Numerical investigation of soil-atmosphere interaction
Outline

- Introduction
- Methodology adopted
- Development of a coupled hydro-thermal model
- Applications
  - Environmental chamber
  - Rouen embankment
  - Héricourt embankment
- Conclusions
Background

Tennessee, USA, after a heavy rainfall (2010)

Rainfall/Evaporation, Solar radiation, etc.

Rainfall/Evaporation, Solar radiation, etc.

Atmosphere

Rainfall/Evaporation, Solar radiation, etc.

Soil hydro-thermal behavior

Water content

Settlement, Cracks, Reduction of stability...

Temperature

Engineering problems

Country Road 687 south of Angleton, Texas, after a long time drought (2011)
Objective

Coupled hydro-thermal model

Soil-atmosphere interaction model

Analyse soil hydro-thermal behavior under climate effect
Methodology adopted

✓ Rainfall \( R_{\text{rain}} \); Runoff \( R_{\text{off}} \);
✓ Evaporation \( E \):
  Air relative humidity, air temperature, wind speed
✓ Net solar radiation \( R_n \):
  Solar radiation, dew temperature, air temperature
✓ Sensible heat \( H \): Air temperature
✓ Latent heat \( L_E \): Evaporation

Soil-atmosphere interaction model:

\[
R_{\text{rain}} = R_{\text{off}} + E + I_{nt}
\]
\[
R_n = L_E + H + G
\]

Initial conditions *:
Soil temperature \( T \) and suction \( \phi \)

Boundary conditions *

Coupled hydro-thermal soil model

Soil temperature + Soil water content/suction
## Coupled hydro-thermal model

### Flow

<table>
<thead>
<tr>
<th>Equation</th>
<th>Heat flow</th>
<th>Water flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>$q_h = -\lambda \nabla(T) + L_v q_v$</td>
<td>$q = q_l + q_v$</td>
</tr>
<tr>
<td>Conservation</td>
<td>$\frac{\partial \Phi}{\partial t} + \nabla \cdot q_h = 0$</td>
<td>$q_l = -k \rho_l \nabla \left( \phi + y \right)$</td>
</tr>
<tr>
<td>Conservation</td>
<td>$\Phi = CT + (\eta - \theta)L_v \rho_v$</td>
<td>$q_v = -D_{atm} \alpha \beta \nabla \rho_v$</td>
</tr>
<tr>
<td>Governing equation</td>
<td>$C_T \frac{\partial T}{\partial t} + C_{T\varphi} \frac{\partial \varphi}{\partial t} = \nabla \cdot [K_T \nabla T] + \nabla \cdot [K_{T\varphi} \nabla \varphi]$</td>
<td>$\frac{\partial w}{\partial t} + \nabla \cdot q = 0$</td>
</tr>
<tr>
<td>Governing equation</td>
<td></td>
<td>$w = \theta \rho_l + (\eta - \theta) \rho_v$</td>
</tr>
<tr>
<td>Governing equation</td>
<td>$C_{\varphi T} \frac{\partial T}{\partial t} + C_{\varphi \varphi} \frac{\partial \varphi}{\partial t} = \nabla \cdot [K_{\varphi T} \nabla T] + \nabla \cdot [K_{\varphi \varphi} \nabla \varphi] + \rho_l \nabla K_w$</td>
<td></td>
</tr>
</tbody>
</table>
### Application 1 - Environmental chamber

#### Data

<table>
<thead>
<tr>
<th>Test number</th>
<th>Air flow rate (L/min)</th>
<th>Temperature in heating tube (°C)</th>
<th>Test duration (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>185</td>
<td>50</td>
<td>11.5</td>
</tr>
<tr>
<td>Test 2</td>
<td>172</td>
<td>200</td>
<td>11.5</td>
</tr>
<tr>
<td>Test 3</td>
<td>130</td>
<td>50</td>
<td>17.5</td>
</tr>
<tr>
<td>Test 4</td>
<td>130</td>
<td>200</td>
<td>30</td>
</tr>
</tbody>
</table>
Soil parameters*

Thermal conductivity curve

![Thermal conductivity curve graph](image)

(Côté and Konrad, 2005)

\[ \lambda = (\lambda_{\text{sat}} - \lambda_{\text{dry}}) \cdot \lambda_r + \lambda_{\text{dry}} \]

\[ \lambda_r = \frac{3.55 \cdot S_r}{1 + (3.55 - 1) \cdot S_r} \]

Soil water retention curve

![Soil water retention curve graph](image)

VG model

\[ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (\alpha \varphi)^n} \right]^m \]

\[ \theta_r = 0.040 \]

\[ \theta_s = 0.356 \]

\[ \alpha = 0.0002 \]

\[ m = 0.3, n = 3.0 \]

Hydraulic conductivity curve

![Hydraulic conductivity curve graph](image)

VG model

\[ K = K_s S_e^{0.5} \left[ 1 - \left( 1 - S_e^{1/m_1} \right)^{m_1} \right]^2 \]

\[ m_1 = 0.05 \]

\[ K_s = 1.36 \times 10^{-5} \text{ m/s} \]
Initial and boundary conditions *

Initial conditions *

Soil temperature $T$ and suction $\varphi$

Boundary conditions *

1. Water flux BC: Evaporation

2. Heat flux BC:

$$H = L_E + G$$

$$T_{vn} = G$$
Results and analysis: Soil temperature

Test 1

Test 2

Test 3

Test 4

Introduction  Methodology  Coupled hydro-thermal soil model  Application  Conclusion
Results and analysis: Soil volumetric water content

Test 1

Test 2

Test 3

Test 4

Introduction | Methodology | Coupled hydro-thermal soil model | Application | Conclusion
Application 2 - Rouen embankment (2D)

- Silt treated by 2% CaO

- 28.2 m long, 1.8 m high,
  Slope 1: 2, 2:3 (Vertical: Horizontal).
Soil parameters*

**Thermal conductivity curve**

- Thermal conductivity curve
  - Volumetric water content (%)
  - Measured data
  - Fitting curve

(De Vrie, 1963; Cui et al., 2005)

\[ \lambda = 2.1818\theta + 0.808 \]

**Soil water retention curve**

- Soil water retention curve
  - Volumetric water content (%)
  - Suction (kPa)
  - Fitting curve
  - Sample 1
  - Sample 2
  - Sample 3

VG model

\[ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (\alpha \varphi)^n} \right]^m \]

- \( \theta_r = 0.004 \)
- \( \theta_s = 0.37 \)
- \( \alpha = 0.0025 \)
- \( m = 0.18, n = 2.2 \)

**Hydraulic conductivity curve**

- Hydraulic conductivity curve
  - Suction (kPa)
  - Measured data
  - Fitting curve

VG model

\[ K = K_s S_e^{0.5} \left[ 1 - \left( 1 - S_e^{1/m_1} \right)^{m_1} \right]^2 \]

- \( m_1 = 0.5 \)
- \( K_s = 10^{-9} m/s \)
Initial conditions *
Soil-atmosphere interaction model

**Water transfer**

Mass balance: \[ R_{rain} = R_{off} + E_a + I_{nt} \]

- Rainfall \( R_{rain} \):
- Runoff \( R_{off} \):
- Evaporation \( E_a \):
  - Air relative humidity, air temperature, wind speed
  - Soil temperature and suction

\[
E_a = e_0 - e_a \\
E_p = e_s - e_a \\
E_p = (a + bu)(100 - h_a)
\]

**Energy transfer**

Energy balance: \[ R_n = G + L_E + H \]

- Net solar radiation \( R_n \): Solar radiation, dew temperature, air temperature
- Sensible heat \( H \): Air temperature
- Latent heat \( L_E \): Evaporation

(Blight, 1997)
Boundary conditions

Water flux BC

$$R_{\text{rain}} = R_{\text{off}} + E + I_{nt}$$

$$L_{vn} = I_{nt}$$

- Infiltration
- Evaporation

Heat flux BC

$$R_n = G + L_E + H$$

$$T_{vn} = G$$

- Heating
- Cooling
Results - water content (?)

- Measured data-3C2
- Calculated data-3C2
- Measured data-3C4
- Calculated data-3C4

Volumetric water content (%)

Rainfall

Rainfall (mm/h)

Introduction
Methodology
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Application
Conclusion
Corrected model dimension*
Corrected model dimension*

1.233 m
1.800 m
6.050 m
2.667 m
5.400 m
1.880 m

0.28 m
0.450 m
1.880 m
5.400 m

BC2
BC3
BC4
BC5
BC6
BC7
BC8

Subgrade

BC4
BC5
BC6
BC7

BC3
BC2

1.800 m
0.233 m
2.667 m
6.050 m
0.450 m
Results and analysis: Soil temperature

- **① near top surface points (point 1C5 and 2C5)**
- **② near slope surface points (point 3C4, 3C2 and 4C0)**
- **③ interior points (point 2C4, 2C2 and 2C0)**
- **④ interior middle points (point 1C4, 1C2 and 1C0)**

*Seasonal variation + daily fluctuations* vs. *Seasonal variation*
Results and analysis: Soil volumetric water content

① near top surface points (point 1C5 and 2C5)

② near slope surface points (point 3C4, 3C2 4C0)

③ interior points (point 3C0, 2C0 and 1C0)

No seasonal variation
Application 3- Héricourt embankment (2D)

Site:
Franche-Comté region, the northeast of France.

Climate type:
Continental climate influenced by ocean.

- 107 m long, 5 m high,
- Slope 1: 2 (Vertical: Horizontal).

Silt treated soil (53.5 m)
Clay treated soil (53.5 m)
Soil parameters* 

Thermal conductivity curve

Soil water retention curve

Hydraulic conductivity curve

(De Vrie, 1963; Cui et al., 2005)

\[ \lambda = 2.1818 \theta + 0.808 \]

\[ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[ \frac{1}{1 + (\alpha \varphi)^n} \right]^m \]

\[ \theta_r = 0.004 \]

\[ \theta_s = 0.4 \]

\[ \alpha = 0.003 \]

\[ m = 0.18, n = 1.8 \]

\[ K = K_s S_e^{0.5} \left[ 1 - \left( 1 - S_e^{1/m_1} \right)^{m_1} \right]^2 \]

\[ m_1 = 0.5 \]

\[ K_s = 10^{-9} \text{ m/s} \]
Field meteorological data (06/07/2011 to 26/07/2011):
Results and analysis: Group 1

Group 1: **Interior points (I1, I2 and I3)**

- Volumetric water content (%)
- Temperature (°C)

Measured data-I1  ▲  Measured data-I2  ▲  Measured data-I3
Calculated data-I1  ▲  Calculated data-I2  ▲  Calculated data-I3

- ST1-65
- TDR probe
- PT100

Introduction  Methodology  Coupled hydro-thermal soil model  Application  Conclusion
Results and analysis: Group 2

Group 2: Near soil surface points (S1, S2 and S3)
Conclusions

- Development of a numerical tool combing fully coupled hydro-thermal model and soil-atmosphere interaction model.

- In environmental chamber, soil hydro-thermal behavior in four tests are simulated correctly, validating the proposed method.

- For Rouen embankment, seasonal variations of soil temperature (+daily variation for points near surface region) are observed and soil volumetric water content show reasonable variations.

- At Héricourt embankment, soil temperature and volumetric water content at the interior points normally keep stable as their initial states. While for the points near surface, their behaviors are influenced effectively by soil-atmosphere interaction.

- Further application for the long term behavior.
- Extension to deformable materials (clay).
Thank you for your attention!