Journal of Zhejiang University-SCIENCE A

Laboratory and numerical study on an enhanced evaporation process in a loess soil column subjected to heating

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Cite this as: Xiao-chuan Liu, Wen-jie Xu, Liang-tong Zhan, Yun-min Chen, 2016. Laboratory and numerical study on an enhanced evaporation process in a loess soil column subjected to heating. *Journal of Zhejiang University SCIENCE A (Applied Physics & Engineering)*, 17(7):553-564. http://dx.doi.org/10.1631/jzus.A1600246

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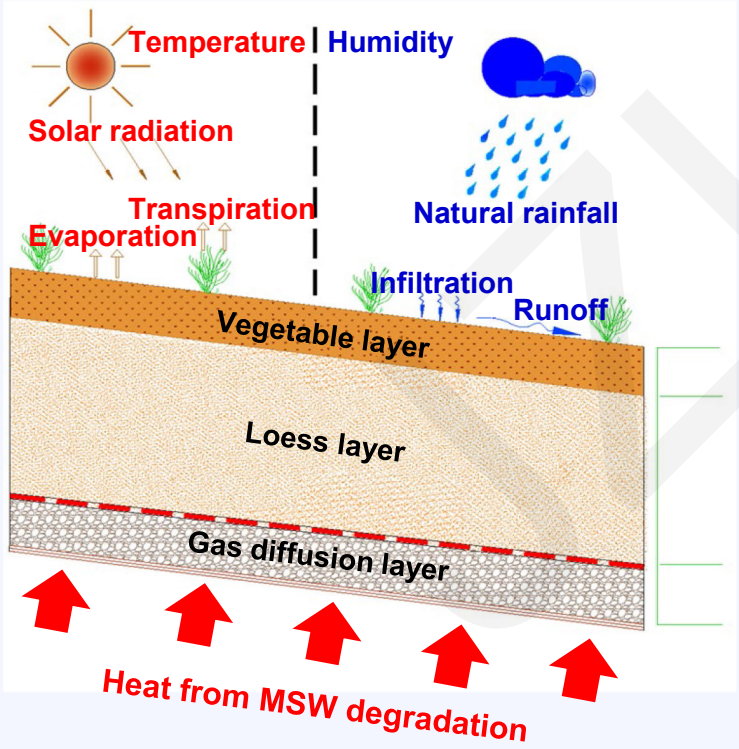
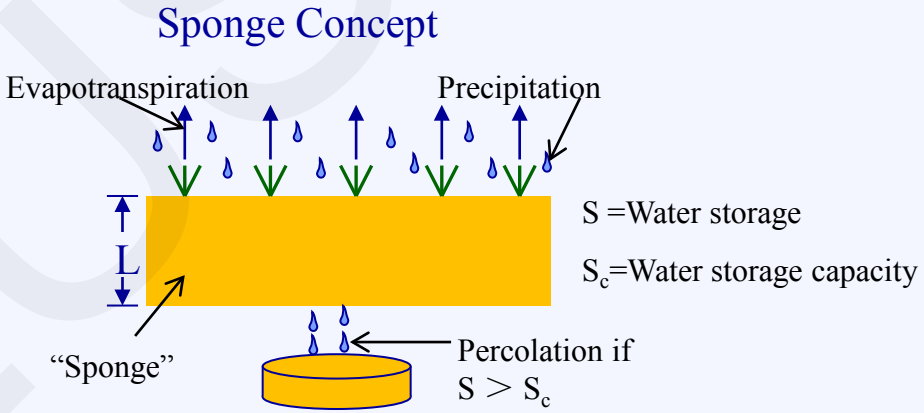
Introduction

Principles & advantages of earthen final covers

- The working principle of EFCs is like a sponge.
- The water vapor diffusion can be enhanced by the heating from municipal solid waste, and significantly impact the evaporation process in the earthen final cover.

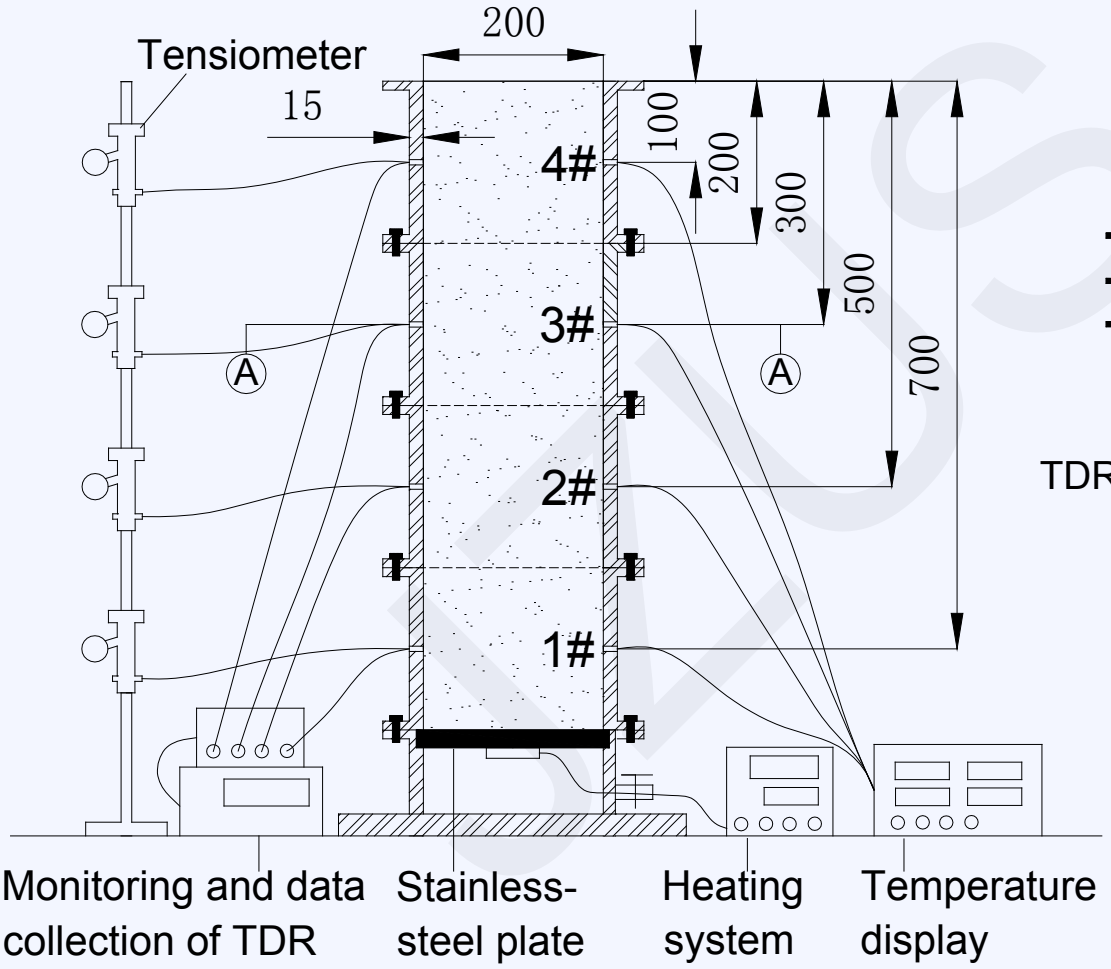


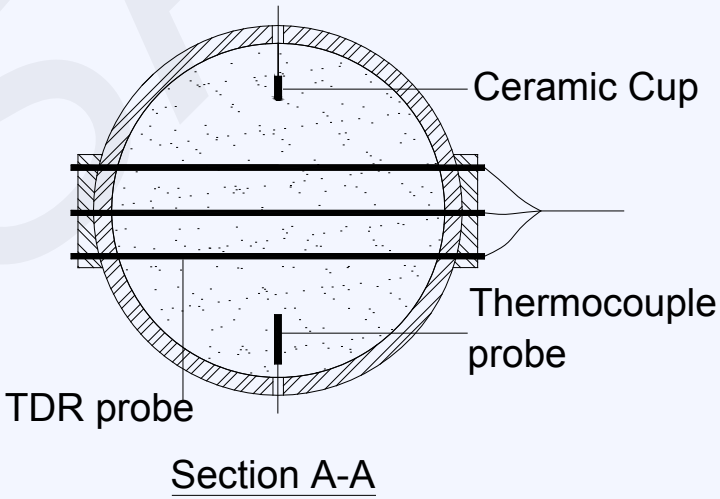




Laboratory experiment

Instrumentation

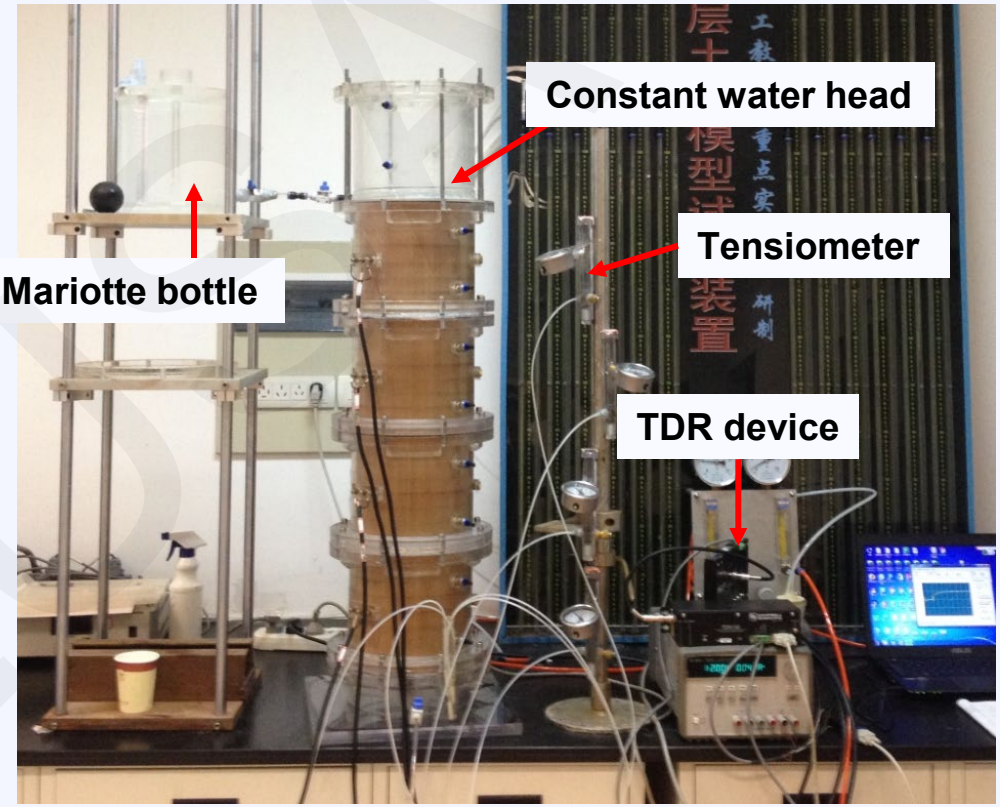




Laboratory experiment

Testing procedure

- **Infiltration**
  - 5 cm constant water head
  - Opening bottom
- **Evaporation**
  - Open top and Sealed bottom
  - Constant temperature was controlled at 70 ℃



Numerical study

Governing equations

$$n\left(\rho^{w}-\rho^{gw}\right)\left(\frac{\partial S_{w}}{\partial p^{c}}\frac{\partial p^{c}}{\partial t}\right)+\left(1-S_{w}\right)n\left(\frac{\partial \rho^{gw}}{\partial p^{c}}\frac{\partial p^{c}}{\partial t}\right)-\mathrm{div}\left(\rho^{g}\frac{M_{a}M_{w}}{M_{g}^{2}}\mathbf{D}\mathrm{grad}\left(\frac{p^{gw}}{p^{c}}\right)\right)$$

$$+\mathrm{div}\left(\rho^{w}\frac{\boldsymbol{k}k^{rw}}{\mu^{w}}\left[-\mathrm{grad}(p^{g})+\mathrm{grad}(p^{c})+\rho^{w}\boldsymbol{g}\right]\right)+\mathrm{div}\left(\rho^{gw}\frac{\boldsymbol{k}k^{rg}}{\mu^{g}}\left[-\mathrm{grad}(p^{g})+\rho^{g}\boldsymbol{g}\right]\right)=0$$

Water phase balance

$$-n\rho^{ga}\left(\frac{\partial S_{w}}{\partial T}\frac{\partial T}{\partial t}+\frac{\partial S_{w}}{\partial p^{c}}\frac{\partial p^{c}}{\partial t}\right)+\left(1-S_{w}\right)n\left(\frac{\partial \rho^{ga}}{\partial T}\frac{\partial T}{\partial t}+\frac{\partial \rho^{ga}}{\partial p^{c}}\frac{\partial p^{c}}{\partial t}+\frac{\partial \rho^{ga}}{\partial p^{g}}\frac{\partial p^{g}}{\partial t}\right)$$

$$-\mathrm{div}\left(\rho^{g}\frac{M_{a}M_{w}}{M_{g}^{2}}\mathbf{D}\mathrm{grad}\left(\frac{p^{ga}}{p^{c}}\right)\right)+\mathrm{div}\left(\rho^{ga}\frac{\boldsymbol{k}k^{rg}}{\mu^{g}}\left[-\mathrm{grad}(p^{g})+\rho^{g}\boldsymbol{g}\right]\right)=0$$

Gas phase balance

$$C\rho\frac{\partial T}{\partial t}+(C^{w}\rho^{w}\mathbf{v}^{w}+C^{g}\rho^{g}\mathbf{v}^{g})\mathrm{grad}T-\mathrm{div}\left(\boldsymbol{\lambda}\mathrm{grad}T\right)=q_{th}$$

Energy balance

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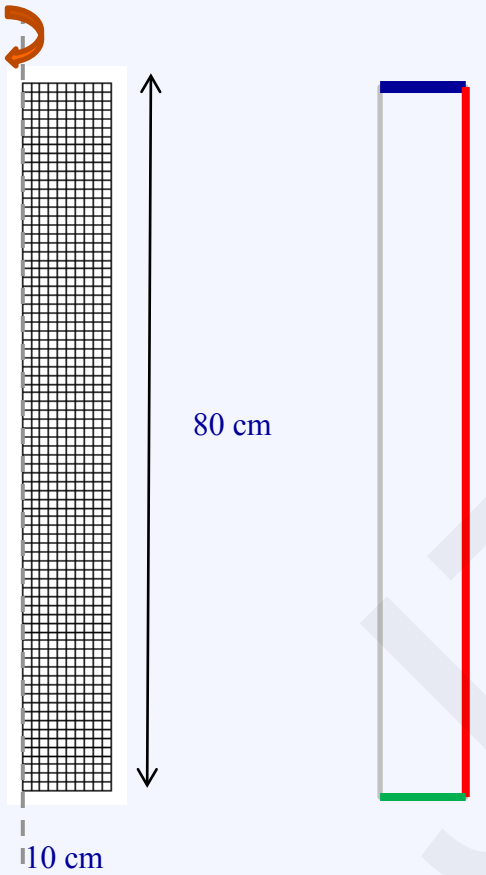
Numerical study

FEM model and boundary conditions



Evaporation BC

$$E_a = E_p \frac{H_s - H_r}{1 - H_r}$$

$$= \left(a + b \cdot n_{wind}\right)\left(100 - H_r\right)\frac{H_s - H_r}{1 - H_r}$$

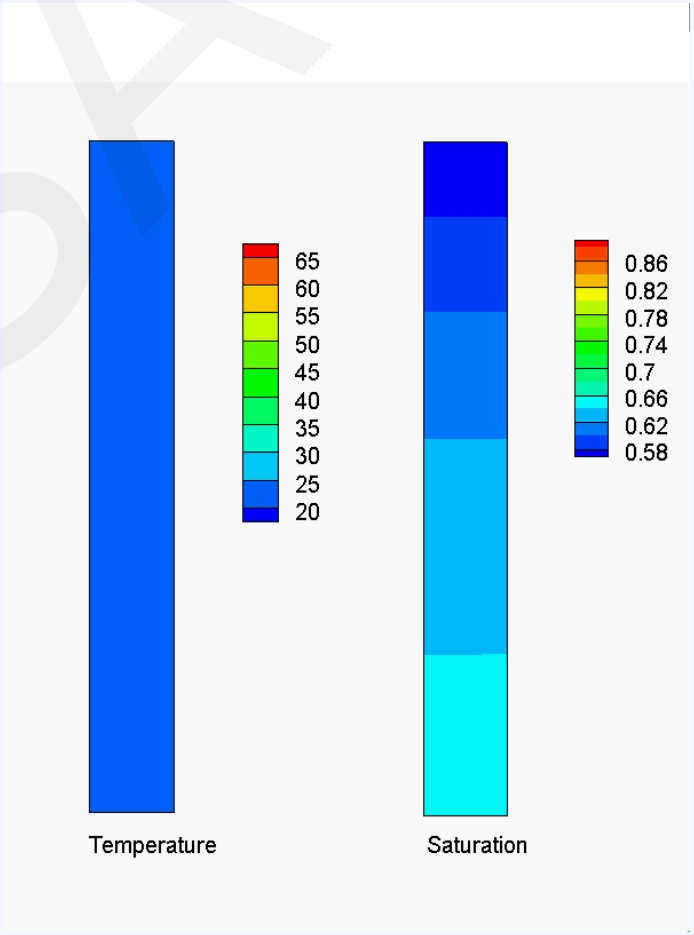
Heat transport BC

$$q_{th} = h\left(T_a - T_s\right)$$

Temperature BC

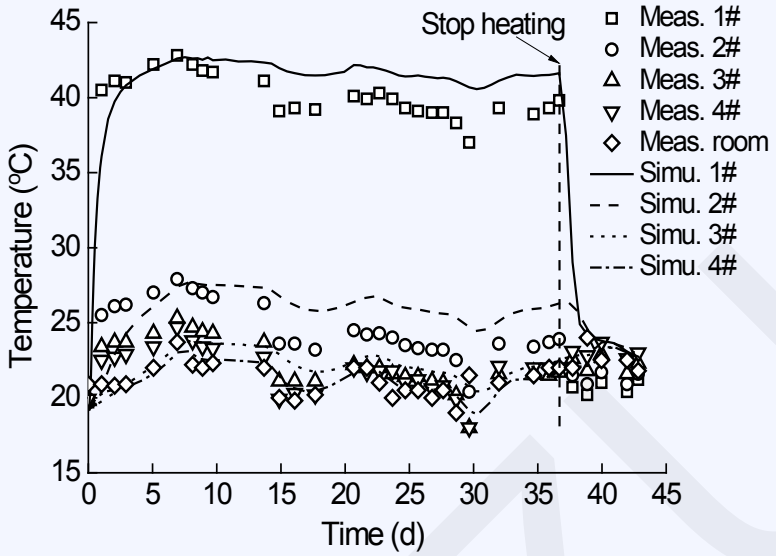
$T = 70\,°C$

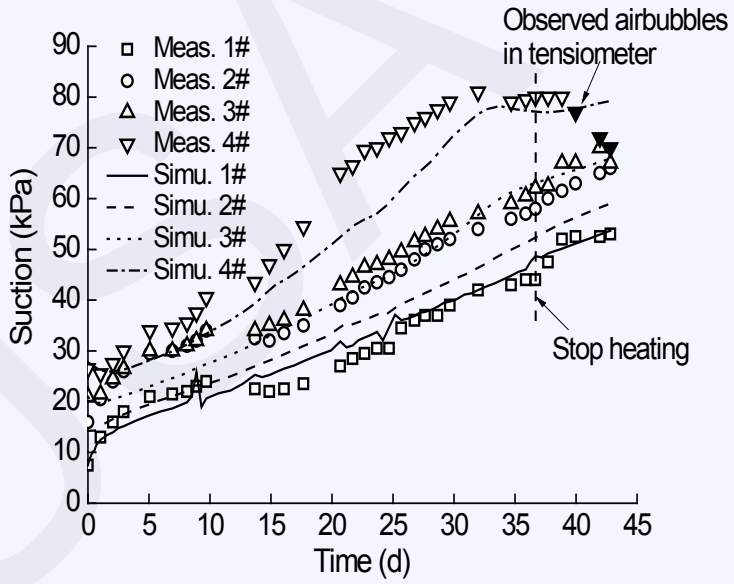
when Time < 880 *hours*

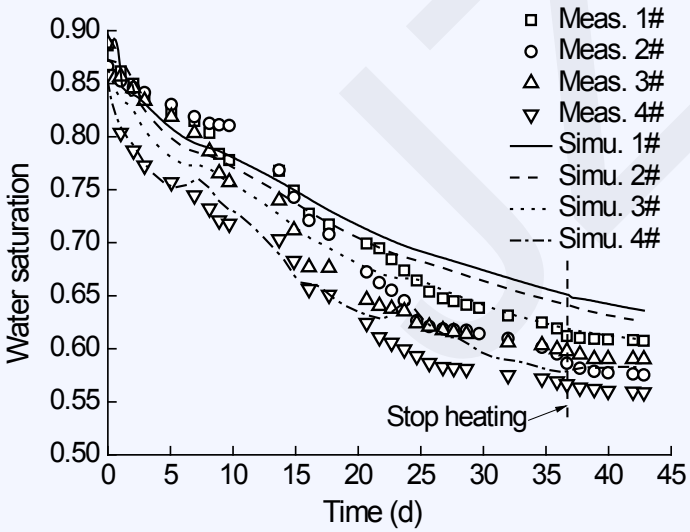


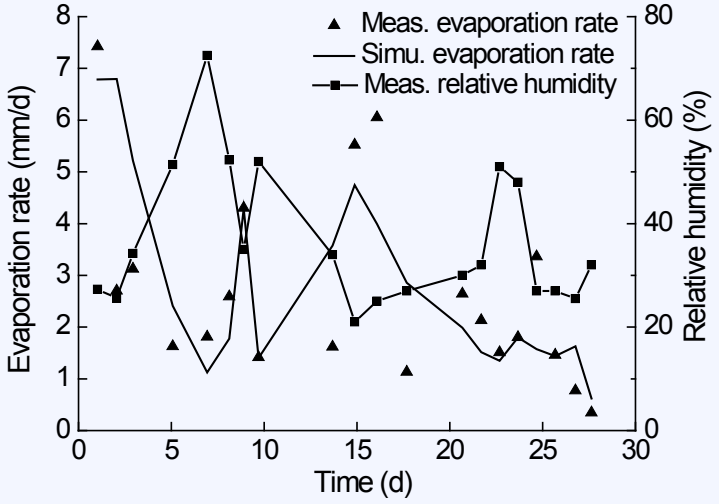
Numerical study

Results



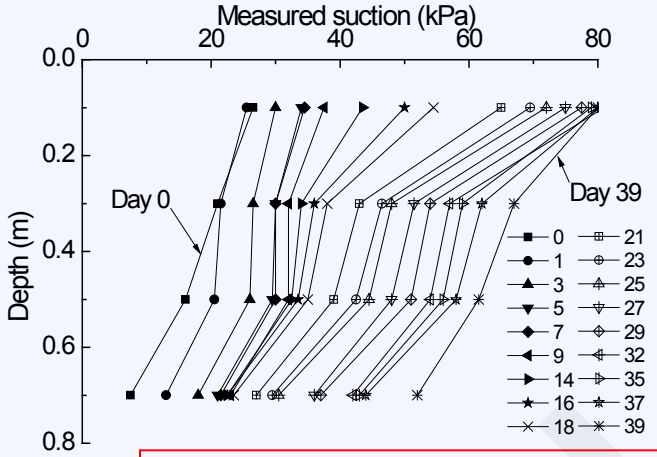


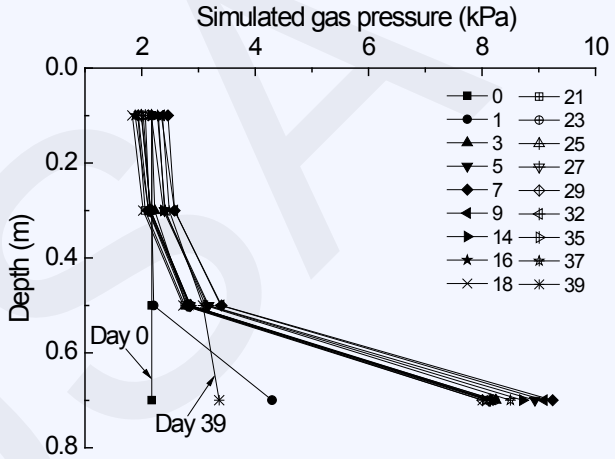




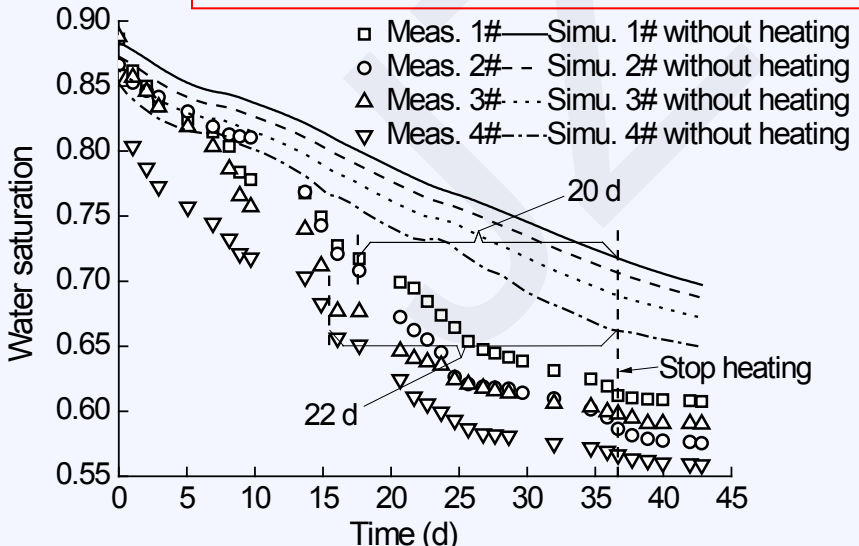
Numerical study

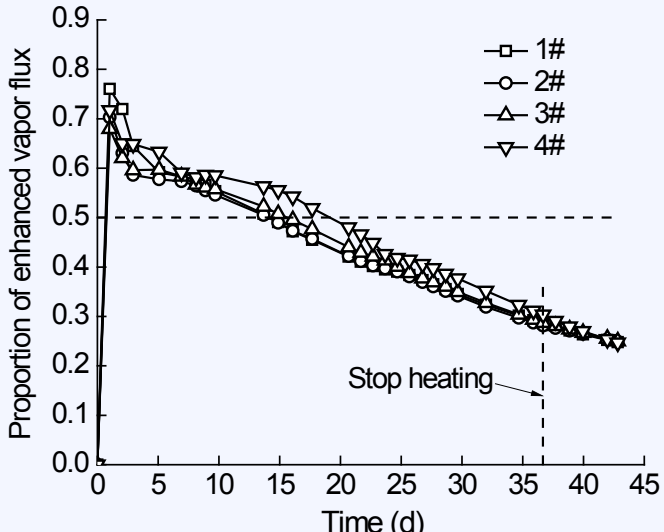
Results





$$W_{\text{Heating}}^{t} = \frac{(S_{\text{w}}^{0} - S_{\text{w, heating}}^{t}) - (S_{\text{w}}^{0} - S_{\text{w, non-heating}}^{t})}{S_{\text{w}}^{0} - S_{\text{w, heating}}^{t}} = \frac{S_{\text{w, non-heating}}^{t} - S_{\text{w, heating}}^{t}}{S_{\text{w}}^{0} - S_{\text{w, heating}}^{t}}$$





Conclusions

- The tortuosity τ of the tested loess for vapor diffusion and the parameter a of the empirical evaporation function were obtained by back analysis using the proposed numerical model. Finally, the tortuosity τ and parameter a were defined as 0.65 and 0.022 mm/d, respectively.
- The heating of the bottom accelerated the drying process of the soil column by almost 22 d compared with the conditions without heating, which indicated that the proposed new method is time- saving. The water vapor diffusion was significantly enhanced by the bottom heating.
- Before Day 15 the proportions of enhanced vapor flux in the total water loss with heating were always higher than 50%, which indicated that water vapor diffusion dominated the evaporation process at this period. After Day 15, the proportions decreased from 50% to 25%.

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