertical strain, $\varepsilon$ [%]

Oedometer simulation
EL -10m

Oedometer simulation
EL -28 m
Results
Conclusions

- Evaluate the parameters over relevant stress increments
- Do not blindly take OCR from oedometer tests
  - Stress path
  - Sample disturbance
- The “simple” SSC model performs OK when we are after vertical deformation profile and pore pressure. As long as we take some care for the OCR we use in modelling.
  - NC clay does not usually have OCR of 1.1…
  - OCR in SSC is a material parameter that defines initial state of the soil (i.e. the state variable \( p_0^{eq} \)), it is not more holy than the other parameters that we use to fit our model to “reality”
  \[ \lambda^*, \kappa^*, \mu^*, \nu, \varphi, c, K_0^{NC} \]
Any Q?