Constitutive modelling of the thermo-mechanical behaviour of soils

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Constitutive modelling of the behaviour of soils

The constitutive analysis in environmental geo-mechanics is based on the effects of the environmental load (temperature, suction, ...) on:

- The (induced) **STRAINS**
- The **DEFORMABILITY** (change)
- The **STRENGTH** (change)

**MECHANICAL PROPERTIES**
Contents

1. Introduction
2. Principal experimental observations
3. Thermo-mechanical framework
4. Constitutive modelling – ACMEG-T
5. Numerical simulations – ATLAS experiment
6. Conclusions
Idealised arrangement of clay particles on the basis of a high-resolution transmission electron microscope computer image (after Veblen et al. 1990).

Sample of soil tested in a triaxial cell.

**Micro-scale**  **Macro-scale (continuum)**

The thermo-mechanical phenomena observed at the macro-scale are a consequence of the micro-structural changes.

The understanding of micro-structural behaviour is required.
Unified Soil Classification System

- Soils that have more than 50% by weight passing the N°200 sieve (grain size of 0.06 mm)
  - Sand
  - Silt
  - Sand/clay mix
  - Clay

Granular materials

- Low plasticity
- High plasticity

Fine grained materials

Cohesive soils

Adsorbed water (solid/fluid interface) plays a major role
Micro-structural forces

- Surface electrical charges:
  - Proportional to the surface areas of the grains
  (diminish with the square of the particule diameter)

  Dominant for cohesive soils

- Self weight of the grains
  - Proportional to the volumes of the grains
  (diminish with the cube of the particule diameter)

  Dominant in granular soils

Temperature influence is mainly on surface charges
Water in clay

Schematic illustration of the two main types of water in saturated soils: i) free water, mainly in the inter-aggregate space and ii) adsorbed water located in the inter-particle and inter-lamellar spaces.

From soil constitutive point of view:

- **Adsorbed water** is considered as a part of the solid constituent
- **Free water** is taken into account only through the THM coupling
Diffuse double layer theory

Clay particle: Surface negative charge ↔ Water: Anions + Cations

Effect of the electrical potential on water
Closer to the particle is the water, higher is his attraction to the particle and lower is his mobility (adsorbed water)

Effect of the electrical potential on the particles interaction
Closer are the particles, greater is the repulsive forces acting between them (overlapping of the double layer)

Temperature effects - Dilation of clay minerals
• Modification of the equilibrium between attractive and repulsive forces
• Failure of some interparticle ties
• Facilitation of particles rearrangement
2. Principal experimental observations

1. Introduction
2. Principal experimental observations
3. Thermo-mechanical framework
4. Constitutive modelling
5. Numerical simulations
6. Conclusions
Hypothesis

- Saturated fine grained soil
- Infinitesimal strains
- Temperature range between 5°C and 90°C (no phase change)
- Results in which changes of state cannot be achieved by homogeneous deformations are excluded
- Cambridge parameters in triaxial conditions

\[
p = \frac{(2\sigma_3 + \sigma_1)}{3} \quad q = \sigma_1 - \sigma_3
\]
Thermo-mechanical loading paths

**Plane 1:**
Thermal paths at constant mechanical stresses

**Plane 2:**
Mechanical paths at different constant temperatures
Thermo-mechanical behaviour

1st cycle: 0-A-B
2nd cycle: B-C-B
3rd cycle: B-C-B

1st cycle: 0-1-2
2nd cycle: 2-3-4
3rd cycle: 4-5-6

Thermal cycle on Kaolin clay under constant isotropic compression

(after Cekerevac & Laloui, 2005)
Thermally induced effects

Influence of overconsolidation ratio on the thermal strain

Temperature increase on Kaolin clay under constant isotropic compression
(Cekerevac & Laloui, 2004)
Mechanical behaviour

Isotropic path

✓ Compressibility independent from temperature
✓ Heating applied prior to loading produces a densification of the sample at constant isotropic pressure.

After Campanella & Mitchell (1968)
Dependency of $p'_c$ from temperature

![Graph showing dependency of $p'_c$ on temperature](image)

- **Natural clay; Tidfors & Sälfrds, 1989**
- **Sulphide silty clay; Eriksson, 1989**
- **Natural Swedish clay, Moritz, 1995**
- **Natural Swedish clay, Moritz, 1995**
- **Natural Canadian c, Boudali et al., 1994**

Thermo-mechanical behaviour
Dependency law for thermal evolution of $p'_c$

The preconsolidation pressure decreases non-linearly with increased temperature:

$$p'_c = p'_{c0} \left\{1 - \gamma_T \log \left[\frac{T}{T_0}\right]\right\}$$

\begin{align*}
p'_{c0} & \quad \text{preconsolidation pressure at reference temperature (}T_0) \\
T_0 & \quad \text{minimal testing temperature}
\end{align*}

(Laloui & Cekerevac, 2003)
Thermally induced effects on stress-strain behaviour

Kaolin clay (Cekerevac & Laloui, 2004)
Deviatoric path: critical state

Friction angle at critical state

Temperature has a very slight influence on the friction angle at critical state
Deviatoric path: Yield surface determination

The pseudo-elastic limit shrinks with increase in temperature.

Isotropic thermal effect

Kaolin clay (Laloui et al., 2003)
Thermo-mechanical yield limits

Deviatoric plane at \( T = T_0 \)

Deviatoric plane at \( T = T_1 > T_0 \)

Isotropic plane
Thermo-hydro-mechanical coupling
Undrained paths

- Heating results in a **significant pore pressure increase**
- The pore pressure growth can induce **failure** in the sample
4. Constitutive modelling

1. Introduction
2. Principal experimental observations
3. Thermo-mechanical framework
4. Constitutive modelling
5. Numerical simulations
6. Conclusions
Summary of thermo-mechanical features of soils to be incorporated in the constitutive modelling

- **Thermal behaviour**
  
  Reversible thermoelasticity
  Irreversible thermoplasticity with a thermal hardening

- **Mechanical behaviour, isotropic path**
  
  Compressibility independent of T
  Preconsolidation pressure varies with T

- **Mechanical behaviour, deviatoric path**
  
  Peak strength varies with T (NC soil)
  Small change of the volumetric strains with T
  Elastic rigidity varies with T
  Friction angle variation with T
Thermo-ElastoPlastic Framework

**Thermo-Elastic Component**

\[ d\varepsilon_{ij}^e = D_{ijkl} \, d\sigma_{ij}' + \beta_{ij} \, dT \]

\[ d\sigma_{ij}' = D_{ijkl}^{-1} \left( d\varepsilon_{kl}' - \beta_{ij} \, dT \right) \]

\[ d\sigma_{ij}' = \left( K - \frac{2}{3} G \right) d\varepsilon_v \, \delta_{ij} \]

\[ + 2G \, d\varepsilon_{ij} - \frac{\beta_s'}{3} K \, dT \, \delta_{ij} \]

\( d\varepsilon_{ij}^e \) is the strain rate component that doesn’t modify the hardening state of the material.

**Thermo-Plastic Component**

\[ d\varepsilon_{ij}^p = d\varepsilon_{ij} - d\varepsilon_{ij}^e \]

\( d\varepsilon_{ij}^p \) is the thermo-plastic strain rate which can be expressed as the part of the total strain rate which is not recoverable.
Thermo-Plastic Component

“ACMEG – T Model”

Thermo-plastic strain rate

Isotropic mechanism in the $p'$- $T$ plane

Deviatoric mechanism in the $p'$- $q$ plane

Yield limit at $T_1$

Yield limit at $T_0$

$T_0$

$p'_c(T_0)$

$p'_c(T_1)$

Mean effective stress, $p'$

$\phi(T_0)$

$\phi(T_1)$

$T_1$

$\frac{\partial \sigma_{ij}}{\partial \sigma_{ij}} = \sum_{k=1}^{2} \lambda_k \frac{\partial g_k}{\partial \sigma_{ij}'}$
Isotropic thermo-plastic mechanism

\[ f_{iso} = p' - p'_c \ r_{iso} \]

Mechanical effect

\[ f_{Ti} = p' - p'_c(T_0) \exp \{ \beta \, \varepsilon'^p \} \{ 1 - \gamma \log \left[ T/T_0 \right] \} \ r_{iso} \]

Thermal effect

\[ p'_c = p'_c(T) \exp \{ \beta \, \varepsilon'^p \} \]

\[ p'_c(T_0) = p'_c(T_0) \{ 1 - \gamma \log \left[ T/T_0 \right] \} \]
Isotropic thermo-plastic mechanism

“ACMEG – T Model”

Evolution of the preconsolidation pressure due to:

Thermal effect

Shape of the yield surface for different values of $\gamma$

$$p'_c(T) = p'_c(T_0) \left\{ 1 - \gamma \log \left[ \frac{T}{T_0} \right] \right\}$$
Deviatoric mechanism

"ACMEG – T Model"

\[
f_{\text{dev}} = q - M p' \left(1 - b \log \frac{d p'}{p'_c}\right) = 0
\]

\[
M (T) = M_0 - g (T - T_0)
\]

\[
\sigma'_c (T) = \sigma'_{c0} (T_0) \exp \{ \beta \varepsilon^p \} \{1 - \gamma \log [T/T_0]\}
\]

Deviatoric yield limit
Friction angle = f (T)
Preconsolidation pressure = f (T)
Advanced Constitutive Model for Environmental Geomechanics – Temperature (ACMEG – T Model)
Mechanical hardening induced by heating

\[ \sigma'_c(T_1) \leftarrow \sigma'_c(T_0) \]

\[ \sigma' = \text{Stress state} \]
Mechanical hardening induced by heating

"ACMEG – T Model"

But the stress state is outside of the yield limit ($f > 0$)

$\Rightarrow$ Inadmissible

$\Rightarrow$ Mechanical hardening of the isotropic yield limit:

$$\frac{d\varepsilon^p_v}{dp'} = \lambda_{iso} \frac{\partial g_{iso}}{\partial p'}$$

The stress state is now on the yield limit ($f = 0$)

$\bullet$ = Stress state
Plastic flow rule

Isotropic mechanism

\[ d \varepsilon_{ii}^{p,iso} = \lambda_{iso} \frac{\partial g_{iso}}{\partial \sigma'_{ii}} = \frac{\lambda_{iso}}{3} \]

Deviatoric mechanism

\[ d \varepsilon_{ij}^{p,dev} = \lambda_{dev} \frac{\partial g_{dev}}{\partial \sigma'_{ij}} = \lambda_{dev} \frac{1}{Mp'} \left[ \frac{\partial q}{\partial \sigma'_{ij}} + \left( M - \frac{q}{p'} \right) \frac{1}{3} \right] \]

with

\[ \frac{\partial q}{\partial \sigma'_{ij}} = \begin{cases} \frac{3}{2q}(\sigma_{ij} - p') & \text{if } i = j \\ \frac{3\sigma_{ij}}{q} & \text{if } i \neq j \end{cases} \]

\[ \begin{align*}
\varepsilon_{v}^{p,iso} &= \lambda_{iso} \frac{\partial g_{iso}}{\partial p'} = \lambda_{iso} \\
\varepsilon_{d}^{p,iso} &= \lambda_{iso} \frac{\partial g_{iso}}{\partial q} = 0
\end{align*} \]

\[ \begin{align*}
\varepsilon_{q}^{p,dev} &= \lambda_{dev} \frac{\partial g_{dev}}{\partial p'} = \lambda_{dev} \frac{1}{Mp'} \left[ M - \frac{q}{p'} \right] \\
\varepsilon_{p}^{dev} &= \lambda_{dev} \frac{\partial g_{dev}}{\partial q} = \lambda_{dev} \frac{1}{Mp'}
\end{align*} \]

“ACMEG – T Model”

Thermo-mechanical behaviour
Determination of the plastic multipliers

“ACMEG – T Model”

- Consistency equations

\[ df_k (\sigma, T, \varepsilon_v^p) = 0 \]

- Solving the two consistency equations

- Two equations with two unknowns

\[
\begin{align*}
\frac{df_{dev}}{d\sigma'} &= \frac{\partial}{\partial \sigma'} f_{dev} d\sigma' + \frac{\partial}{\partial T} f_{dev} dT + \frac{\partial}{\partial \varepsilon_v^p} f_{dev} \\
&= \frac{\lambda_{dev}}{M'} \left[ \frac{1}{M'} \left[ M - \frac{q}{p'} \right] + \lambda_{iso} \right] = 0
\end{align*}
\]

\[
\begin{align*}
\frac{df_{iso}}{d\varepsilon_v^p} &= \frac{\partial}{\partial \varepsilon_v^p} f_{iso} d\varepsilon_v^p + \frac{\partial}{\partial T} f_{iso} dT + \frac{\partial}{\partial r} f_{iso} dr + \frac{\partial}{\partial \varepsilon_v^p} f_{iso} \\
&= \frac{\lambda_{dev}}{M'} \left[ \frac{1}{M'} \left[ M - \frac{q}{p'} \right] + \lambda_{iso} \right] = 0
\end{align*}
\]
Thermo-hydro-mechanical coupling
Undrained paths

THM coupling in anelastic porous media:
• 2 phases (water, solid); 3 fields (THM)
• Mass conservation of each constituent
  + homogenisation (averaging procedure):

\[ \frac{1}{n\beta_f} \left( \partial_t \varepsilon_v^e + \partial_t \varepsilon_v^T_p + \left[ n\beta'_f + (1-n)(\beta'_{s0} + \zeta T)\xi \right] \partial_t T \right) \]

- water compressibility
- Thermal coefficients

Pore-pressure generation
5. Numerical simulations

1. Introduction
2. Principal experimental observations
3. Thermo-mechanical framework
4. LTVP constitutive model
5. Numerical simulations
6. Conclusions
Thermo-mechanical paths

Mechanical loading at constant temperature

Thermal loading
Thermal loading
Isotropic mechanism

"ACMEG – T Model"

Normally consolidated sample

Hardening of the monotonic surface

Heating induces plastic compaction
Thermal loading
Isotropic mechanism

“ACMEG – T Model”

Slightly overconsolidated sample

Heating induces an elastic dilation followed by a plastic compaction
Thermal loading
Isotropic mechanism

“ACMEG – T Model”

Highly overconsolidated sample

Heating induces an elastic dilation
Thermal loading
Isotropic mechanism

T [°C]

95

21.5

p' [MPa]

1

2

6

Simulation of an heating-cooling cycle for different degrees of overconsolidation (OCR=1, 2 and 6) (experimental test of Baldi et al.,1991)

<table>
<thead>
<tr>
<th>Elastic [Kref, Gref, n] [MPa], [MPa], [-]</th>
<th>150, 130, 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic [β, d, p'co] [-], [-], [MPa]</td>
<td>47, 1.3, 6</td>
</tr>
<tr>
<td>Hardening [c] [-]</td>
<td>0.0004</td>
</tr>
<tr>
<td>Domain [r_{ela}] [-]</td>
<td>0.01</td>
</tr>
<tr>
<td>Thermal [β'_{ao}, γ] [°C^{-1}], [-]</td>
<td>3.10^{-5}, 0.18</td>
</tr>
</tbody>
</table>
Thermo-mechanical paths

Mechanical loading at constant temperature

Thermal loading
Mechanical loading at constant temperature
Isotropic mechanism

"ACMEG – T Model"

First loading
= Plastic loading

\[ r_i^m = 1 \]

\[ \varepsilon_v > 0 \Rightarrow \sigma'_c(T_0) \text{ increases} \]
Mechanical loading at constant temperature
Isotropic mechanism

"ACMEG – T Model"

Unloading
= Elastic unloading

\[ \varepsilon_v = 0 \Rightarrow \sigma'_c (T_0) = \text{constant} \]
Mechanical loading at constant temperature
Isotropic mechanism

“ACMEG – T Model”

Elastic reloading
Inside the elastic nuclei

\[ r_i^c = \text{constant} \]
\[ \varepsilon'_v = 0 \Rightarrow \sigma'_c(T_0) = \text{constant} \]
Mechanical loading at constant temperature
Isotropic mechanism

Plastic reloading
Inside the monotonic surface

\[\varepsilon' = \varepsilon^{p,cyc} > 0 \Rightarrow \sigma'_c(T_0) \text{ increases}\]
\[\Rightarrow r_i^c \text{ increases}\]
Mechanical loading at constant temperature
Isotropic mechanism

"ACMEG – T Model"

Plastic loading
Hardening of the monotonic surface

$r_i^{m} = 1$

$\varepsilon_v > 0 \Rightarrow \sigma'_c(T_0)$ increases

O = Initial state

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LL / BF 46

Thermo-mechanical behaviour
Mechanical loading at constant temperature
Isotropic mechanism

Result of simulation of mechanical compression tests on silty sand at constant temperature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>$K_{ref}$, $n$</td>
</tr>
<tr>
<td></td>
<td>[MPa], [-]</td>
</tr>
<tr>
<td>Plastic</td>
<td>$\beta$, $d$, $\sigma'_c$</td>
</tr>
<tr>
<td></td>
<td>[-], [-], [kPa]</td>
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<tr>
<td>Hardening</td>
<td>$c$</td>
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<td></td>
<td>[-]</td>
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<tr>
<td>Domain</td>
<td>$r_\text{ela}$</td>
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<td></td>
<td>[-]</td>
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</tbody>
</table>
Mechanical loading at constant temperature
Pontida clay (1/3)

Drained triaxial tests for 2 OCR values (experiment from Baldi et al., 1991)
Mechanical loading at constant temperature
Pontida clay (2/3)

Drained triaxial tests for 2 OCR values (experiment from Baldi et al., 1991)

- T=20°C
- T=95°C

OCR values: OCR = 12.5, OCR = 5
Mechanical loading at constant temperature
Pontida clay (3/3)

Undrained creep and heating test on an initially anisotropic sample
(experiment from Hueckel & Pellegrini, 1991)

1->2: undrainded loading
2->3: creep test during 48h
3->4: undrained thermal loading

**Chart 1:**
- **X-axis:** Axial deformation [%]
- **Y-axis:** Pore pressure [MPa]
- **Legend:**
  - Experiment
  - Numerical simulation

**Chart 2:**
- **X-axis:** Mean pressure [MPa]
- **Y-axis:** Deviatoric stress [MPa]
- **Legend:**
  - Experiment
  - Numerical simulation

1. T=22 °C
2. T=22.5 °C
3. T=39.5 °C
4. T=56 °C
5. T=68 °C
6. T=79 °C
Thermo-mechanical paths

Mechanical loading at constant temperature

Thermal loading

Thermo-mechanical loading
Thermo-mechanical loading
Isotropic mechanism

(Experiment from Baldi et al., 1991)
Thermo-mechanical undrained loading

The ACMEG – T Model parameters for the Kaolin-MC clay are determined on the following experimental paths:

- Triaxial shear test in NC state at $T=20^\circ$C
- Triaxial shear test in OCR=2.2 state at $T=20^\circ$C
- Thermal loading path: $T=20^\circ$C to 90°C in NC state
- Triaxial shear test in NC state at $T=90^\circ$C

Experimental results (Kuntiwattakul, 1991)
Thermo-mechanical undrained loading

Numerical back-prediction

numerical predictions

experimental results

Initial states

Deviatoric stress, $q$ [kPa]

Axial strain, $\varepsilon_1$ [%]

T=20°C

T=90°C

Pore pressure [kPa]

Axial strain, $\varepsilon_1$ [%]

T=20°C

T=90°C

Experimental result (20 °C)

Experimental result (90 °C)

Numerical simulation (20 °C)

Numerical simulation (90 °C)
Global view of the HADES-URF in Mol

The ATLAS experiment (horizontal plane)
ATLAS experiment - Presentation
ATLAS experiment – Thermal loading
ATLAS experiment – Material parameter (Boom Clay)

Experiment from Baldi et al. (1991)
ATLAS experiment – Comparison with experiment

Comparisons between numerical predictions and measurement in the two instrumented boreholes

Temperature

Pore water pressure

- Experimental data
- Simulation results (Elastic)
- Simulation results (Elasto-plastic)

Graphs showing temperature and pore water pressure variations over time.
ATLAS experiment – Results
LAGAMINE FE code

Thermo-mechanical behaviour

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>1 year</th>
<th>end of phase 1</th>
<th>end of phase 2</th>
<th>4.5 years</th>
<th>6 years</th>
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<td>120</td>
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<table>
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<th>Pore water pressure [MPa]</th>
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<td>1.8</td>
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<td>1.6</td>
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<td>1.4</td>
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<table>
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<th>Mean effective stress [MPa]</th>
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<td>2.4</td>
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<td>2.1</td>
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<td>2.0</td>
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<td>1.9</td>
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<td>1.8</td>
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<tr>
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<thead>
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<th>Volumetric plastic strain [%]</th>
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<td>25</td>
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ATLAS experiment – Results
LAGAMINE FE code
ATLAS experiment – Results (stress paths)
LAGAMINE FE code

(a) $x = 0.21 \text{ m}$
(b) $x = 0.75 \text{ m}$
(c) $x = 1.45 \text{ m}$

- Deviatoric stress [MPa]
- Mean effective stress [MPa]

- 1st phase
- 2nd phase
- 3rd phase
ATLAS experiment – Results (Temperature)
LAGAMINE FE code

VIDEO
ATLAS experiment – Results (Pore water pressure)
LAGAMINE FE code

VIDEO
ATLAS experiment – Results (Mean effective stress)
LAGAMINE FE code

VIDEO
ATLAS experiment – Results (Deviatoric stress)
LAGAMINE FE code
ATLAS experiment – Results (Volumetric plastic strain)
LAGAMINE FE code

VIDEO
ATLAS experiment – Results (Displacements)
LAGAMINE FE code

VIDEO
Conclusions

✓ Thermally induced effects on soils are complex including non-linearity and plasticity

✓ The presented ACMEG-T constitutive model is able to reproduce the main features of the behaviour of soils under thermo-mechanical loading

✓ The ACMEG-T model associated with the LAGAMINE FE code allows to reproduce the observed THM behaviour at the field scale.