Thermal effect characterisation in the Excavation Damaged Zone around tunnels for the nuclear waste disposal in argillaceous rocks

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• Thermo-mechanical behaviour of clays

• Development of a thermo-mechanical model

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34 million years ago…

Tertiary Boom Clay Formation (Rupelian)
Introduction

- **Geological description**: marine deposit composed of alternating clay-rich and silt-rich beds
  Illite, Smectite, Kaolinite, interstratified mixed layer...

- **Geotechnical description**: Overconsolidated plastic clay
  Very low permeability ($K=±10^{-12}$ m/s)

- **Applications**: - Brick industries
  - One of the two potential host rocks for nuclear waste disposal
Introduction

- Radioactive wastes, what are the solutions?

- Disposal in galleries located in impervious geological layers

- Engineering Barrier System (EBS) for high level and long-lived nuclear wastes (Belgian concept)
Belgian concept, nuclear waste disposal in practice:

1. Cooling period of ± 60 years
2. Excavation and lining
3. Stand-by phase (± 5 years)
4. Deposit of the supercontainer
5. Backfill and sealing of the gallery
Introduction

- Excavation of gallery:
  - Excavation Damaged Zone (EDZ)

- Deposit of the nuclear waste:
  - Dissipation of heat from the waste (≥ 80°C)

(Blümling et al., 2007)
Introduction

- In this context: potential growth of EDZ with temperature?

  - study of the thermo-hydro-mechanical behaviour of clay

  - Implementation of thermo-mechanical law in a finite element code (*LAGAMINE*)

  - Applications and thermal effects on the EDZ (“plastic zone”)

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*EDH EURODICE GHZ*
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Thermo-mechanical behaviour of clays

- Thermal effects on different media

**Metal**

- Thermal expansion
- Thermal contraction

**Clays**

- Thermal expansion
- Thermal contraction

Metallic beam
Thermo-mechanical behaviour of clays

- Thermal effects on different media

**Metal**

- Thermal dilation and contraction
- Metallic beam

**Clays**

- Irreversible thermal contraction
Thermo-mechanical behaviour of clays

- Heating/cooling cycle at different constant pressures in drained conditions in OC and NC states
  - Volumetric plastic thermal strain (contraction)

Volumetric strain during heating/cooling cycle (Sultan et al., 2002)
Thermo-mechanical behaviour of clays

- Decrease of the preconsolidation pressure with an increase in temperature

\[ \text{Log}(p') \text{ [MPa]} \]

\[ p'_c(T_0) > p'_c(T_1) \]

(Laloui et Cekerevac, 2003)
Thermo-mechanical behaviour of clays

- Shear tests for different temperatures at 23°C (1) and 98°C (2) on Pontida silty clay (Hueckel and Baldi, 1990)

- Modification of the shear strength (depends on the tested soils...)

![Graphs showing stress-strain relationship for different OCR values and temperatures.](image-url)
Thermo-mechanical behaviour of clays

- Undrained behaviour: excess pore pressure generation
  - Difference in dilation coefficient between the solid phase and the liquid phase

Undrained heating experiment on a saturated illite (Campanella and Mitchell, 1968)
Thermo-mechanical behaviour of clays

- Undrained behaviour
  - Excess pore pressure generation: failure of the specimen

Undrained heating test on Boom Clay (Hueckel et al., 2009)
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Thermo-mechanical model

- Thermo-mechanical constitutive law developed by CERMES (Sultan, 1997; Cui et al., 2000)
  - Extension of Hueckel and Borsetto (1990)
  - Modified Cam-Clay model with two thermo-plastic mechanisms (TY, LY)
  - Similarity with Basic Barcelona Model (LC≈LY; SI≈TY)
Thermo-mechanical model

Thermo-plastic mechanisms:

- TY: Thermal Yield limit, volumetric thermo-plastic strain
  \[ d\varepsilon_v^{T,p} = \alpha_p \left[ \exp(\alpha_p \Delta T) - a \right] dT \]

- LY: Loading Yield limit, preconsolidation pressure reduction
  \[ p'_c(T) = p'_c(T_0) \exp(-\alpha_0 \Delta T) \]
Thermo-mechanical model

- **Developed model**: extension of a cap-model to thermo-plasticity
  - Multi-mechanisms plasticity
    - Modified Cam-Clay model
    - Friction angle criterion (Van Eekelen, Drucker-Prager)
    - Tensile strength criterion
    - Thermo-plasticity (TY, LY)

![Diagram of Thermo-mechanical model](image)
Thermo-mechanical model

- Thermo-mechanical constitutive law developed in LAGAMINE
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Model validation

- Validation of the developed thermo-mechanical constitutive law on drained heating test on Boom Clay at different OCR (Baldi et al., 1991)

**Experimental results**: volumetric thermal strain with temperature
Model validation

- Heating test for an overconsolidated clay ($OCR = 6$)
  - T: $20^\circ C \rightarrow 95^\circ C \rightarrow 20^\circ C$
  - $p' = 1$ MPa; $p'_c = 6$ MPa

![Graphs showing temperature, mean effective stress, and volumetric strain.](image-url)
Model validation

- Heating test for an overconsolidated clay ($OCR = 2$)
  - T: $20^\circ C \rightarrow 95^\circ C \rightarrow 20^\circ C$
  - $p' = 3$ MPa; $p'_c = 6$ MPa
Model validation

- Heating test for a normally consolidated clay ($\text{OCR} = 1$)
  - $T$: 20°C $\rightarrow$ 95°C $\rightarrow$ 20°C
  - $p' = 6$ MPa; $p'_c = 6$ MPa
Model validation

- Summary comparisons with experimental results from Baldi et al. (1991)
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Application: PRACLAY heater test

- Large scale heater test in Boom Clay in Mol
- Main goal of the experiment:
  - Demonstrate the feasibility of the nuclear waste disposal in clay formation
  - Heating test (10 years) in the most penalising conditions (undrained boundary conditions)
Application: PRACLAY heater test

- Modelling work: reproduce the PRACLAY experiment in blind predictions
- Different phases of the simulation: Excavation (1 day) Stand-by phase (3.5 years) Heating (±10 years)

- 2D plane strain modelling using the developed thermo-mechanical law
Application: PRACLAY heater test

- Results in terms of temperature and pore water pressure

Radial profile of the temperature
Application: PRACLAY heater test

- Results in terms of temperature and pore water pressure

Radial profile of pore water pressure
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone
- Deviatoric and volumetric plastic strain during the simulation

![Graphs showing deviatoric and volumetric plastic strain](image)

Deviatoric plastic strain

Volumetric plastic strain
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path at the gallery wall during excavation, stand-by
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path at the gallery wall during excavation, stand-by and the heating
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path at the gallery wall in the $(p', T)$ plane

- $TY$: Initial curve
- $TY$: Final curve

Excavation, stand-by

Temperature, $T$ [°C]

Mean effective stress, $p'$ [MPa]
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path during excavation, stand-by and the heating for point P35E
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path in the \((p', T)\) plane for point P35E

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\(TY: \text{Initial curve}\)

\(TY: \text{Final curve}\)

Stress path in the \((p', T)\) plane for point P35E
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path during excavation, stand-by and the heating for point P38E
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone

Stress path in the \((p', T)\) plane for point P38E
Application: PRACLAY heater test

- Mechanical analysis of the plastic zone
- Deviatoric and volumetric plastic strain during the simulation

![Graphs showing deviatoric and volumetric plastic strain over radial distance from the axis of the PRACLAY gallery.](image-url)
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Conclusions

- Thermo-mechanical behaviour of Boom Clay (one of the potential host rocks for nuclear waste disposal in Belgium)

- Development of a thermo-mechanical constitutive law in order to analyse the evolution of the plastic zone with temperature

- Validation on experimental works shows good agreement

- Applications to the large scale heater test PRACLAY
  
  Main observations: - No extension of the deviatoric plastic zone but increase of the strains near the wall
  - Extension of a thermal plastic zone (volumetric plastic strain) but low values in comparisons with the deviatoric strains
Thank you for your attention!