Numerical investigation of soil-atmosphere interaction in an experimental embankment

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ABSTRACT: An experimental embankment was constructed at Héricourt in France with complete information recorded from 06/07/2011 to 26/07/2011, including meteorological data (solar radiation, rainfall, wind speed, air temperature, relative humidity, etc.) and soil variables (volumetric water content and temperature). A numerical approach combining the coupled hydro-thermal model and soil-atmosphere interaction model is adopted to study the interaction between soil and atmosphere in this experimental embankment. In this study, the water and heat transfers between soil and atmosphere are analyzed in-depth. Moreover, it is suggested that the influence depth of climate in terms of soil volumetric water content and temperature needs to be estimated separately.

1 INTRODUCTION

In geotechnical and geo-environmental engineering for constructions undergoing the effect of climate changes, it is necessary to study the soil-atmosphere interaction in order to assess the subsequent variations of soil thermo-hydro-mechanical behavior and to further evaluate the constructions' durability. The interaction between soil and atmosphere can be reflected by the water and heat transfers between soil and atmosphere and described by the variations of soil surface boundary conditions (Blight 1997).

Water and heat transfers in soil are normally coupled and synchronously influence the soil volumetric water content and temperature. This aspect was widely studied and various hydro-thermal or thermo-hydro-mechanical (THM) coupled models were proposed (Luikov 1961, Dakshanamurthy and Fredlund 1981, Thomas 1985, Wilson 1990, Wilson et al. 1994, Thomas and King 1994, Fayer 2000, Saito et al. 2006, Seetharam et al. 2007, Bittelli et al. 2008, Cui et al. 2010, Hemmati et al. 2012). These models were found to give good estimations of soil volumetric water content/suction and temperature variations. Nevertheless, merely soil-atmosphere interaction was taken into account. Moreover, the above-mentioned studies have not yet addressed soil hydro-thermal behavior in two dimensions even though it is essential for some earth constructions as embankments.

In this paper, a numerical approach combining a fully coupled hydro-thermal soil model and a soil-atmosphere interaction model is adopted to estimate the water and heat boundary conditions at the soil-atmosphere interfaces. Through the numerical modelling, the influence depth of climate in terms of soil volumetric water content and temperature is further discussed.

2 FILED MONITORING

An embankment was constructed at Héricourt in Franche-Comté region within a France national ANR project – TerDouest (Froumentin 2012). The field view of this embankment is presented in Figure 1a. It has a total length of 107 m, a height of 5 m, a slope of 1:2 (Vertical: Horizontal) for the two sides. Specifically, this embankment includes two parts: lime/cement treated clay and lime/cement treated silt parts with the same length of 53.5 m. The cross section of this studied embankment with details is drawn in Figure 1b.

2.1 *Soil monitoring*

In this study, the lime/cement treated silt part is selected to investigate the soil-atmosphere interaction. As presented in Figure 1b, soil temperature and volumetric water content were measured using TDR every three hours for the studied points (points P1, P2 and P3). During construction, a 20cm soil layer was added on the slopes to maintain the sensors near the surface. More information related to the construction and monitoring of this embankment can be found in the report by Froumentin (2012).

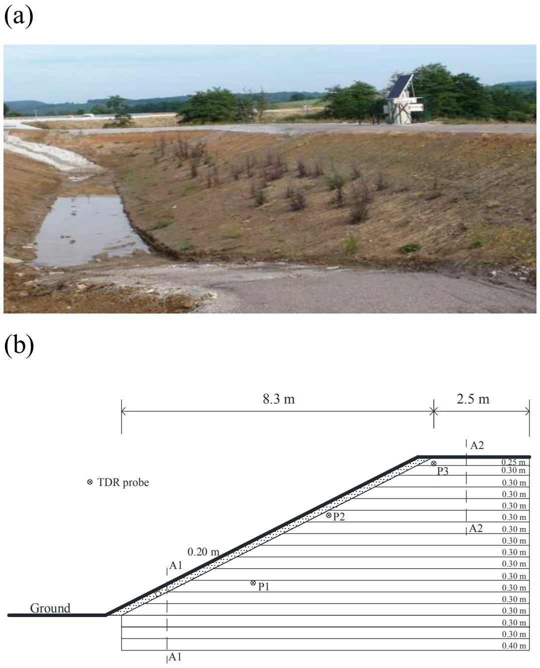

Figure 1. (a) Field site view of Héricourt embankment in 06/2011; (b) Cross section of embankment and its instrumentation: TDR sensors for recording soil volumetric water content and temperature variations (points P1~3)

2.2 *Meteorological data*

This embankment is situated in a region with continental climate influenced by ocean. A weather station was installed on the top of this embankment, recording meteorological data half-hourly: solar radiation, rainfall, wind speed, air relative humidity and temperature at the height of 0.5 m, etc. Besides, runoff occurred when the rainfall rate exceeded the infiltration rate at soil surface. Its value was collected hourly by a continuous measurement system on the slope surface (An et al. 2017b).

Data recorded from 06/07/2011 to 26/07/2011 is complete including all meteorological data, runoff and soil variables (volumetric water content/temperature). Thereby, this period of 20 days is chosen in this study. Figure 2 presents the information of meteorological data and runoff during the studied period.

3 NUMERICAL MODELLING

In the numerical modelling of Héricourt embankment, several assumptions are made for simplification: 1) Soil is assumed to be homogeneous and isotropic in the whole embankment; 2) The positions of sensors for recording soil temperature and volumetric water content are assumed to be at the right place shown in Figure 1b; no offset of sensors during the construction happened; 3) The water and heat flux boundary conditions are assumed to be the same for all points at the same surface boundaries; 4) The surface of field embankment is bare; no vegetation effect is considered.

3.1 *The numerical approach*

The adopted numerical approach includes two parts: coupled hydro-thermal soil model and soil-atmosphere interaction model. The coupled hydro-thermal soil model proposed by An et al. (2017a) is adopted. The details are not presented here due to the length limitation. Soil-atmosphere interaction model is applied to describe the water and heat transfer between soil and atmosphere, allowing the estimation of water and heat boundary conditions at soil-atmosphere interfaces (Blight 1997).

3.1.1 *Mass balance*

The mass balance at the soil surface is expressed as:

$$P = I_{nf} + R_{off} + E_a + I_{nt} \tag{1}$$

where P (m/s) is the rainfall; I_{nf} (m/s) is the infiltration rate; R_{off} (m/s) represents the runoff rate on soil surface; E_a (m/s) is the actual evaporation rate; I_{nt} (m/s) is the rate of water intercepted by plants. In this study, field rainfall was monitored half hourly by the weather station (Figure 2b). Runoff was collected hourly as shown in Figure2f. Evaporation is estimated using the method developed by Song (2014),

$$\frac{E_a}{E_p} = \frac{e_0 - e_a}{e_s - e_a} \tag{2}$$

$$E_p = (a + bu)(100 - h_a) \tag{3}$$

where E_{p} (m/s) represents potential evaporation; u (m/s) is wind speed; h_{a} is relative humidity; a and b are empirical parameters: a= 0.022, b= 0.031 (Song, 2014). Soil surface vapor pressure e_0, saturation vapor pressure at soil surface $e_{\mathrm{s},}$ air vapor pressure e_{a} and relative humidity of soil surface h_s calculation are related intimately with the soil surface temperature and suction. The details can be found in An et al. (2017a). As there is no vegetation effect considered for this embankment, I_{nt} is equal to zero. Depending on this method, the water flux boundary condition I_{nf} at soil surface can be determined continuously.

3.1.2 *Energy balance*

As far as the heat transfer is concerned, solar radiation is the only exterior heat resource. The net solar radiation is equal to the sum of latent heat, soil heat and sensible heat. The energy balance at the soil surface is expressed as (Blight 1997):

$$R_n = G + L_E + H \tag{4}$$

where R_{n} (W/m^2) is the net radiation flux; G (W/m^2) is the soil heat flux; L_{E} (W/m^2) is the latent heat flux which represents the product of the evaporative flux E_a (m/s) and the latent heat of vaporization of water L_v (J/kg); H (W/m^2) is the sensible heat flux.

The method to determine net solar radiation in half hourly without soil temperature is adopted here (An et al., 2017), considering the measured solar radiation R_{si} (W/m^2) (Figure 2a) and the recorded air temperature (Figure 2e). Besides, latent heat and sensible heat are calculated respectively by (Blight 1997):

$$L_E = L_v E_a \tag{5}$$

$$H = \rho_a c_p K_H \left(\frac{\partial T_a}{\partial z} \right) \tag{6}$$

where L_E (W/m^2) is the latent heat flux which represents the product of the evaporative flux E_a (m/s) and latent heat of vaporization of water L_v (J/kg); H (W/m^2) is the sensible heat flux; ρ_a (kg/m^3) is the air density; c_p (J/(kg·K)) is the specific heat of air; K_H (m^2/s) is the eddy diffusivity for heat through air; $\left(\frac{\partial T_a}{\partial z} \right)$ is the vertical temperature gradient in the air near soil surface.

Based on the energy balance, the value of soil heat flux G is calculated and applied as the heat flux boundary condition at the soil and atmosphere interfaces.

3.2 *Model dimensions*

Through analyzing four different dimensions for this embankment, An et al. (2016) proposed the proper dimensions (Figure 3) after concluding that the effect of model dimension is not significant for the study of soil hydro-thermal behavior in two-dimensional embankments. The initial conditions of this numerical modelling are set depending on the measurements of soil volumetric water content and temperature at the initial moment of the studied period. The bottom boundary (BC3) is assumed to keep a saturated state with a constant temperature. No water and heat transfers are considered at the lateral boundaries (BC2 and BC6). The water and heat boundary conditions at the soil-atmosphere interfaces (BC3, BC4 and BC5) are determined depending on the soil-atmosphere interaction model introduced above.

The validation work of this numerical approach has been conducted depending on the calculations and measurements of soil volumetric water content and temperature at the studied points as introduced by An et al. (2017a).

3.3 *Soil parameters*

The hydro-thermal properties of treated silt are required for the numerical analysis. The thermal

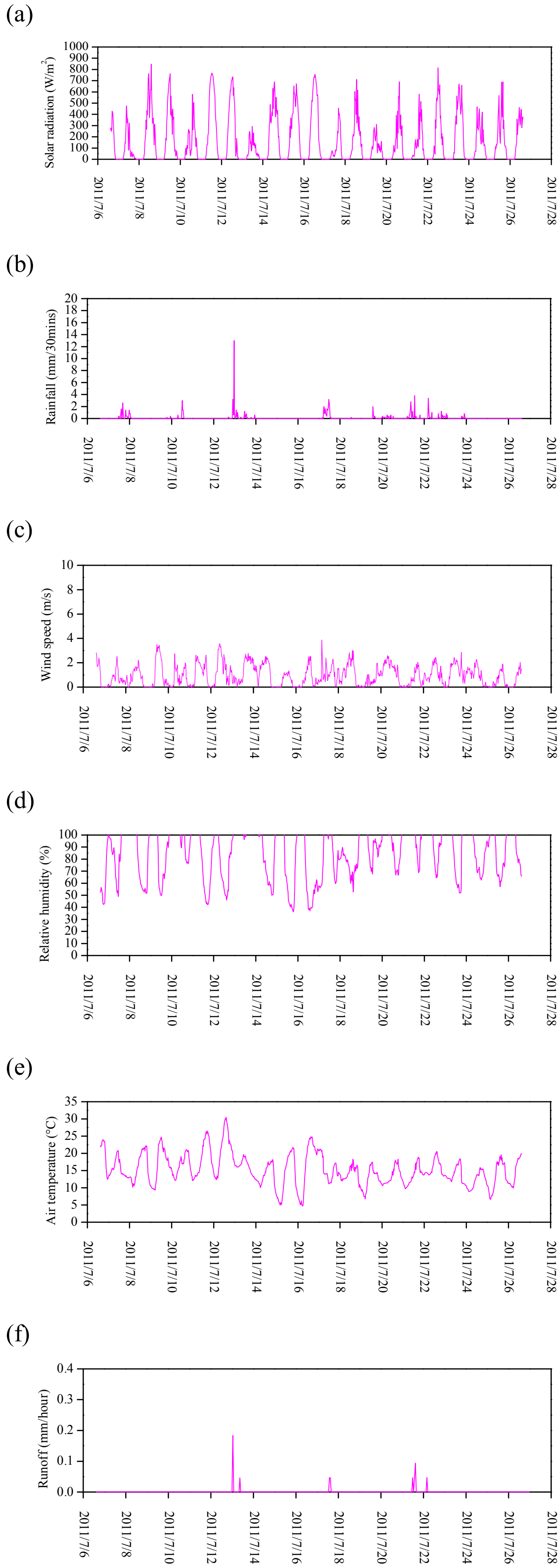

Figure 2. Field meteorological data from 06/07/2011 to 26/07/2011: (a) solar radiation; (b) rainfall; (c) wind speed; (d) relative humidity at 0.5 m above the embankment surface; (e) air temperature at 0.5 m above the embankment surface; (f) runoff measured on the slope surface

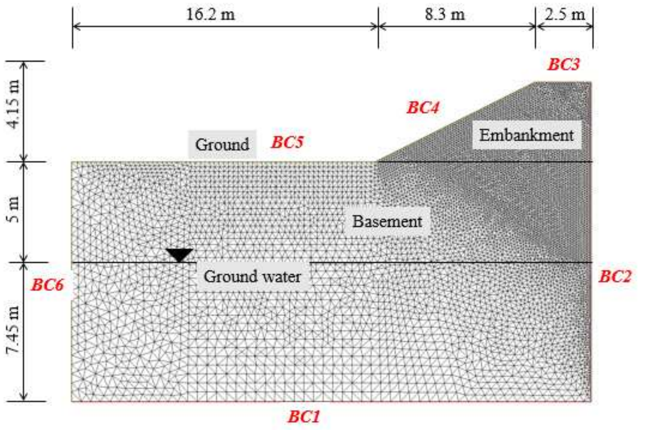

Figure 3. Numerical model dimensions for Héricourt embankment with mesh indication

conductivity, soil water retention curve and hydraulic conductivity of the studied treated silt are determined and presented below (An et al. 2017a) .

A linear relationship between soil thermal conductivity and volumetric water content is chosen for the studied treated silt (Figure 4a):

$$\lambda = 2.1818 \cdot \theta + 0.808 \tag{7}$$

where λ (W/(m·K)) is soil thermal conductivity; θ is soil volumetric water content.

Based on van Genuchten model (van Genuchten 1980), the expression for the soil water retention curve is built:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\varphi)^n} \right]^m \tag{8}$$

where the saturated volumetric water content $\theta_s = 0.4$; the residual volumetric water content $\theta_r = 0.004$; parameters $\alpha = 0.003$ kPa^{-1}, $m = 0.18$ and $n = 1.8$. With the measurement data, a fitting curve is drawn as shown in Figure 4b.

As shown in Figure 4c, the soil hydraulic conductivity at unsaturated state can be estimated using van Genuchten model (van Genuchten 1980) as:

$$K = K_s S_e^{0.5} \left[1 - \left(1 - S_e^{1/m_1} \right)^{m_1} \right]^2 \tag{9}$$

where $m_1 = 0.5$; saturated hydraulic conductivity $K_s = 10^{-9}$ m/s; other parameters have the same values as for Formula 8.

As for the 20 cm soil layer added on the slope of embankment, its thermal conductivity is assumed to be 0.25 W/(m·K) and its hydraulic conductivity is taken equal to 10^{-8} m/s. Its soil water retention curve is regarded as the same as that of the treated silt.

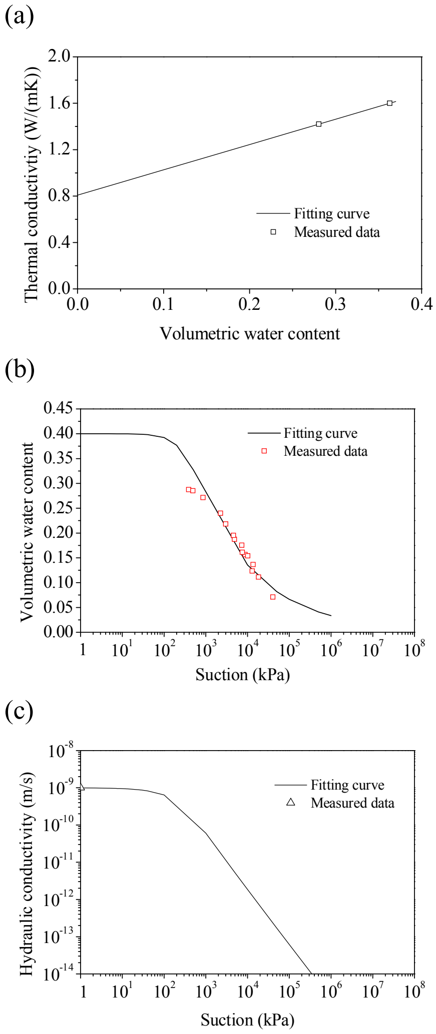

Figure 4. Soil parameters: (a) soil thermal conductivity curve versus volumetric water content; (b) soil water retention curve; (c) hydraulic conductivity versus suction

4 RESULTS AND DISCUSSION

4.1 *Water and heat transfers between soil and atmosphere*

Depending on soil-atmosphere interaction model, water and heat flux boundary conditions at soil-atmosphere interfaces can be determined. As they are related intimately with the values of surface soil volumetric water content/suction and temperature, their values are iterated at each time step during the numerical modelling. Other boundaries interacting with atmosphere (BC4 and BC5) own the similar water and heat flux conditions. The details of water and heat transfers between soil and atmosphere at the top surface of this embankment (BC3) are presented in Figure 5 and Figure 6, respectively.

The runoff value was recorded by the runoff collector system (Figure 2f). As shown in Figure 5a, the rainfall and infiltration are in the same order of magnitude 10^{-6} m/s, much larger than the evaporation and runoff values 10^{-8} m/s (Figure 5b). Therefore, it is obvious that rainfall is able to affect the water flux boundary effectively. The infiltration represents the value of water flux boundary condition on the top surface. Its positive value means that water flows into soil. By contrast, water evaporates from soil to atmosphere when it is negative.

The heat transfer between soil and atmosphere can be reflected by the variations of different heat fluxes introduced in energy balance at soil-atmosphere interface. Figure 6 shows that soil heat flux is governed by the net solar radiation with positive values during day time and negative values during night time (Figure 6a). Latent heat flux represents the energy consumed by evaporation and is negative (Figure 6b) during the whole period. Sensible heat flux represents the energy supplied by sun to heat air. When it is negative, soil temperature is higher than air temperature. Relying on the energy balance, soil heat flux can be estimated by net solar radiation, latent and sensible heat fluxes together.

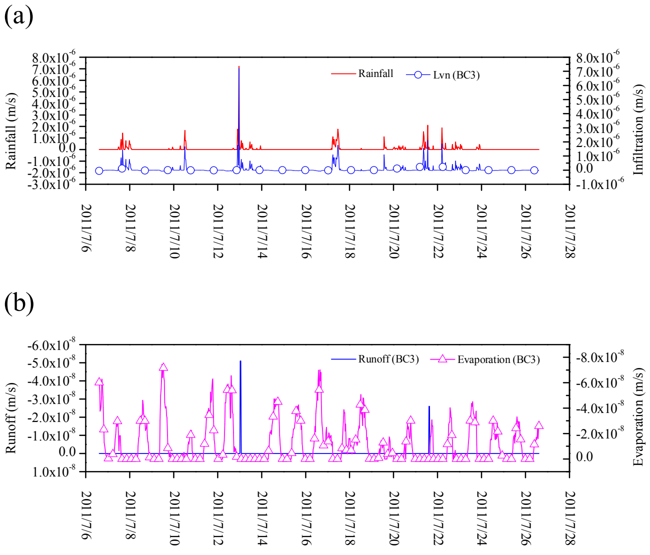

Figure 5. Water fluxes at the top soil surface of Héricourt embankment (BC3): (a) rainfall and infiltration; (b) runoff and evaporation.

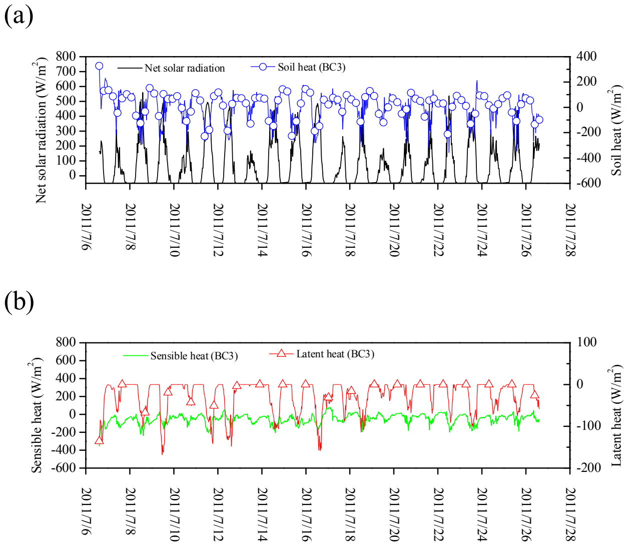

Figure 6. Heat fluxes at the top soil surface of Héricourt embankment (BC3): (a) net solar radiation and soil heat; (b) sensible heat and latent heat

4.2 *Influence depth of climate in terms of soil volumetric water content and temperature*

With the accurate estimation of water and heat boundary conditions, soil volumetric water content and temperature can be easily determined through numerical modelling. In the field situation, it is time and economy consuming to identify the influence depth of climate in terms of volumetric water content and temperature. Numerical modelling can be applied for this purpose. In this study, section A1 and section A2 are selected as shown in Figure 1b. Figures 7 and 8 illuminate the variations of soil volumetric water and content temperature profiles at these two sections, respectively.

In Figure 7, it is observed that the influence depths in terms of soil volumetric water content at sections A1 and A2 are estimated to be 2 m (Figure 7a) and 3 m (Figure 7b), respectively. Specifically, the soil volumetric water content at the depth of 4 m at section A1 varies due to the effect of underground water table as indicated in Figure 3. Nevertheless, Figure 8 reveals that the soil temperatures below the depth of 4 m at both sections A1 and A2 keep nearly stable and are not influenced by the surface boundary conditions. Larger variations can be identified for the temperatures at section A2 as compared to those at section A1, showing the contribution of the slope surface boundary conditions.

The results reveal that the slope surface boundary conditions have a larger effect on soil temperature than on volumetric water content variations. This can be explained as follows: heat is transferred homogeneously in all directions in a homogeneous material while soil volumetric water content variation is dominantly controlled by the vertical water flow due to the gravity effect. Therefore, it is recommended to investigate the influence depths in terms of soil volumetric water content and temperature separately in different zones of the two-dimensional embankment, because the temperature changes are related to the thermal boundary condition while the volumetric water content changes are governed by the hydraulic boundary condition.

5 CONCLUSIONS

Due to soil-atmosphere interaction, the water flux boundary condition at soil surface is affected by rainfall effectively, whilst the soil heat flux needs to be estimated by net solar radiation, latent heat and sensible heat fluxes together.

In addition, the effects of climate conditions are limited to different depths in terms of soil volumetric water content and temperature. The case of the Héricourt embankment shows that the influence depth of climate in terms of soil volumetric water content and temperature needs to be estimated separately.

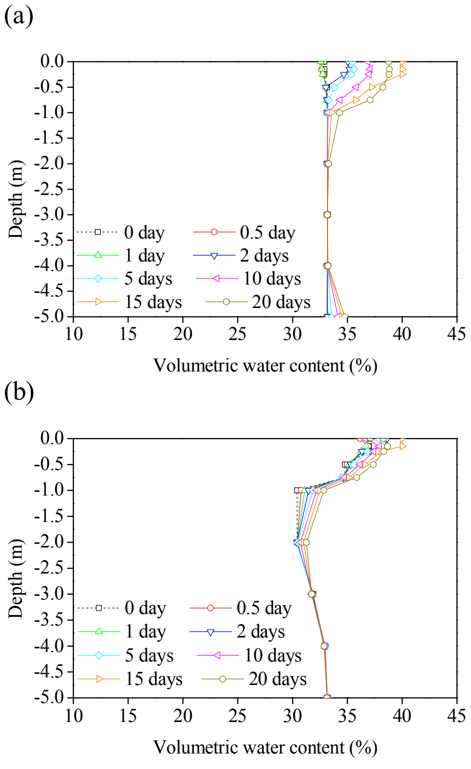

Figure 7. Soil volumetric water content profiles at different times: (a) section A1 and (b) section A2

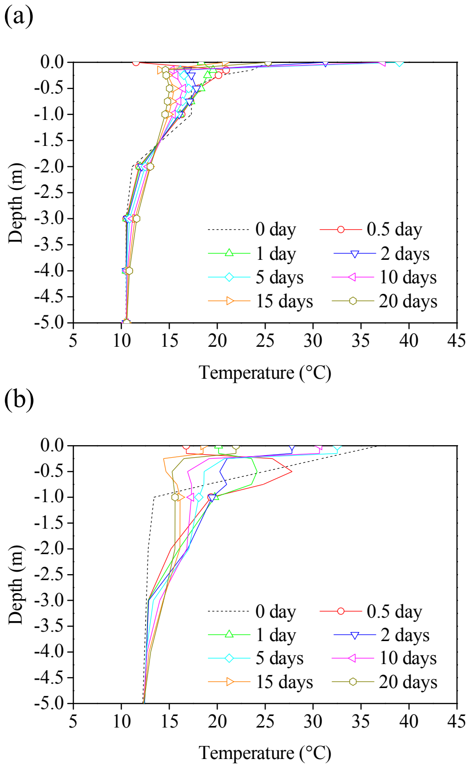

Figure 8. Soil temperature profiles at different times: (a) section A1 and (b) section A2

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