École des Ponts
ParisTech

Comité Français de Mécanique des Sols
et de Géotechnique

CFMS
Association régie par la loi du 1.07.1901

Jubilé du Professeur François SCHLOSSER

Numerical investigation of soil-atmosphere interaction

Ni AN

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)

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

Atmosphere ⇨ Rainfall/Evaporation, Solar radiation, etc.

⇩

Soil hydro-thermal behavior ⇨ Water content, Suction, Temperature

⇩

Engineering problems ⇨ Settlement, Cracks, Reduction of stability…

Objective

Coupled hydro-thermal model

Soil-atmosphere interaction model

Analyse soil hydro-thermal behavior under climate effect

Methodology adopted

- ✓Rainfall R_{ain}; Runoff R_{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 surface temperature ***T*** and suction φ

Soil-atmosphere interaction model:

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

$$R_n = L_E + H + G$$

Boundary conditions *****

Initial conditions ***** :
Soil temperature ***T*** and suction φ

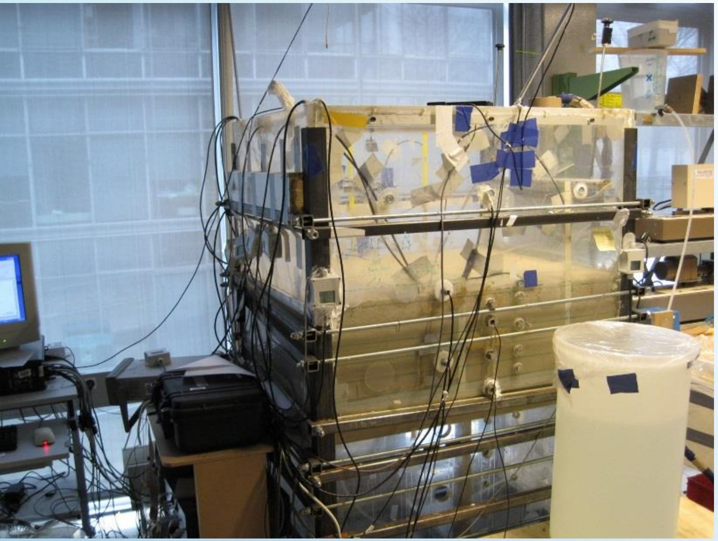
Coupled hydro-thermal soil model

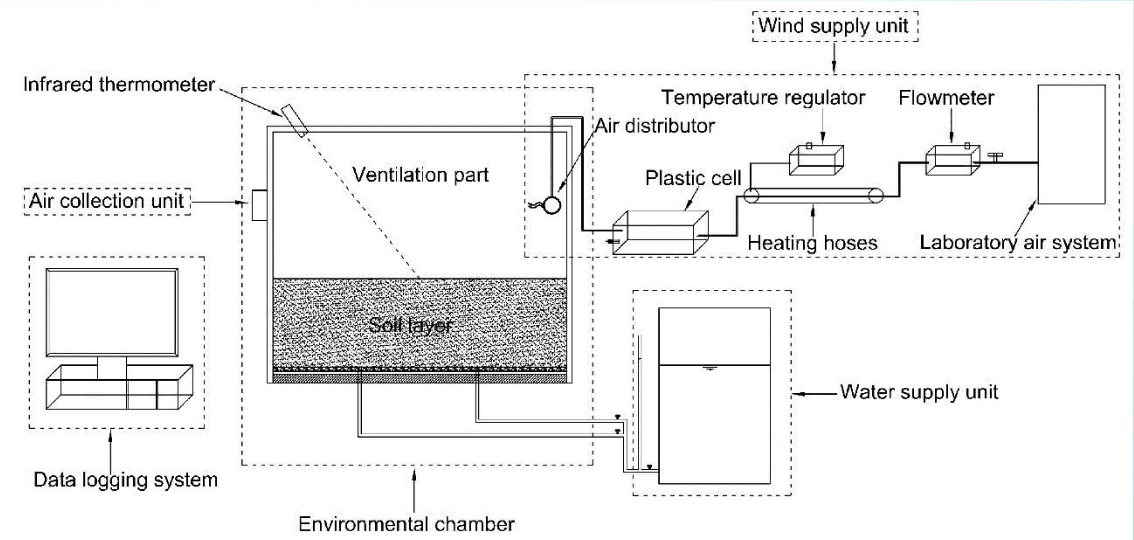
Soil temperature + **Soil water content/suction**

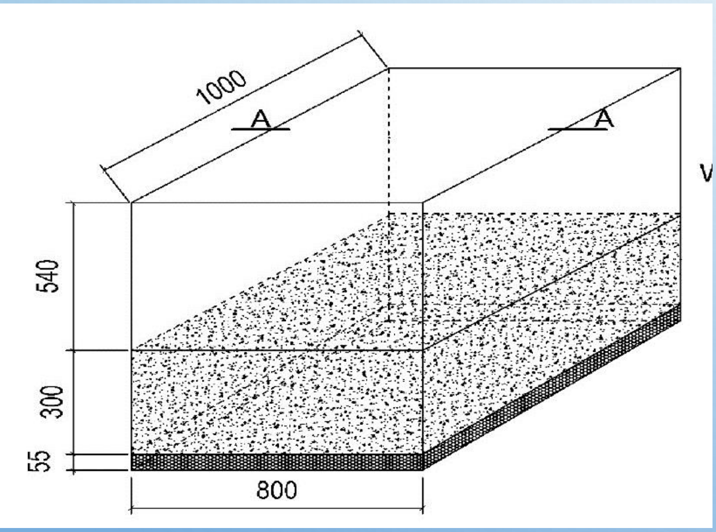
Coupled hydro-thermal model

Flow / Equation	Heat flow	Water flow
Flow	$q_h = -\lambda \nabla (T) + L_v q_v$	$q = q_l + q_v$ $q_l = -k\rho_l \nabla(\varphi + y)$ $q_v = -D_{atm}\alpha\beta\nabla(\rho_v)$
Conservation	$\frac{\partial \Phi}{\partial t} + \nabla \cdot q_h = 0$ $\Phi = CT + (\eta - \theta)L_v \rho_v$	$\frac{\partial w}{\partial t} + \nabla \cdot q = 0$ $w = \theta\rho_l + (\eta - \theta)\rho_v$
Governing equation	$C_T \frac{\partial T}{\partial t} + C_{T\varphi}\frac{\partial \varphi}{\partial t} = \nabla \cdot [K_T \nabla T] + \nabla \cdot [K_{T\varphi}\nabla\varphi]$	$C_{\varphi T}\frac{\partial T}{\partial t} + C_\varphi \frac{\partial \varphi}{\partial t} = \nabla \cdot [K_{\varphi T}\nabla T] + \nabla \cdot [K_\varphi \nabla \varphi] + \rho_l \nabla K_w$

Application 1- Environmental chamber



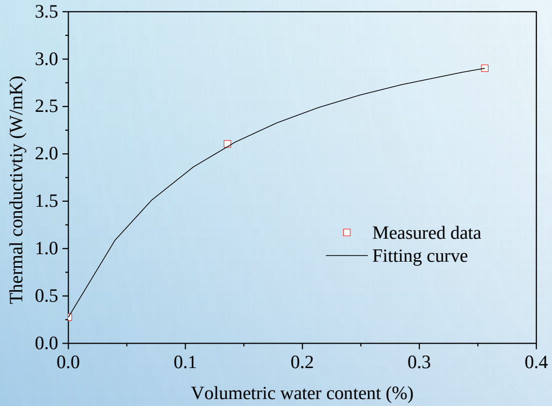




Test number	Air flow rate (L/min)	Temperature in heating tube (° C)	Test duration (day)
Test 1	185	50	11.5
Test 2	172	200	11.5
Test 3	130	50	17.5
Test 4	130	200	30

Soil parameters*

Thermal conductivity curve

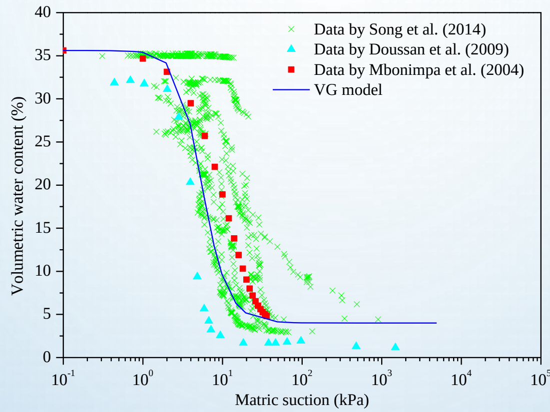


(Côté and Konrad, 2005)

$$\lambda = (\lambda_{sat} - \lambda_{dry}) \cdot \lambda_r + \lambda_{dry}$$

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

Soil water retention curve



VG model

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

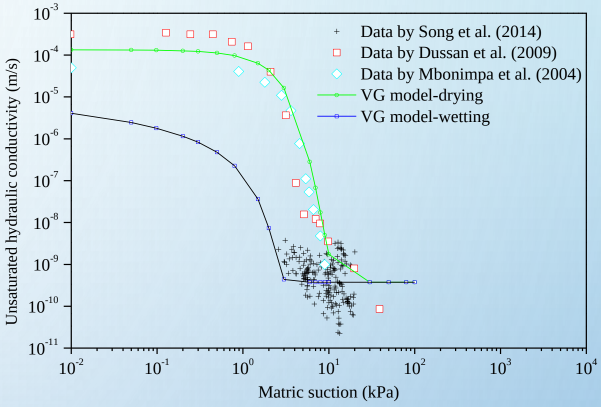
$$\theta_r = 0.040$$

$$\theta_s = 0.356$$

$$\alpha = 0.0002$$

$$m = 0.3, n = 3.0$$

Hydraulic conductivity curve



VG model

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

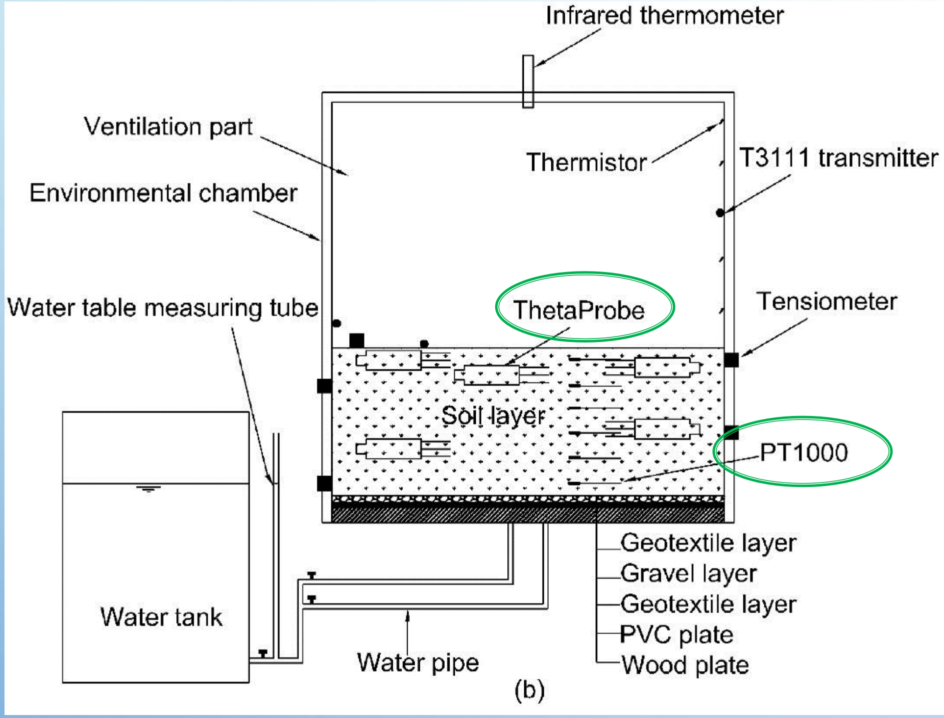
$$m_1 = 0.05$$

$$K_s = 1.36 \times 10^{-5} m/s$$

Initial and boundary conditions *

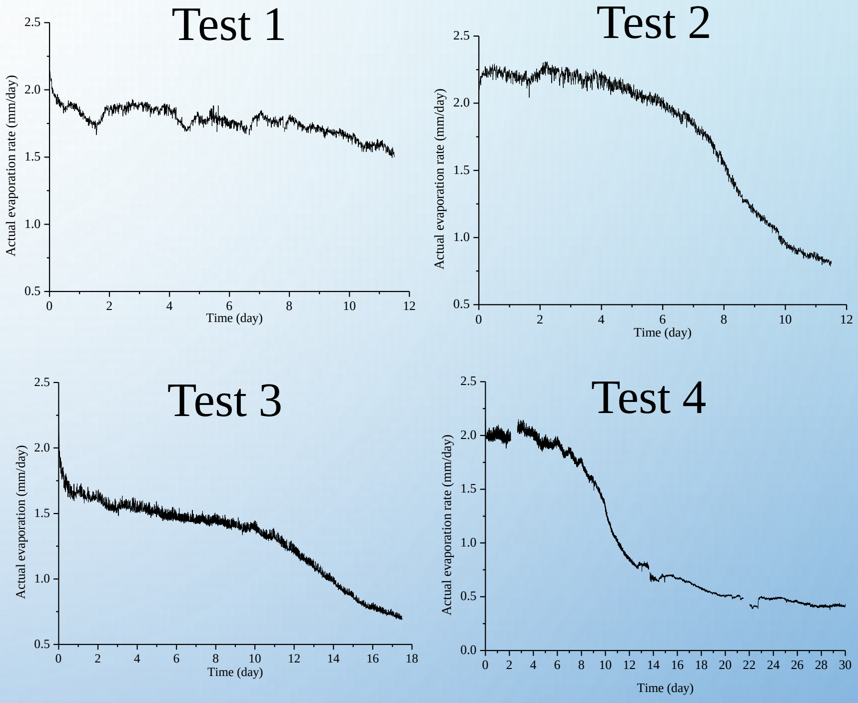
Initial conditions *

Soil temperature $\boldsymbol{T}$ and suction φ



Boundary conditions *

① Water flux BC: Evaporation

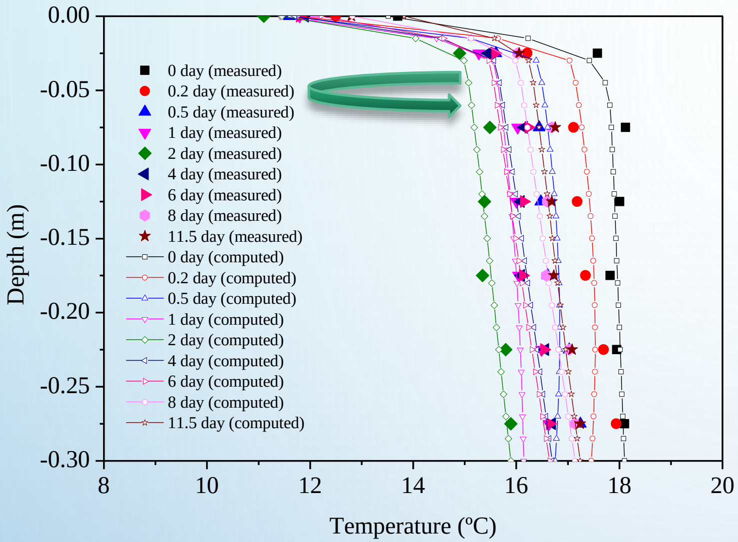


② Heat flux BC: $H = L_E + G$

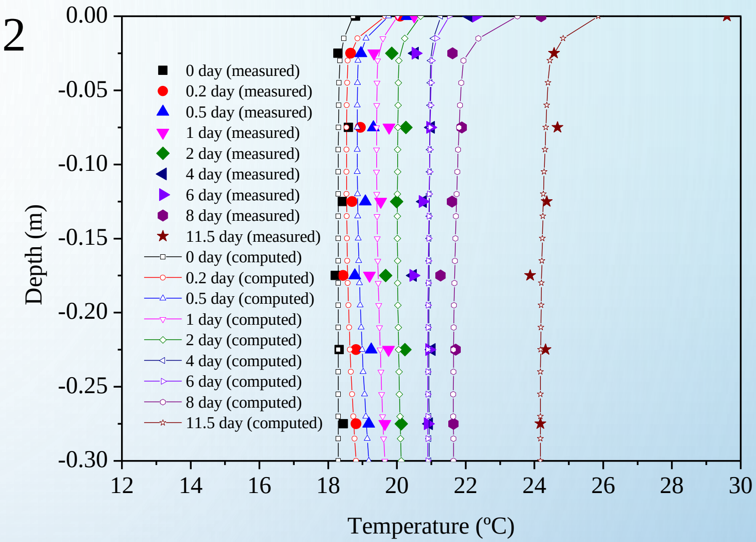
$$T_{vn} = G$$

Results and analysis: Soil temperature

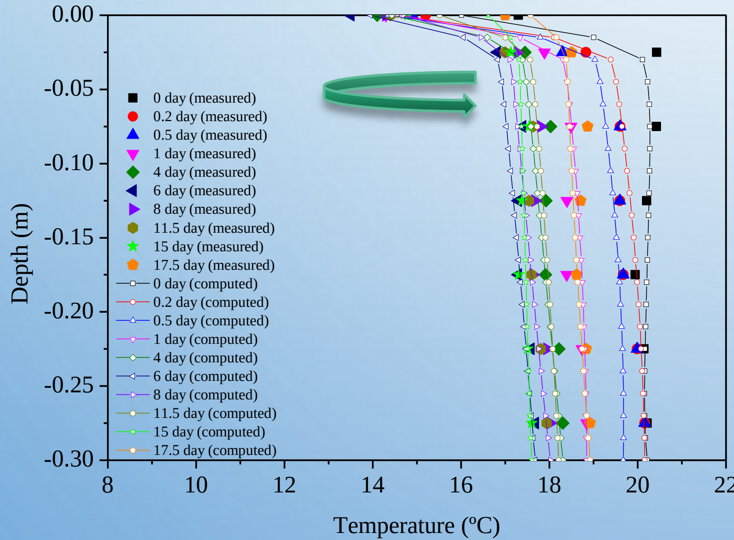
Test 1



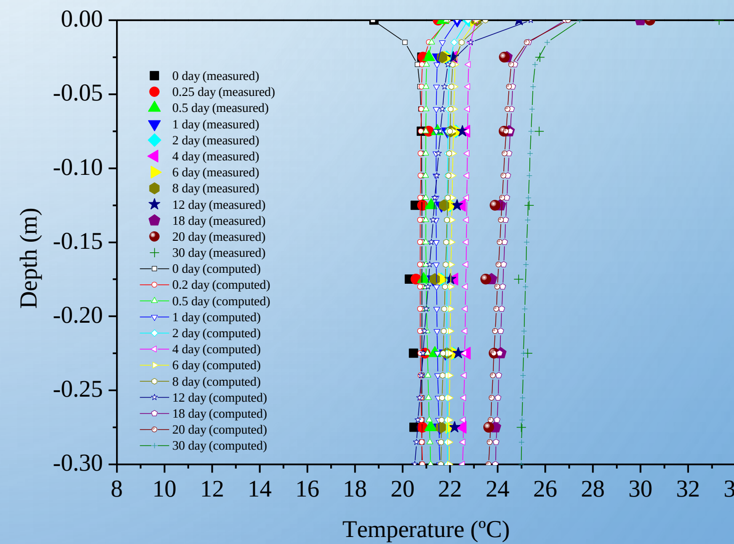
Test 2



Test 3

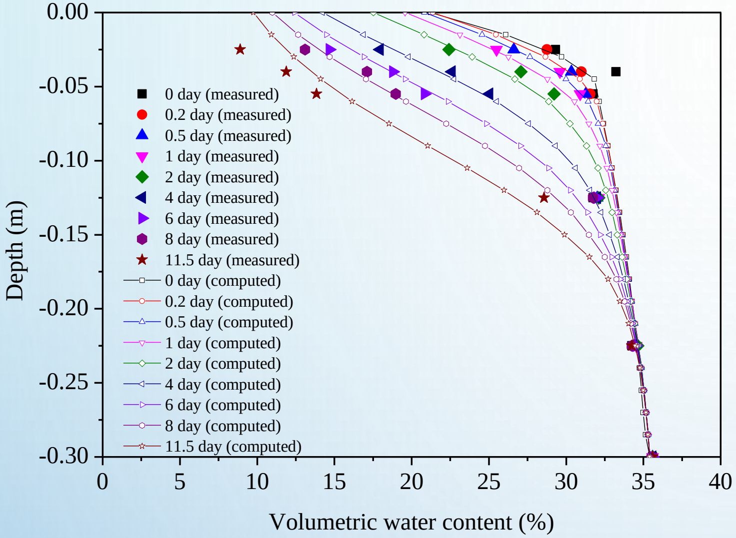


Test 4

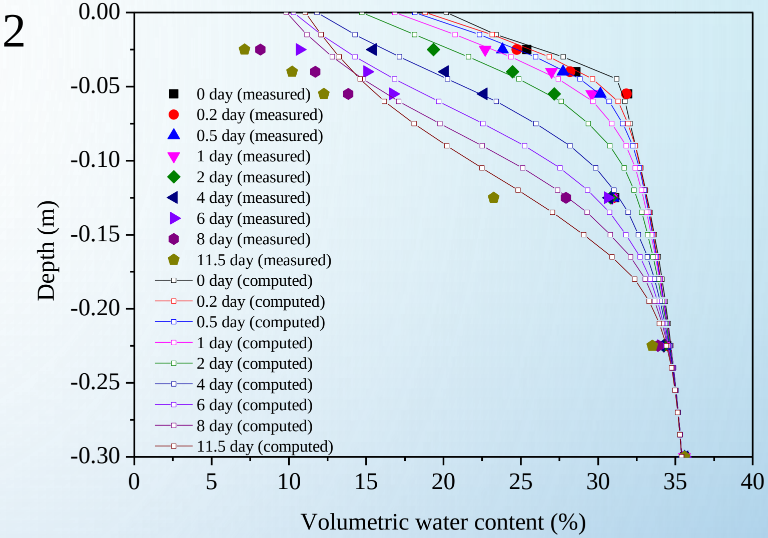


Results and analysis: Soil volumetric water content

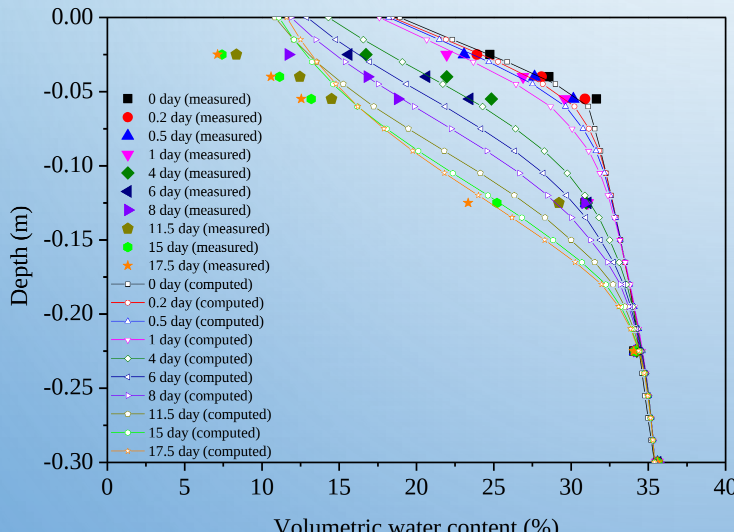
Test 1



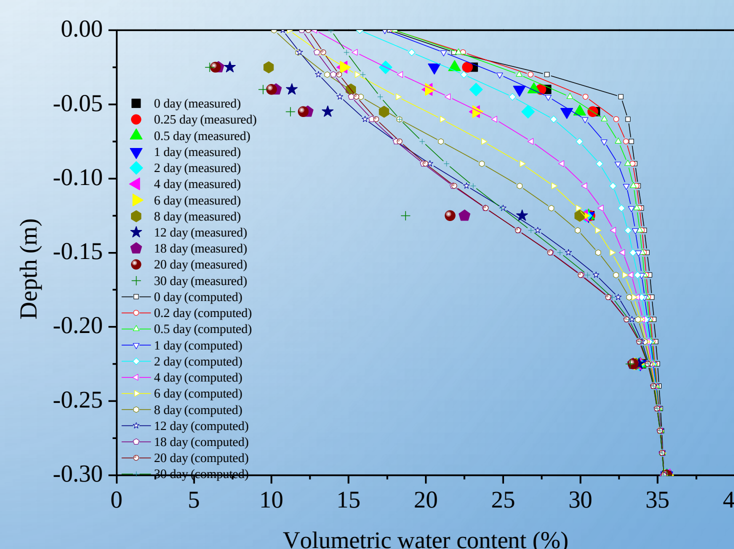
Test 2



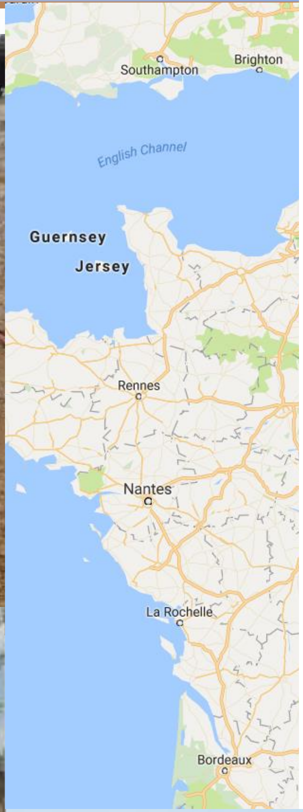
Test 3

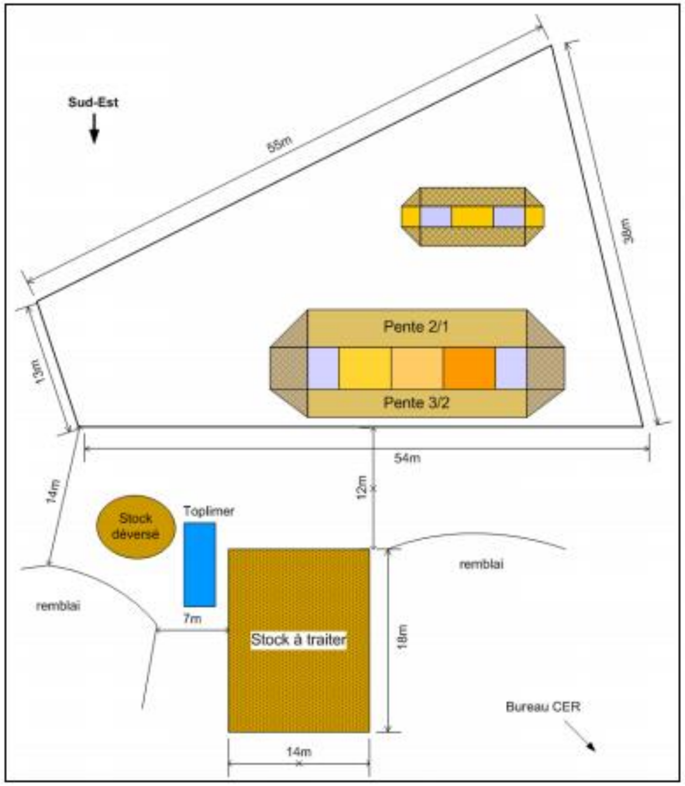


Test 4



Application 2- Rouen embankment (2D)

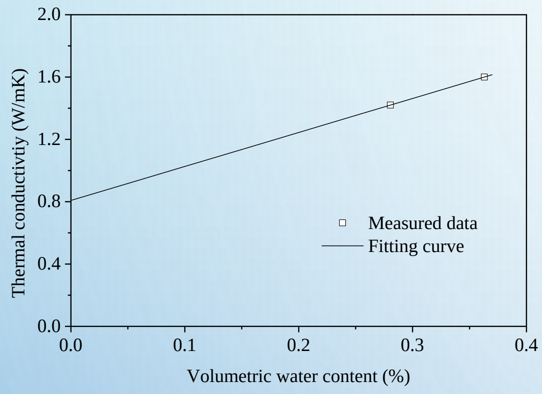




28.2 m long, 1.8 m high,
Slope 1: 2, 2:3 (Vertical: Horizontal).

Soil parameters*

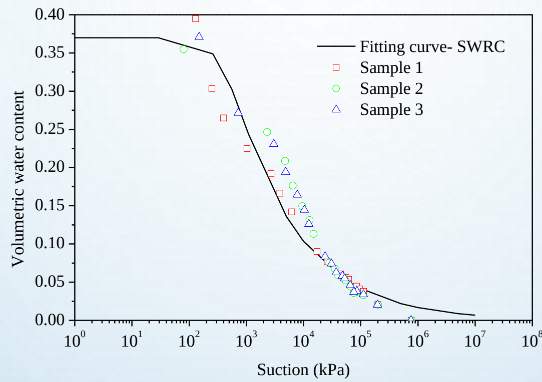
Thermal conductivity curve



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

$$\lambda = 2.1818\theta + 0.808$$

Soil water retention curve



VG model

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

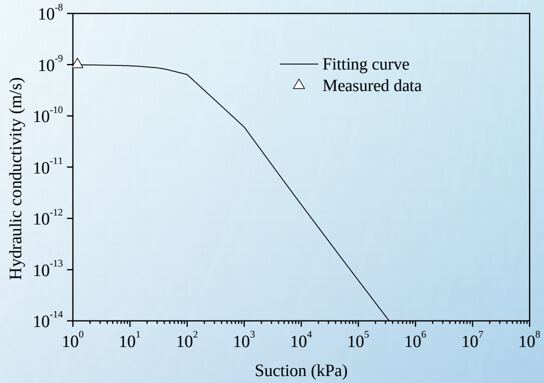
$$\theta_r = 0.004$$

$$\theta_s = 0.37$$

$$\alpha = 0.0025$$

$$m = 0.18, n = 2.2$$

Hydraulic conductivity curve



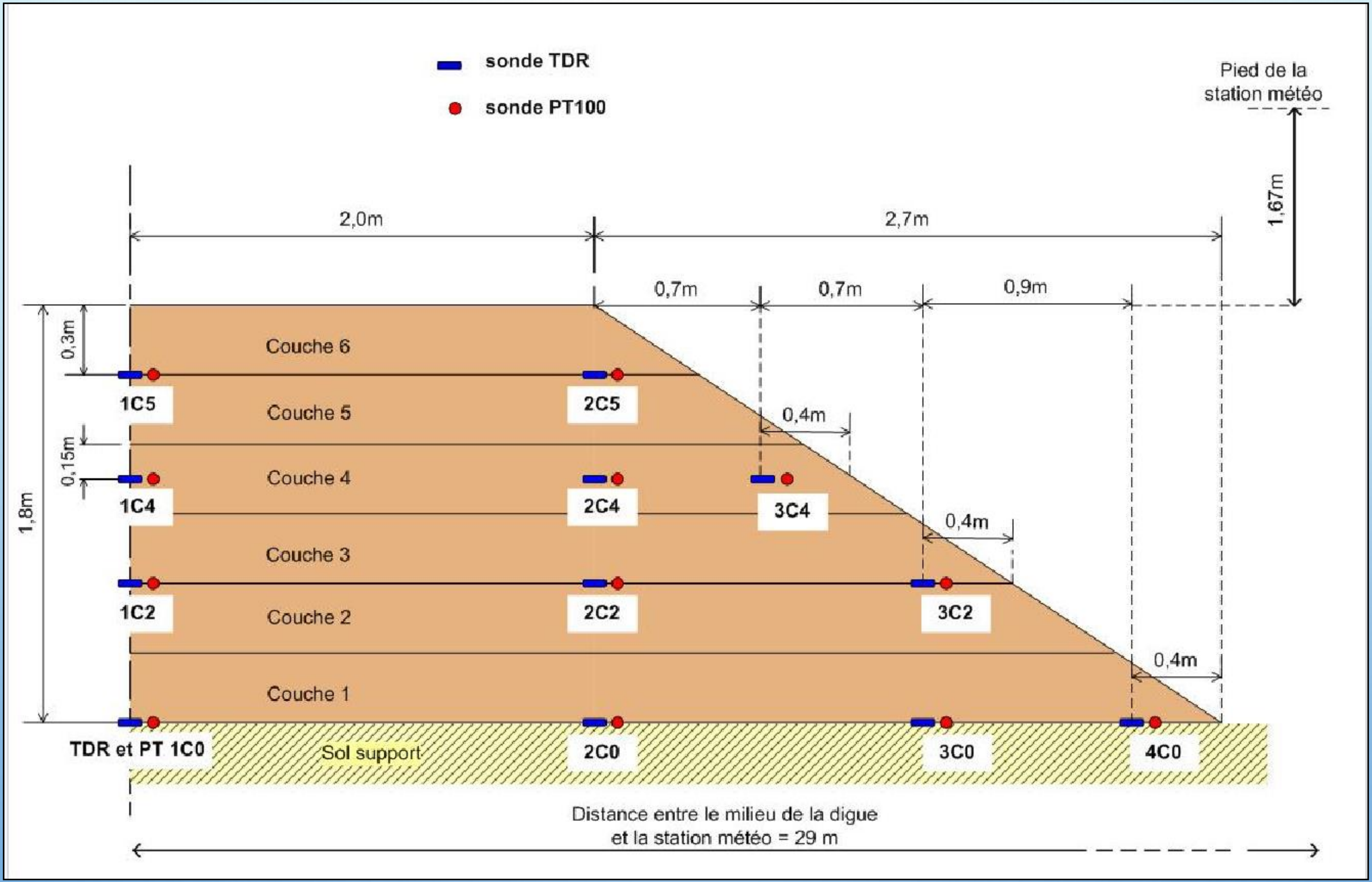
VG model

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

$$m_1 = 0.5$$

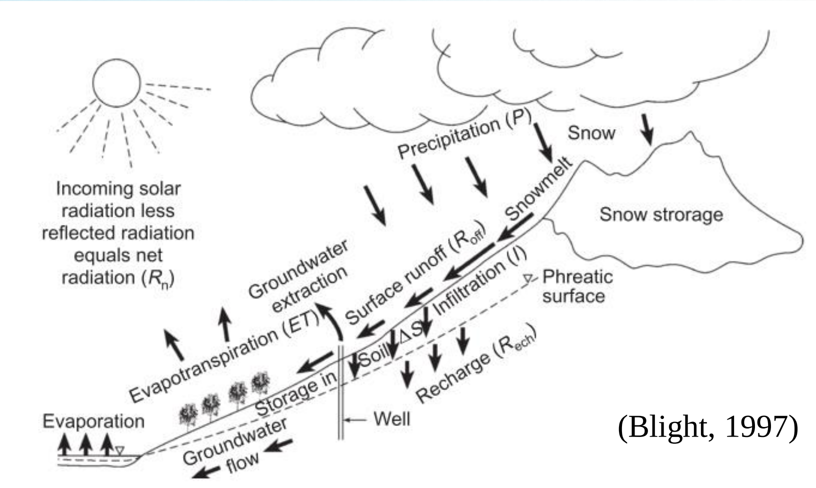
$$K_s = 10^{-9} m/s$$

Initial conditions *



Soil-atmosphere interaction model

Water transfer



Mass balance: $R_{rain} = R_{off} + E_a + I_{nt}$

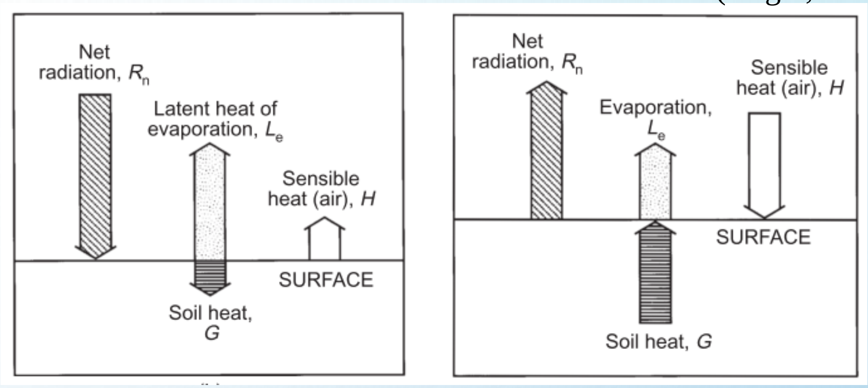
- ✓ Rainfall R_{ain} :
- ✓ Runoff R_{off} :
- ✓ Evaporation E_a:
  - ➢ *Air relative humidity, air temperature, wind speed*
  - ➢ *Soil temperature and suction*

$$\frac{E_a}{E_p} = \frac{e_0 - e_a}{e_s - e_a}$$

$$E_p = (a + bu)(100 - h_a)$$

Energy transfer

(Blight, 1997)



Daytime Nighttime

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*

Boundary conditions *

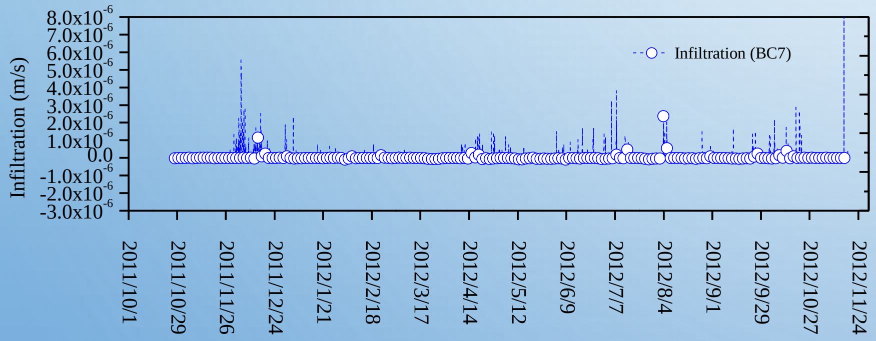
Water flux BC

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

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

\+ Infiltration

\- Evaporation



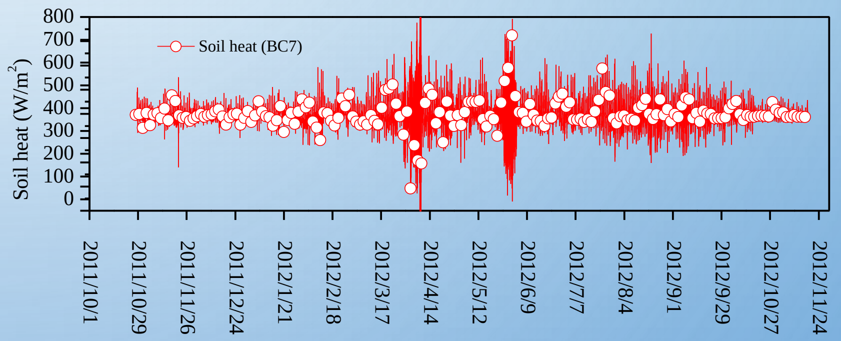
Heat flux BC

$$R_n = G + L_E + H$$

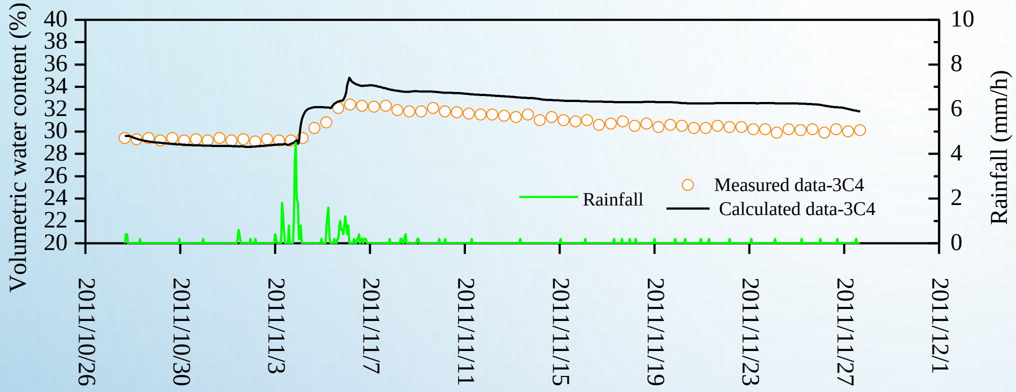
$$T_{vn} = G$$

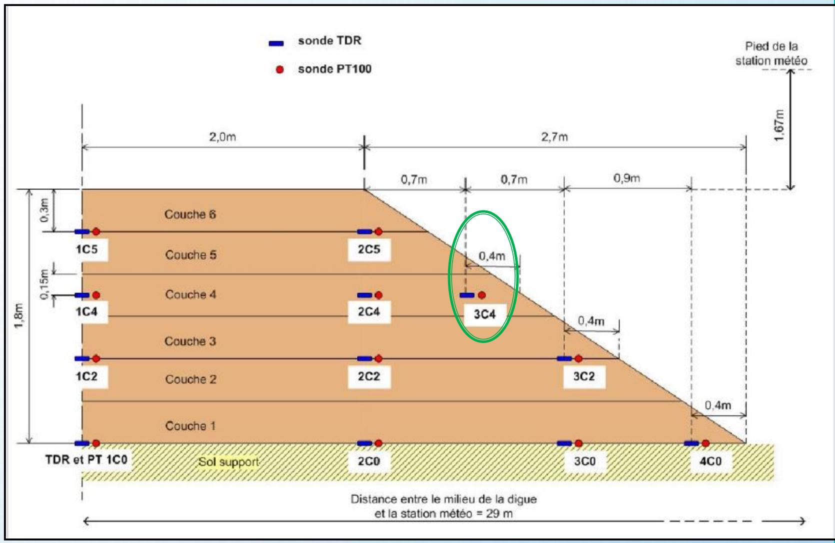
\+ Heating

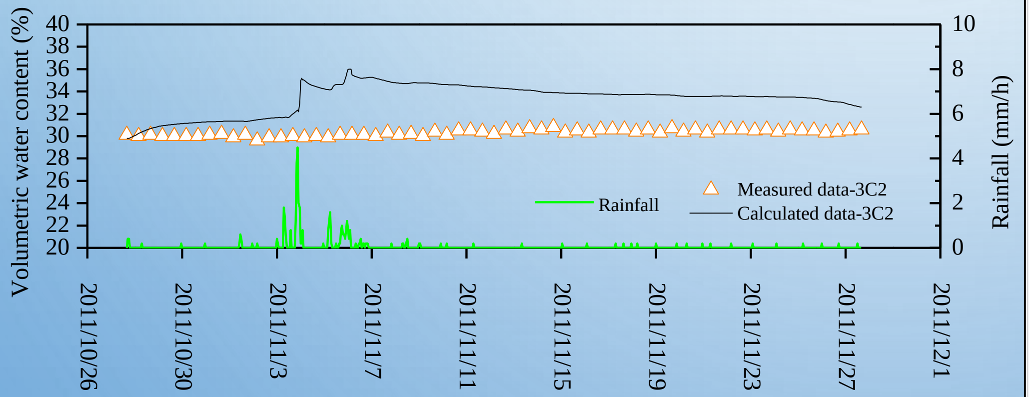
\- Cooling

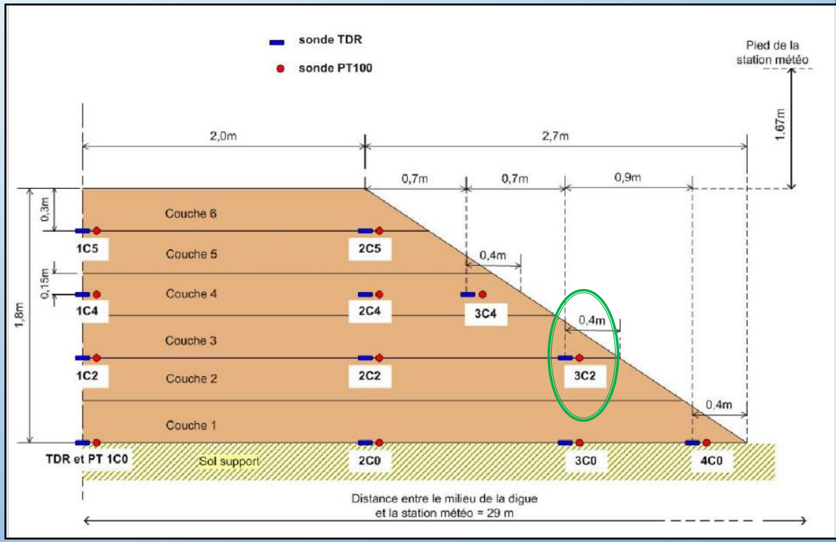


Results- water content (?)

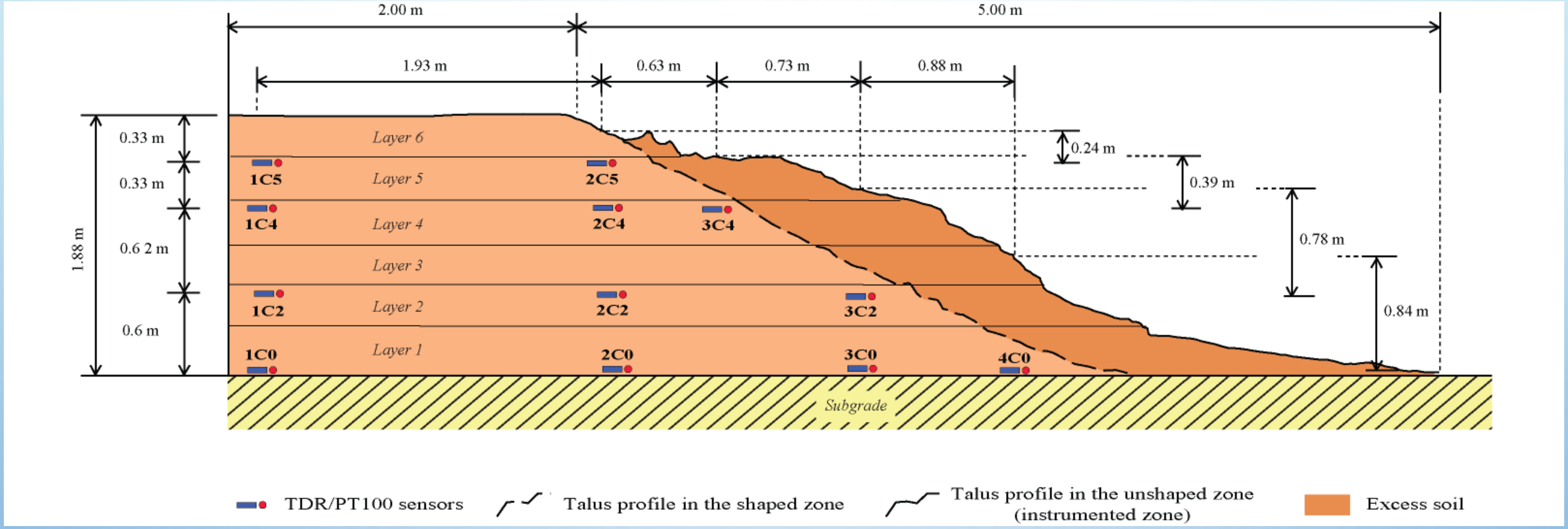




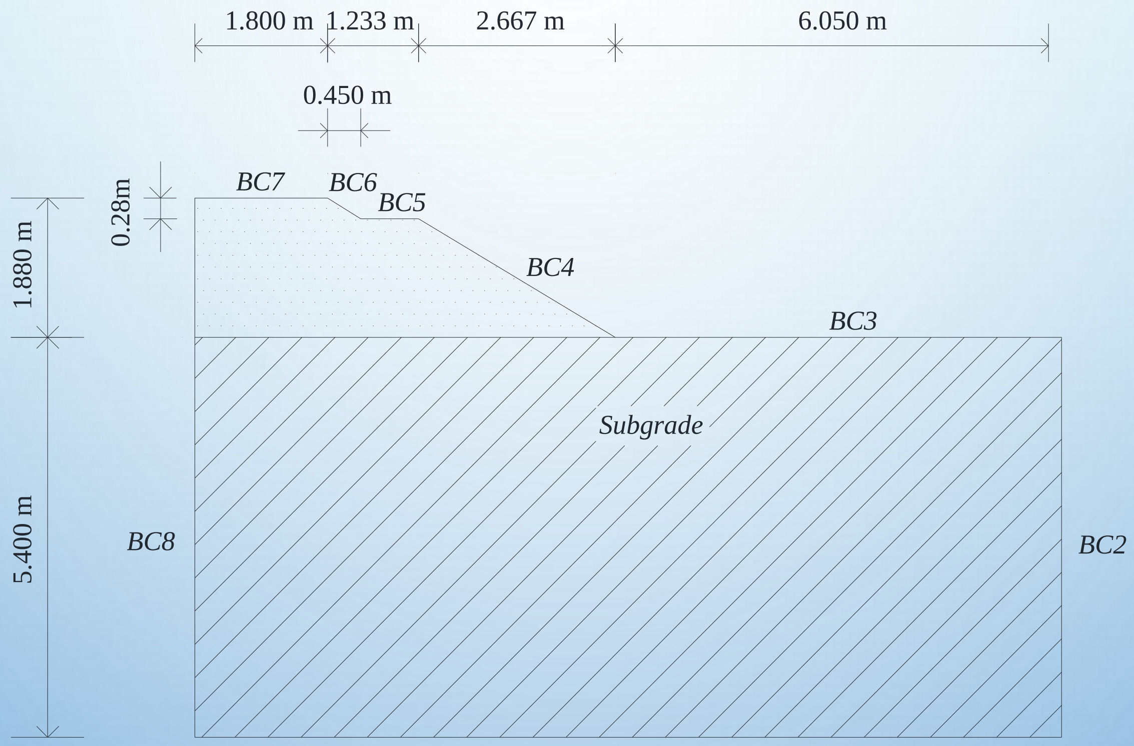




Corrected model dimension*

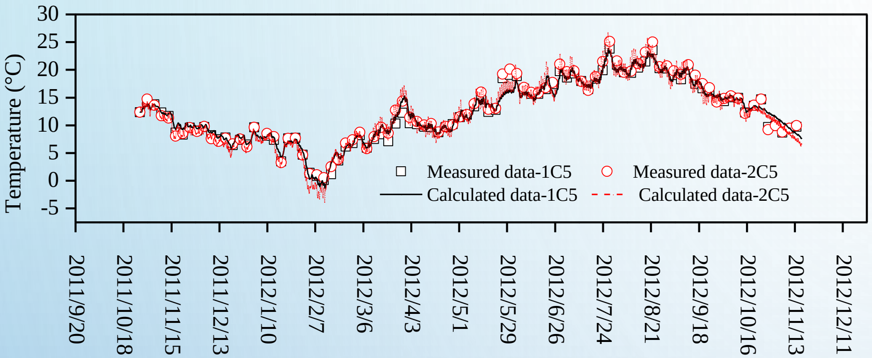


Corrected model dimension*

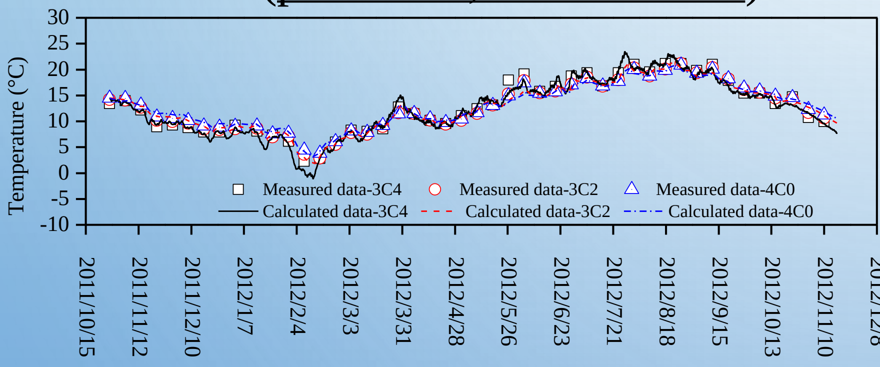


Results and analysis: Soil temperature

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

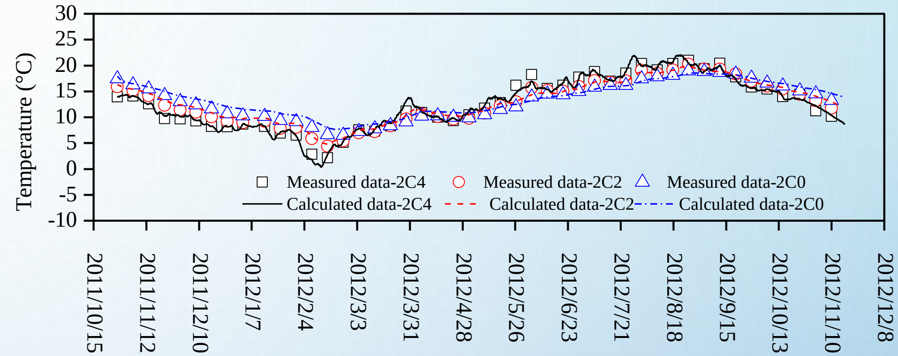


② near slope surface points
(point 3C4, 3C2 and 4C0)

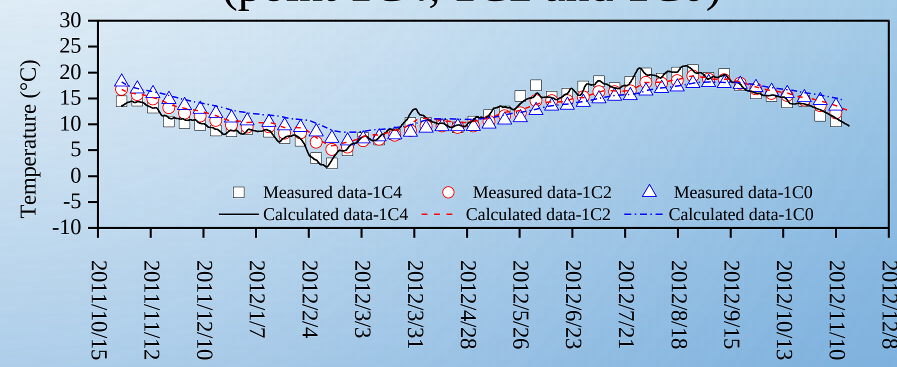


Seasonal variation+ daily fluctuations

③ interior points
(point 2C4, 2C2 and 2C0)



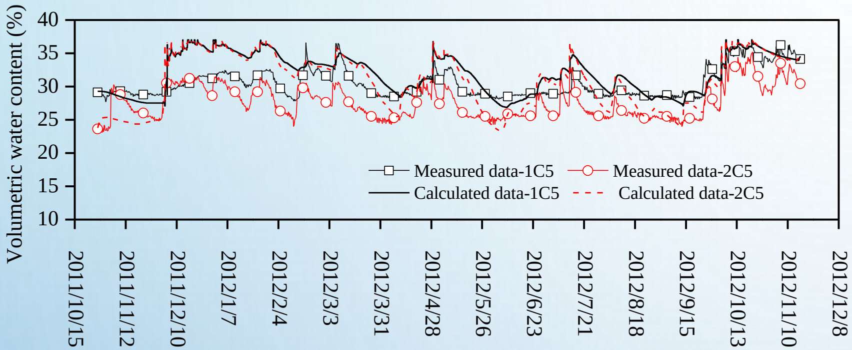
④ interior middle points
(point 1C4, 1C2 and 1C0)



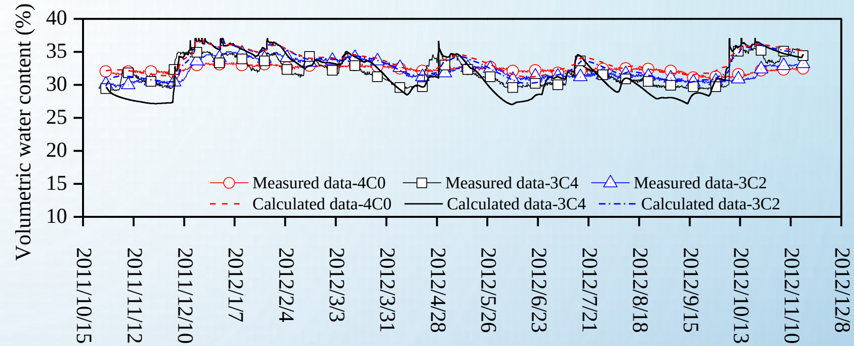
Seasonal variation

Results and analysis: Soil volumetric water content

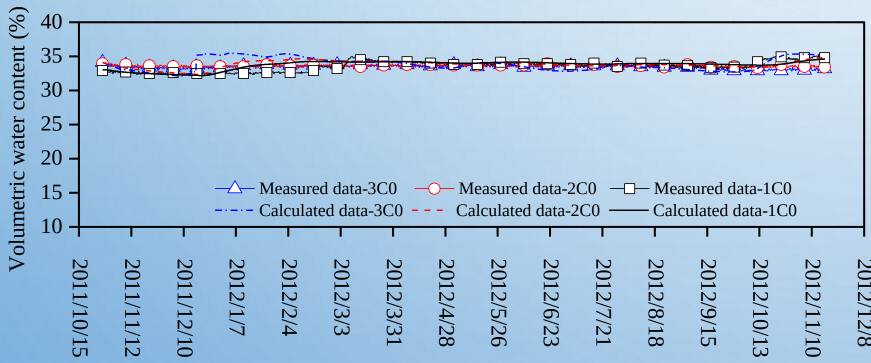
① near top surface points
(point 1C5 and 2C5)



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



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

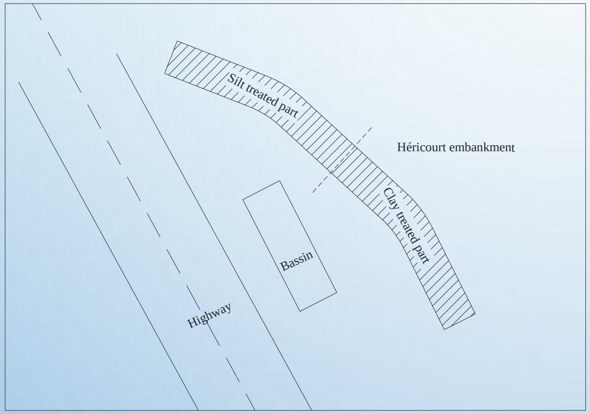


No seasonal variation

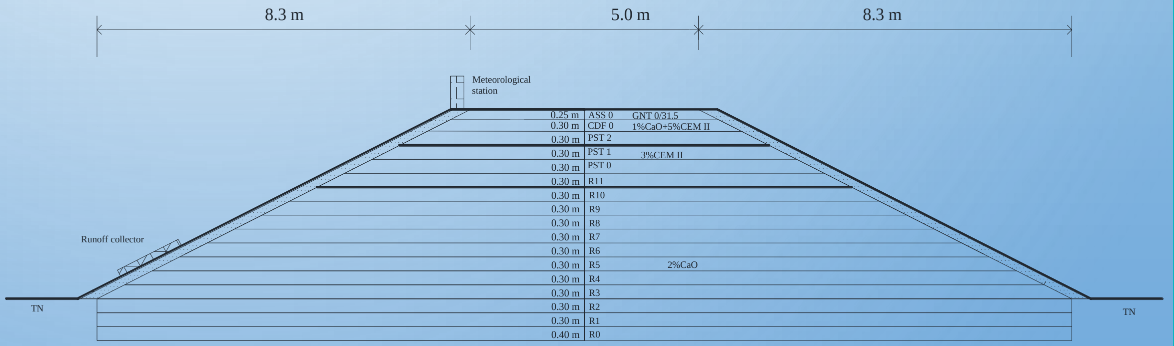
Application 3- Héricourt embankment (2D)

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

Climate type:
Continental climate influenced by ocean.

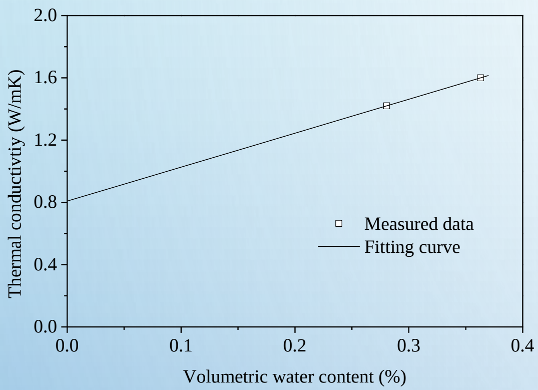


- 107 m long, 5 m high,
- Slope 1: 2 (Vertical: Horizontal).



Soil parameters*

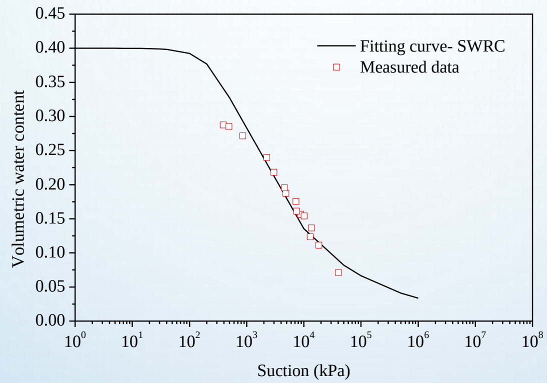
Thermal conductivity curve



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

$$\lambda = 2.18180\theta + 0.808$$

Soil water retention curve



VG model

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

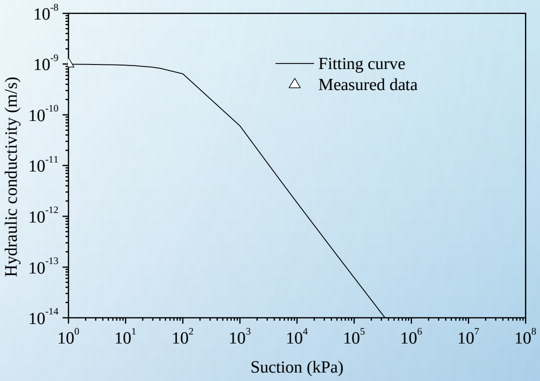
$$\theta_r = 0.004$$

$$\theta_s = 0.4$$

$$\alpha = 0.003$$

$$m = 0.18, n = 1.8$$

Hydraulic conductivity curve



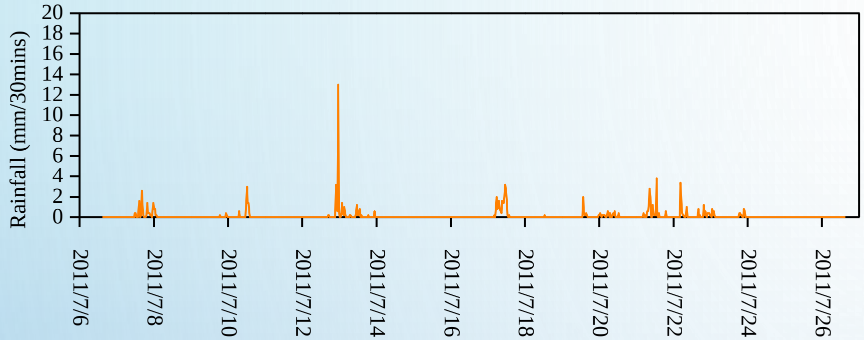
VG model

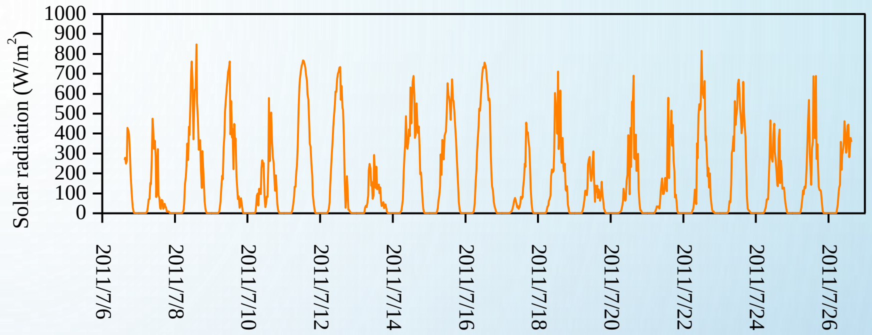
$$K = K_s S_e^{0.5}\left[1 - \left(1 - S_e^{1/m_1}\right)^{m_1}\right]^2$$

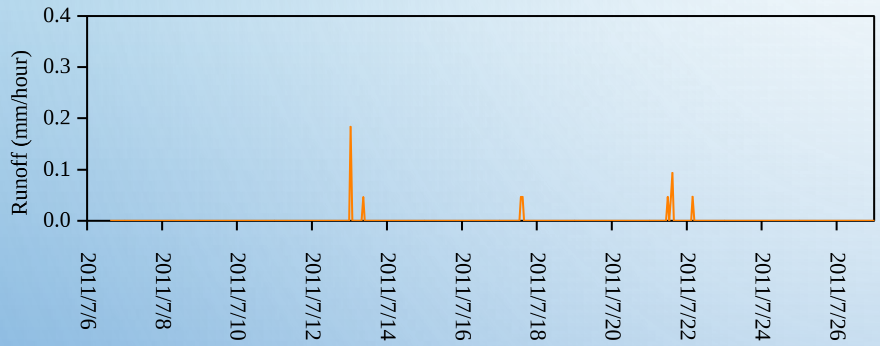
$$m_1 = 0.5$$

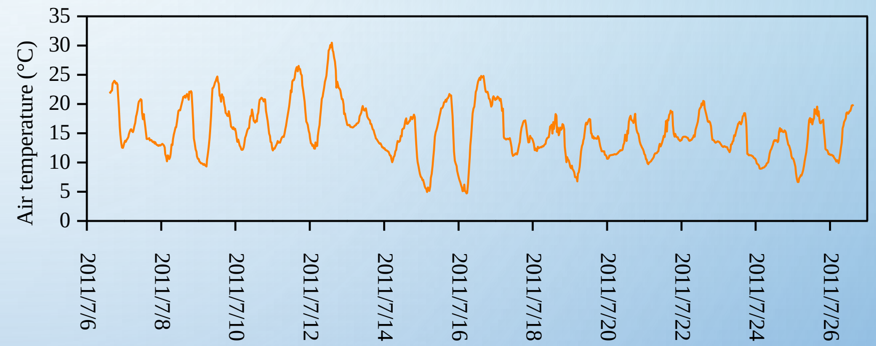
$$K_s = 10^{-9} m/s$$

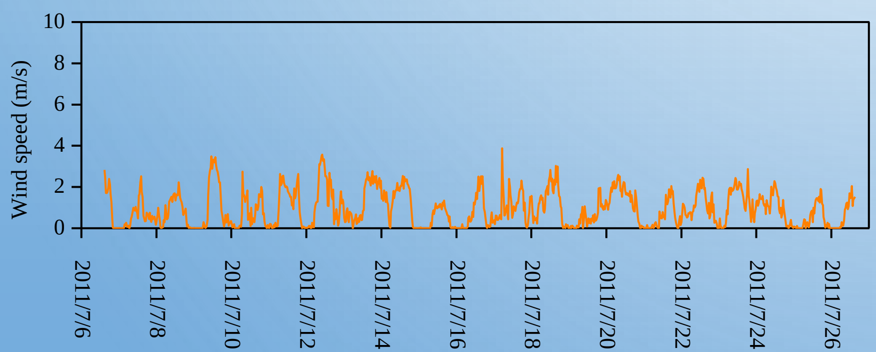
Field meteorological data (06/07/2011 to 26/07/2011):

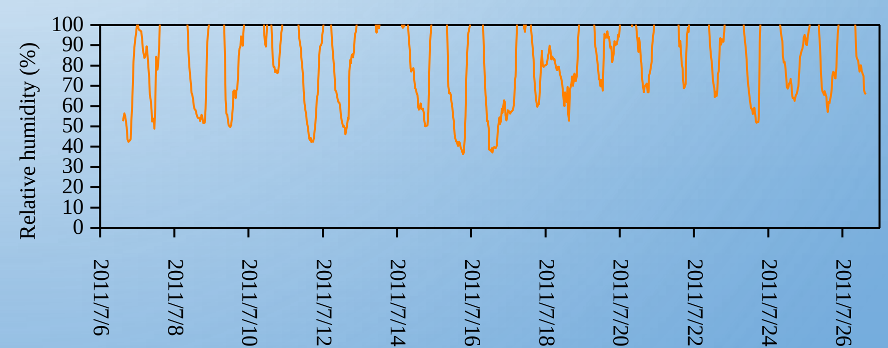






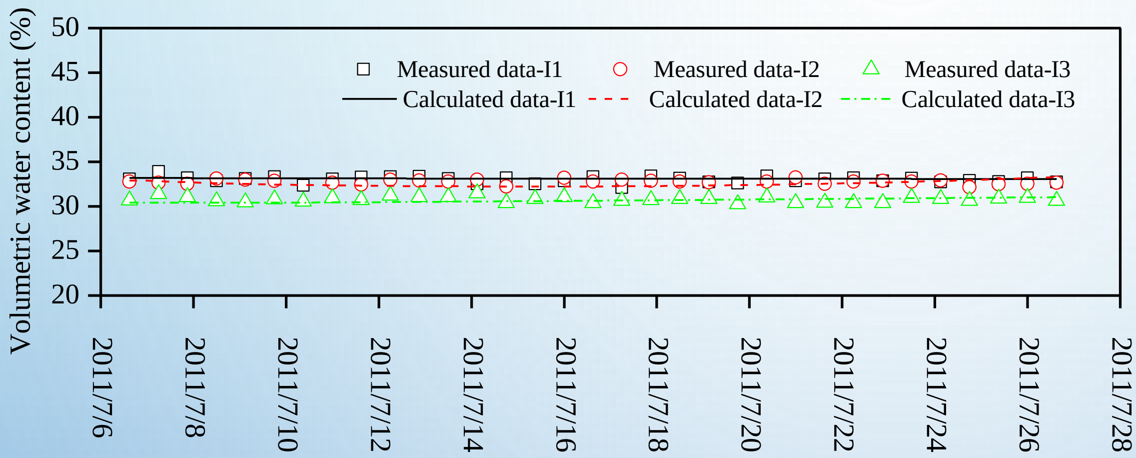


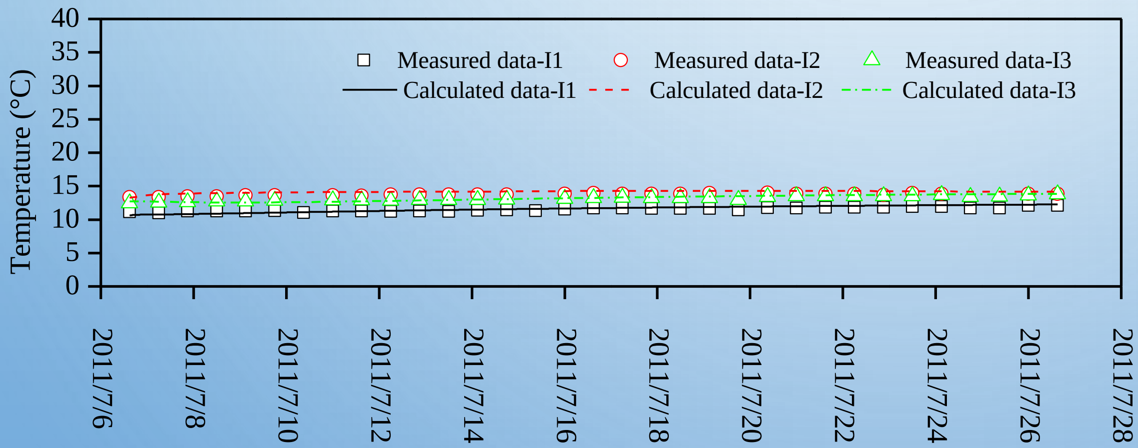


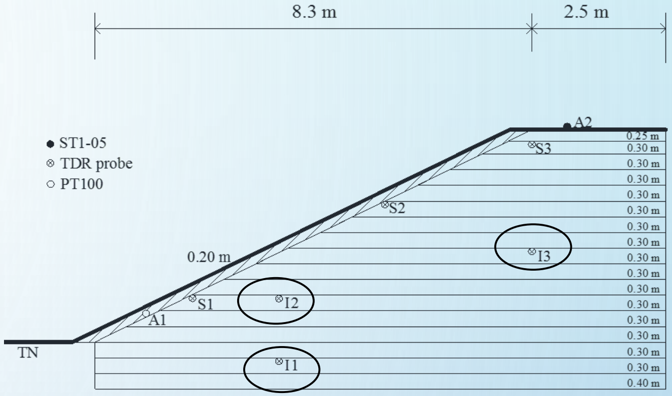


Results and analysis: Group 1

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

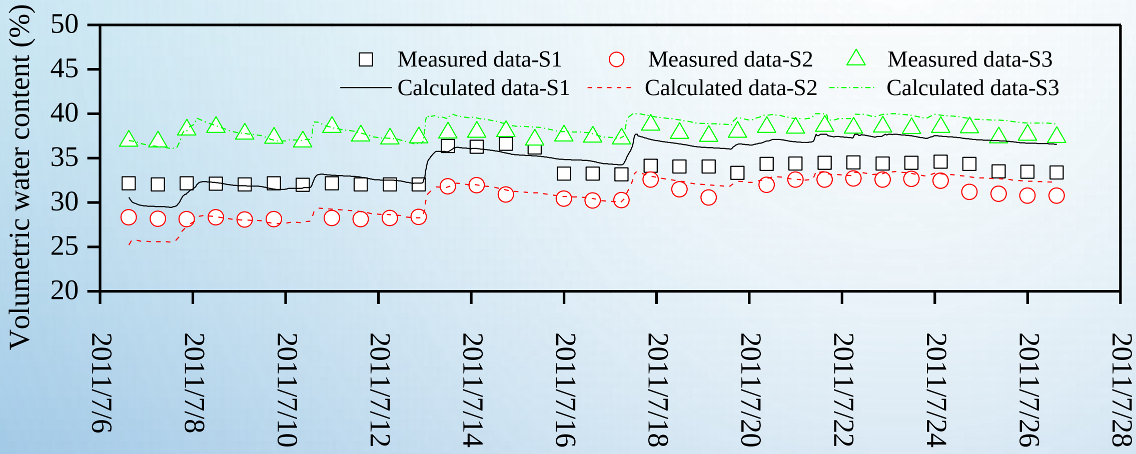


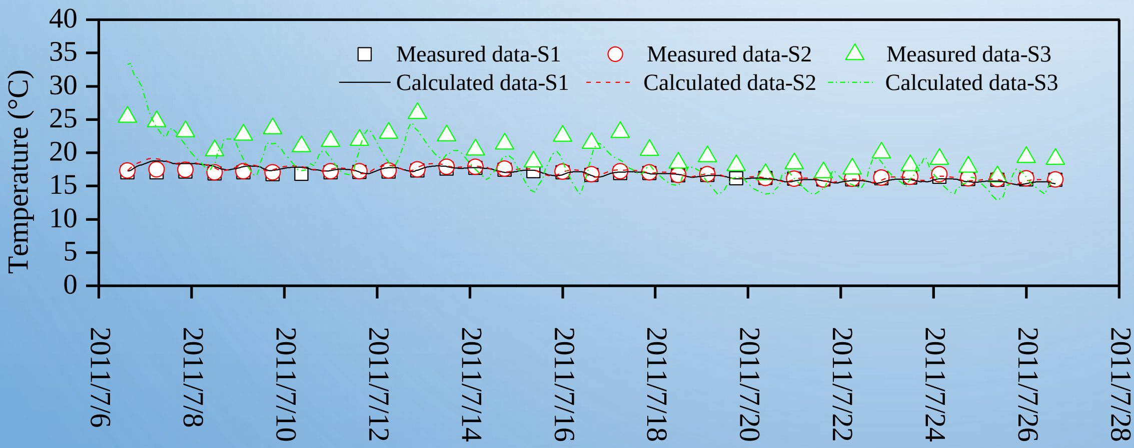


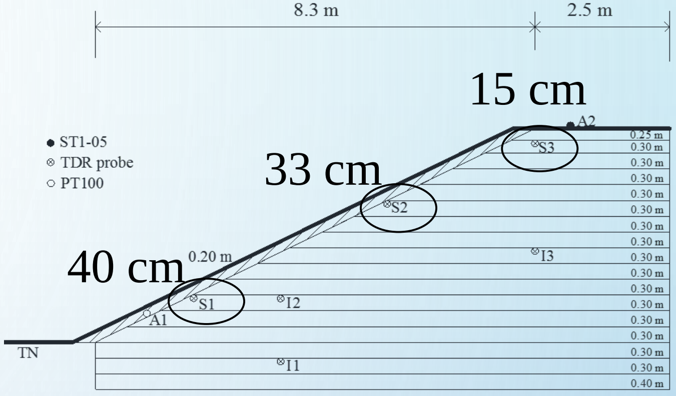


Results and analysis: Group 2

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 !