Numerical Simulation and Back Analysis of Coupled THM Behavior of Unsaturated Soil

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Motivation - THM behavior

Thermo-Hydro-Mechanical (THM) experiment
Numerical simulation
Sensitivity analysis
Back analysis

Laboratory of Soil Mechanics, Meeting F-GB-CY-D, 23/24 February 2009, Weimar

\[ T = T(t) \]
\[ s = s(t) \]
\[ \sigma^* = \sigma^*(t) \]
THM experiment

THM experimental apparatus

External Collar
Top load cell
Cell body
TEFLON
Relative humidity Sensor
Porous disk
Heater
Ceramic disk
Bottom load cell
Base plate

Compacted Sample

Burette

Water content and Temperature Sensor

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Balance equations

1. **Mass balance of water**

\[
\frac{\partial}{\partial t} \left( \theta_l S_l \phi + \theta_g S_g \phi \right) + \nabla \cdot \left( j_l^w + j_g^w \right) = f^w
\]

2. **Momentum balance for the medium**

\[
\nabla \cdot \sigma + b = 0
\]

3. **Internal energy balance for the medium**

\[
\frac{\partial}{\partial t} \left( E_s \rho_s (1 - \phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi \right) + \nabla \cdot \left( i_c + j_{Es} + j_{El} + j_{Eg} \right) = f^Q
\]
### Constitutive equations

<table>
<thead>
<tr>
<th>EQUATION</th>
<th>VARIABLE NAME</th>
<th>VARIABLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darcy's law</td>
<td>liquid and gas advective flux</td>
<td>$q_l, q_g$</td>
</tr>
<tr>
<td>Fick's law</td>
<td>vapour and air non-advective fluxes</td>
<td>$i_{g^w}, i_{l^a}$</td>
</tr>
<tr>
<td>Fourier's law</td>
<td>conductive heat flux</td>
<td>$i_c$</td>
</tr>
<tr>
<td>Retention curve</td>
<td>Liquid phase degree of saturation</td>
<td>$S_l, S_g$</td>
</tr>
<tr>
<td>Mechanical constitutive model</td>
<td>Stress tensor</td>
<td>$\sigma$</td>
</tr>
</tbody>
</table>
Hydration test simulation

HM Model

Water pressure
\( P = 10 \text{Kpa} \)

Mechanical restrain

300 mm

2x75 mm
Heating test simulation

THM Model

Mechanical restrain

Heater 80°C

2x75mm

300 mm

THM Model

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Soil parameters

- Mechanical parameters: Augus, 2005 (our lab)
- Thermal parameters: Bentonite in FEBEX’s project
- Hydraulic parameters: Laboratory experiment

### TEP Elastic Parameters

<table>
<thead>
<tr>
<th>λ_{io}^{(b)}</th>
<th>κ_{so}</th>
<th>ν</th>
<th>α_{ss}^{(b)}</th>
<th>α_{i}^{(b)}</th>
<th>α_{sp}^{(b)}</th>
<th>α_{o}^{(T)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>0.0029</td>
<td>0.1426</td>
<td>-0.1128</td>
<td>-0.006</td>
<td>-0.3</td>
<td>1.10^{-5}</td>
</tr>
</tbody>
</table>

### TEP Plastic Parameters

<table>
<thead>
<tr>
<th>λ (0)</th>
<th>r</th>
<th>β</th>
<th>λ^{(T)}</th>
<th>k</th>
<th>p^{c}</th>
<th>M</th>
<th>α</th>
<th>p_{o}^{*}^{(b)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.083</td>
<td>0.5165</td>
<td>1.372</td>
<td>0.2</td>
<td>7.32E-03</td>
<td>3.39</td>
<td>1.412</td>
<td>0.426</td>
<td>4.139</td>
</tr>
</tbody>
</table>

### Hydraulic parameters

<table>
<thead>
<tr>
<th>P_{o}^{(b)}</th>
<th>λ^{(b)}</th>
<th>k_{o}^{(b)}</th>
<th>D^{(b)}^{(T)}</th>
<th>τ^{(b)}^{(T)}</th>
<th>n^{(b)}^{(T)}</th>
<th>φ_{o}</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>-</td>
<td>(m^{2})</td>
<td>(m^{2}K^{-1}Pa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>0.53</td>
<td>2.07×10^{-19}</td>
<td>5.9×10^{-6}</td>
<td>0.8</td>
<td>2.3</td>
<td>0.228</td>
</tr>
</tbody>
</table>

(b): This parameter will be used for back analysis.
(T): This parameter is only used in THM analysis.
Soil parameters

\[ \lambda = \lambda_{\text{sat}} S_i \lambda_{\text{dry}} \left(1 - S_i \right) \]

\[ \lambda_{\text{sat}} = 1.507 \text{(WmK}^{-1}) \; ; \; \lambda_{\text{dry}} = 1.0 \text{(WmK}^{-1}) \].

\[ S_e = \frac{S_i - 0}{1 - 0} = 1 + \left( \frac{s}{P_o} \right)^{\frac{1}{1-\lambda}} \]

\[ S_e \]: effective degree of saturation  
\[ S_i \]: degree of saturation of liquid  
\[ \lambda \]: Thermal conductivity Retention curve

\[ \lambda_{\text{sat}} \]: Thermal conductivity of saturated soil  
\[ \lambda_{\text{dry}} \]: Thermal conductivity of dry soil

Degree of saturation \( S \)
Soil parameters

Intrinsic permeability model

Darcy’s law:

\[ q_\alpha = -\frac{k_{r\alpha}}{\mu_\alpha} (\nabla P_\alpha - \rho_\alpha g) \]

Fick’s law: Molecular diffusion of vapour

\[ D_{m,\text{vapor}} = D \tau \left( \frac{273.15 + T}{P_g} \right)^n \quad (m^2 / s) \]
Basic formulas

- **Determination of scaled sensitivity (SS)**
  
  \[ SS_{i,j} = \left( \frac{\partial y_i}{\partial x_j} \right) \cdot x_j \sqrt{\omega_i} \]

- **Determination of composite scaled sensitivity (CSS)**
  
  \[ CSS_j = \sqrt{\frac{1}{N} \sum_{i=1}^{N} SS_{i,j}^2} \]

- **Determination of factor (γ_j)**
  
  \[ \gamma_j = \frac{CSS_j}{\max(CSS)} \]
Sensitivity analysis: Results

Sensitivity analysis for degree of saturation
- P_0
- Lamda retention
- Boundary
- Temperature
- Diffusion
- Initial intrins. perm.
- Initial porosity
- Initial suction

Sensitivity analysis for Temperature
- Lamda_sat
- Lamda_dry
- Boundary
- Temperature
- Diffusion
- Initial intrins. perm.
- Initial porosity
- Initial suction
Sensitivity analysis: Results

Sensitivity analysis for global swelling pressure

- Alpha_0
- Alpha_sp
- Alpha_i
- Alpha_ss
- K_so
- K_io
- Lamda_sat
- Lamda_dry
- BBT*
- Diffusion coeff.
- Initial intrins. perm.
- Initial porosity
- Initial suction

* : Bottom boundary condition

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Algorithm

Start:
guess of parameter values

Optimization algorithm:
Setting parameter values

Execution of forward calculation

Calculation of deviation between calculated values and measurements

Extraction of relevant calculated values

End:
Stop criteria satisfied

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Back analysis: Model of hydration test optimization

Before optimization

After optimization
Back analysis: Model of heating test optimization

Before optimization

After optimization
Two laboratory tests (hydration test and heating test) have been simulated

Sensitivity analysis is performed in order to investigate the responses of the models under the variation of soil parameters, initial and boundary conditions.

Model parameters have been determined by back analysis approach.

For assessing the goodness of the model fit, this method requires more experimental data from experiments.
Conclusions

1. Two laboratory tests (hydration test and heating test) have been simulated.

2. Sensitivity analysis is performed in order to investigate the responses of the models under the variation of soil parameters, initial and boundary condition.

3. Model parameters have been determined by back analysis approach.

4. For assessing the goodness of the model fit, this method requires more experimental data from experiments.
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THANK YOU

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