Accounting for long term effects for the structural design of deep tunnels in claystones

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4. Comparison in terms of structural forces
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Introduction

- Complex behaviour of claystones or shales: multiscale material, thermo-hydro-mechanical couplings, brittle/ductile, anisotropy, short and long term behaviour ...
- Large bibliography with complex models: hard to choice and certainly to use
Introduction

- Complex behaviour of claystones or shales: multiscale material, thermo-hydro-mechanical couplings, brittle/ductile, anisotropy, short and long term behaviour ...
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In situ measurements
Different models tested

Seyedi et al. (2017)
Introduction

From an engineer point of view, where structures have to be designed:
- “simple” models are preferred but able to catch evolution of forces in structure
- especially when long term effects play an important part in final loadings = extrapolation

Normal force, bending moment?
Introduction

Example of “simple” model in the context of the Meuse/Haute-Marne laboratory - Saitta et al. (2017):
- Mohr-Coulomb’s criterion and Norton’s law
- 2 domains define from in-situ observations (intact and disturbed zones) -> anisotropy forced

- In consistency with principal results in terms of displacement of the soil in a quasi-isotropic stress state and with isotropic laws

Saitta et al. (2017)
Accounting for long term effects

Norton’s law, initially developed for steels at high temperatures (1929)

- visco-plastic strain rate:

\[
\dot{\varepsilon}_{ij}^{vp} = \frac{3}{2} (\dot{\varepsilon}_{vp}) \frac{s_{ij}}{q} \text{ where } \dot{\varepsilon}_{vp} = \gamma < q - q_0 >^n
\]

\(\dot{\varepsilon}_{vp}\) depends only of deviatoric stress \(q\)
independent of mean stress \(p\)
Accounting for long term effects

Modified Norton’s law
- \( \dot{\varepsilon}_{vp} \) depends on the strength mobilization \((p,q\text{ and } \text{Lode angle } \theta)\):

\[
\dot{\varepsilon}_{ij}^{vp} = \frac{3}{2} (\dot{\varepsilon}_{vp}) \frac{s_{ij}}{q} \text{ where } \dot{\varepsilon}_{vp} = A \times f(X)
\]

\[
f(X) = \frac{1}{1 + \left(\frac{a}{X}\right)^a} \quad f(X) \in [0,1]
\]

\[
X = \frac{d_1}{d_2} \quad X \in [0, +\infty]
\]
Accounting for long term effects

Modified Norton’s law
- $\dot{\varepsilon}_{vp}$ depends on the strength mobilization ($p, q$ and Lode angle $\theta$):

$$
\dot{\varepsilon}_{ij}^{vp} = \frac{3}{2} \left( \dot{\varepsilon}_{vp} \right) \frac{s_{ij}}{q}
$$

where $\varepsilon_{vp} = A \times f(X)$

with

$$
f(X) = \frac{1}{1 + \left( \frac{a}{X} \right)^{\alpha}} \quad f(X) \in [0, 1]
$$

$$
X = d_1 \frac{d_1}{d_2}
$$

$X \in [0, +\infty]$

$$
d_1(q) = <q - q_0>
$$

$$
d_2(p, q, \theta) = \frac{|M(\theta) \times p + q - N(\theta)|}{\sqrt{M(\theta)^2 + 1}}
$$

$$
\cos 3\theta = \frac{3\sqrt{3}}{2} \times \frac{J_3}{J_2^{3/2}}
$$
Accounting for long term effects

Modified Norton’s law

- \( q = q_0 : X = \frac{d_1}{d_2} = 0 \rightarrow f(X) = 0 \rightarrow \dot{\varepsilon}_{vp} = 0 \)
- \( q = q_{max} : X = \frac{d_1}{d_2} = \infty \rightarrow f(X) = 1 \rightarrow \dot{\varepsilon}_{vp} = A \)

\[
f(X) = \frac{1}{1 + (\frac{1}{X})^\alpha}
\]

\[
f(X) = \frac{1}{1 + (\frac{1}{X})^a}
\]

\[\theta = \pi/3, \quad p = 13.8 \text{ MPa}, \quad q_0 = 0, \quad c = 6 \text{ MPa} \quad \text{and} \quad \phi = 20\]
Calibration with measurements in terms of displacements

Application to the Meuse/Haute-Marne laboratory

Parameters:

\[ \varepsilon_{vp} = A \times \langle q - d_r \rangle^n \]

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<td>( n )</td>
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\[ \varepsilon_{vp}(t) = A \times \left( \frac{1}{1 + \left( \frac{a}{(d_1/d_2)} \right)^\alpha} \right) \]

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<td>( \alpha )</td>
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Comparison in terms of structural forces

Forces in rigid structure

- Normal force: quite similar
- Bending moment: quite different and more logical with in-situ observations (to be confirm)
- Bending moment more sensitive with variations of normal and shear stresses.
Conclusion

- Models (simple and complex) have to be compared to measurements in terms of displacements and forces (only displacement not sufficient for structure design)
- Modified Norton’s law proposed here:
  - is still a simple law based on a simple approach
  - seems more reliable
- Others comparisons have to be done to confirm these results

- Test new idea is quite simple with Flac thanks to fish functions!

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