CIGEO radioactive waste repository project

An observation-based model of claystone behavior for thermomechanical FLAC3D simulations

M. Camusso\textsuperscript{1}, A. Saitta\textsuperscript{2}, O. Ozanam\textsuperscript{3} & M. Vu\textsuperscript{3}

\textsuperscript{1} ITASCA Consultants S.A.S., France
\textsuperscript{2} EGIS Tunnel, France
\textsuperscript{3} ANDRA, France
Outline

• Study context

• Modelling considerations:
  1. Claystone behavior
  2. Tunnel components

• Setting of the thermo-mechanical coupling approach

• Results of the sensibility study on thermal and creep effects

• Conclusions
Context of the study
The CIGEO project

- Geological layer: Callovo-Oxfordian claystone, homogeneous across a wide surface area and very thick (>=140 meters)
- Depth: ~500 meters

- Waste type: HLW and ILW-LL
- ~100 years of operation
The CIGEO project

ILW-LL zone

Drift section

Repository drift

σ

σ

σ

σ

σ
Study purpose

• Design of segmental lining to withstand with creep and thermal loading over the repository reversal period (~100 years)

• Study conditions:
  ❖ Tunnel oriented along $\sigma_H$
  ❖ Excavation diameter ~10m
  ❖ Support: concrete lining / compressible material
  ❖ 2D modelling conditions

![Diagram showing stress components $\sigma_H = 17.1$ MPa, $\sigma_h = 13.2$ MPa, $\sigma_V = 13.5$ MPa over time.](image)

- COG110A thermal loading

![Graph showing thermal power (W/canister) over time (years).](image)
Modelling considerations
The claystone behavior

- Characteristics to be accounted for: the EDZ region and the claystone creep behavior

- Extensive data available from in situ tests and monitoring performed at the near-by Meuse/Haute-Marne URL:
  - Structure and stress anisotropy
  - Rock properties from laboratory tests (elastic moduli, UCS, TX, …)
  - EDZ obtained from borehole data
  - Tunnel convergences

Influenced by the orientation of the tunnel relative to the major and minor horizontal stresses

Armand et al. (2014)
Excavation Damaged Zone

Geometry mainly depends on the tunnel orientation… … but the structure is similar independently on the excavation size

Armand et al. (2014)
Influence of EDZ on tunnel convergences

\[ \frac{\sigma}{\sigma_H} \]

Armand et al. (2013)
Modelling of claystone behavior

- Modelling hypotheses based on a previous work (Saitta et al., 2017) in which the Mohr-Coulomb/Power Law (POWER-MOHR) constitutive model has been calibrated to reproduce displacement developed around tunnels of the near-by URL of Bure

- Residual strength parameters are considered for volumetric elements included in the EDZ region

Initial deviatoric stress considered as creep threshold

<table>
<thead>
<tr>
<th>Property</th>
<th>Intact zone</th>
<th>EDZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus</td>
<td>E (GPa)</td>
<td>4</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>ν (-)</td>
<td>0.3</td>
</tr>
<tr>
<td>Cohesion</td>
<td>c (MPa)</td>
<td>6.4</td>
</tr>
<tr>
<td>Friction angle</td>
<td>φ (°)</td>
<td>20</td>
</tr>
<tr>
<td>Dilatancy angle</td>
<td>ψ (°)</td>
<td>0</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>σ_t (MPa)</td>
<td>0.9</td>
</tr>
<tr>
<td>Norton coefficient</td>
<td>A (-)</td>
<td>2.5 (10^{-6})</td>
</tr>
<tr>
<td>Norton coefficient</td>
<td>n (-)</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Tunnel components

Segmental concrete lining including a compressible layer

ANDRA / CMC patent

Elastic model
Concrete part (50cm) $f_{ck}=60$MPa

Double Yield model (only volumetric criterion)
Compressible layer (20cm) Integrated on concrete outer surface
Assembly of crushable clay/cement mixture beads

Axial stress (MPa)
Elastic phase
Plastic plateau
Crushed beads Stiffer behavior
Calibration of compressible material properties (DY)

Calibration of the hardening curve $p$-$e^p$ to reproduce oedometer results

\[ p = \frac{\sigma^{ax}}{3} \]

No expansion in direction perpendicular to loading direction

\[ e^{pv} = 3e^{p,ax} = 3(\varepsilon^{ax} - \varepsilon^{e,ax}) = 3 \left( \varepsilon - \frac{\sigma^{ax}}{E} \right) \]

\[ \Delta e^{pv} = \Delta e_1^{pv} + \Delta e_2^{pv} + \Delta e_3^{pv} = 3 \left( \frac{1}{3} \lambda^p \right) \]
Thermo-mechanical coupling approach
Coupling approach

- Different needs associated with thermal and mechanical process simulation

**Model size**

Thermal simulation requires for large model to limit the influence of boundary conditions on diffusion processes

In mechanical simulations, the distance of the boundaries can be reduced to 5D

**Solution:** use of two different meshes for the thermal and mechanical calculations with different **extensions** and **discretization**

- Practically...a thermal calculation is first performed and obtained temperature maps are then injected into the mechanical model as the creep simulation proceeds

- Possible because of the unidirectional coupling (low kinetic energy associated with mechanical deformations)

**Discretization**

Mechanical simulation requires for finer elements for a reliable estimation of lining stresses

Thermal simulations are less sensitive to the element sizes. Also, smaller sizes imply smaller thermal timesteps
Model meshes

- 420m
- 438m
- 469m
- 484m
- 520m
- 544m
- 591m
- 620m

USC
UT
UA2
UA3
UA1

- 438m
- 484m
- 520m
- 570m
- 591m
- 620m

Mechanical model

3 zones
6 zones

Tunnel spacing
50m

Thermal model

25m
50m

UT
UA2
UA3
UA1
**Thermal calculation**

---

**Model initialization**
Initialization of gridpoint temperature and zone thermal properties depending on the depth

---

**Application of the thermal flux**
A time dependent thermal flux condition (W/m²) is applied on internal faces of the disposal chamber, according to the thermal power curve of the waste. Time from waste conditioning to disposal is also considered.

---

**Simulation over 100 years**
... and dumping of temperature maps over the time (higher dump frequency at the beginning when change in temperature are higher)
**Mechanical calculation**

- **Model initialization**
  - Initialization of gridpoint temperature and zone thermal properties depending on the depth

- **Application of the thermal flux**
  - A time dependent thermal flux condition (W/m²) is applied on internal faces of the disposal chamber, according to the thermal power curve of the waste. Time from waste conditioning to disposal is also considered

- **Simulation over 100 years**
  - ... and dumping of temperature maps over the time (higher dump frequency at the beginning when change in temperature are higher)

- **Model initialization**
  - Initialization of zone mechanical properties and stress field

- **Simulation of the excavation**
  - Relaxation of tunnel boundary forces until 90% (Saitta et al., 2017)
  - Lining installation
  - Complete relaxation of tunnel boundaries

- **Simulation over 100 year**
  - Creep over 4 years, i.e. the time before the introduction of waste into the drift
  - Thermo-mechanical simulation over 100 year with a continuous update of the gridpoint temperature according to thermal simulation results
Thermal model results

1 year

10 years

50 years

100 years
# Thermal-mechanical modelling

- **Main purpose:** Design of compressible lining to withstand with thermal and mechanical loading with time
- **Analysis of thermal and creep contributions on the long-term behavior**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Active processes</th>
<th>$\dot{\varepsilon} = A\sigma^n$</th>
<th>$M$</th>
<th>$C$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM – A=0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>M</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TM - A=A23</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>TM - A=f(T) - $A_{80}/A_{23}$=3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

« $A$ » calibrated from convergence measures of Bure URL tunnels, where $T=23^\circ$.

$A(T) = A_0 \exp \left( -\frac{B}{RT} \right)$
Thermal-mechanical modelling – Tunnel convergence

TM – A=0 (only thermal expansion)
Thermal-mechanical modelling – Tunnel convergence

TM – A=0 (only thermal expansion)

M (no thermal expansion)
Thermal-mechanical modelling – Tunnel convergence

- **TM – A=0** (only thermal expansion)
- **M** (no thermal expansion)
- **TM – A=A23**

**M + thermal expansion**
**Thermal-mechanical modelling – Tunnel convergence**

CH > CV

- Anisotropy in tunnel convergences is mainly due to the excavation process and the generation of the EDZ.

- Increase of displacement over the long term is mainly isotropic (thermal and creep properties of the EDZ are equal to those of the intact rock.)
Radial strains and stresses, 100 years after waste disposal

Isotropic distribution of stresses and strain along the tunnel boundary
Thermal-mechanical modelling – Lining stress resultants

\( f_{ck} = 60 \text{MPa} \)
Conclusions
Conclusions

• FLAC3D thermo-mechanical analyses have been performed for the design of CIGEO disposal tunnels with exothermic waste canisters

• Following previous work by Saitta et al, 2017 and based on extensive in situ observations, a simplified modelling of the rock mass around the drift has been accounted for, including:
  
  ❖ A simple constitutive law (POWER-MOHR), based on a Mohr-Coulomb criterion
  
  ❖ An indirect modelling of the EDZ through a zone of weaker properties, whose size and orientation reproduce in situ measurements of the fractured mass

• Analysis of the effect of creep and thermal processes on drift behavior has shown that creep is the major phenomenon.

• When both thermal and creep processes are active, convergences and resultants become the highest and their values mainly depend on the evolution of the viscosity parameter with the temperature.
Thank you for your attention