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Research Paper

Numerical analysis of soil volumetric water content and temperature variations in an embankment due to soil-atmosphere interaction

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ABSTRACT

In this study, soil volumetric water content and temperature variations are analyzed in an embankment constructed at Héricourt in France. A fully coupled hydro-thermal soil model is developed allowing two dimensional analysis. With meteorological data, soil surface heat flux and water flux boundary conditions are estimated considering soil-atmosphere interaction. Comparisons between measurements and simulations reveal the relevance of the proposed approach, in particular in terms of suitable boundary conditions and soil parameters. Both field monitoring and numerical modeling indicate that the influence depth of soil-atmosphere interaction is limited for volumetric water content, but it is much greater for temperature.

1. Introduction

In geotechnical and geo-environmental engineering for constructions undergoing the effect of climate changes, it is essential to determine the temperature and water content/suction changes in soil in order to assess the subsequent changes in the soil thermo-hydro-mechanical behavior and to further analyze the durability of constructions. Generally, soil temperature and volumetric water content are measured by buried sensors for targeted period. However, unpredictable problems during sensors' operation in the long-term period may happen. Moreover, for near soil surface region, direct monitoring of volumetric water content and especially suction may have difficulties [1]. In these cases, indirect numerical methods are of great help in assessing the direct measurements and in predicting the long-term variations. To the author's knowledge, only a few researchers [1–6] tried to predict the variations in both temperature and volumetric water content/suction indirectly by considering soil-atmosphere interaction. In this indirect method involving hydro-thermal coupled soil model, it is important to apply rational boundary conditions at the soil-atmosphere interface.

Soil surface boundary conditions depend on soil-atmosphere interaction. Blight [7] proposed the mathematical expression of soil-atmosphere interaction relying on energy and mass balance, with infiltration/evaporation applied directly as the surface water flux boundary condition. Infiltration can be calculated based on meteorological data and soil surface condition. The evaporation process at soil surface has been studied widely [8–12]. Regarding the surface heat flux boundary condition, it needs to be estimated based on energy balance with net solar radiation, sensible heat and latent heat [1,5,7,13–15].

Heat and mass transfer in soil are normally coupled. This aspect was widely studied and various hydro-thermal or thermos-hydro-mechanical (THM) coupled soil models were proposed [2,4–6,9,15–23]. Hydro-thermal coupled soil model was proposed initially to study the hydro-thermal behavior of unsaturated soils, especially soil moisture content changes under temperature gradients [9,16–19]. Coupled THM models were proposed to account for the deformability of soils under the combined thermo-hydro-mechanical effects [5,21,22]. These models were found to give good predictions of soil temperature and volumetric water content/suction variations. Nevertheless, merely the effect of climate changes was taken into account. Moreover, none of the above-mentioned studies addressed soil hydro-thermal behavior in two dimensions even though it is essential for some earth constructions as embankments.

In this study, a treated soil embankment is analyzed. Considering the negligible volume change measured (the mean vertical strain was found to be less than 0.3%), the analysis focus on the soil

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Nomenclature

C	volumetric heat capacity of the soil (J/(m^3·K))	Q	transferred heat flux through soil-atmosphere interface (W/m^2)
$C_{T\varphi}$	volumetric isothermal capacity of the structure (J/(m^3·K))	q	density of moisture flow rate (kg/(m^2·s))
C_T	volumetric thermal capacity of the structure (J/(m^3·K))	q_l	liquid flux density (kg/(m^2·s))
$C_{\varphi T}$	volumetric thermal capacity of moisture (kg/(m^3·K))	q_v	vapor flux density (kg/(m^2·s))
C_φ	volumetric isothermal capacity of moisture (kg/(m^3·K))	R	universal gas constant (8.31432 (J/(mol·K))
$c_{\rho l}$	specific heat capacity of water liquid (J/(kg·K))	R_{sa}	extraterrestrial solar radiation (W/m^2)
$c_{\rho s}$	specific heat capacity of structure (J/(kg·K))	R_{s0}	solar radiation in clear sky (W/m^2)
$c_{\rho v}$	specific heat capacity of pore vapor (J/(kg·K))	R_{si}	solar radiation (W/m^2)
$c_{\rho a}$	specific heat capacity of air (J/(kg·K))	R_{off}	runoff rate on soil surface (m/s)
K_H	eddy diffusivity for heat through air (m^2/s)	R_n	net radiation flux (W/m2)
D_{atm}	molecular diffusivity of vapor in the air (m^2/s)	T	absolute temperature (K)
D_{Tv}	thermal vapor diffusivity (m^2/(s·K))	T_a	air temperature (°C)
$D_{T\varphi}$	isothermal vapor diffusivity (m^2/s)	T_d	mean daily dew point temperature (°C)
E_a	actual evaporation rate (m/s)	T_s	soil surface temperature (°C)
E_p	potential evaporation (m/s)	W_v	molecular mass of water vapor (18.016e−3 kg/mol)
EL_{msl}	site elevation above the mean sea level (m)	w	moisture content (kg/m^3)
e_s	saturation vapor pressure at soil surface	α	soil surface albedo
e_a	air vapor pressure	u	wind speed (m/s)
e_0	soil surface vapor pressure	w	moisture content (kg/m^3)
e_d	mean daily saturated vapor pressure	y	elevation above a nominal datum (m)
H	sensible heat flux (W/m^2)	α	tortuosity factor for soil
H	relative humidity	β	cross-sectional area of the soil that is available for vapor flow
h_s	relative humidity of soil surface	η	soil porosity
I_{nf}	infiltration rate (m/s)	θ	volumetric water content
I_{nt}	rate of water intercepted by plants (m/s)	θ_s	saturated volumetric water content
G	soil heat flux (W/m^2)	θ_r	residual volumetric water content
K_T	thermal soil structure diffusivity (W/(m·K))	φ	matric suction head (m)
$K_{T\varphi}$	isothermal soil structure diffusivity (W/m)	λ	thermal conductivity of soil (W/(m·K))
$K_{\varphi T}$	thermal moisture diffusivity (m^2/(s·K))	λ_w	thermal conductivity of water (W/(m·K))
K_φ	isothermal moisture diffusivity (m^2/s)	λ_v	thermal conductivity of vapor (W/(m·K))
K	unsaturated hydraulic conductivity (m/s)	λ_a	thermal conductivity of air (W/(m·K))
K_s	saturated hydraulic conductivity (m/s)	ρ_0	density of saturated water vapor (kg/m^3)
L_E	latent heat flux (W/m^2)	ρ_l	liquid density (kg/m^3)
L_v	latent heat of vaporization of water (J/kg)	ρ_v	vapor density (kg/m^3)
P	rainfall (m/s)		

volumetric water content and temperature changes. A fully coupled hydro-thermal soil model is developed and a soil-atmosphere interface is accounted to define the top and the slope boundary conditions of the embankment. Comparisons between measurements and simulations results show the relevance of the adopted approach.

2. Field embankment monitoring

An embankment was constructed at Hericourt in Franche-Comte region in the north east of France, characterized by a continental climate influenced by ocean. The site plan and the view of the embankment are presented in Fig. 1a and b. The embankment is 107 m long, 5 m high, with a 1:2 slope (Vertical:Horizontal) at both sides. The embankment consists of two parts, one with lime/cement treated clay and another with lime/cement treated silt, each part being 53.5 m long. In this study, only the lime/cement treated silt part is considered. A weather station was installed on the top of the embankment, recording meteorological data such as solar radiation, rainfall, wind speed, air temperature and air relative humidity. As runoff occurs when the precipitation rate exceeds the infiltration rate at the soil surface, it was monitored specifically by a continuous measurement system on the slope surface [24]. Fig. 2a–f present respectively the variations of these parameters in the period from 07/06/2011, 14:42:52, to 07/26/2011, 14:42:52. As a complete set of meteorological data, runoff and also soil variables (temperature/volumetric water content) are needed in the numerical analysis, only this short period of 20 days are chosen in this study. Note that all the meteorological data were recorded half-hourly and the runoff was recorded hourly.

Fig. 3 presents the soil details in different layer thicknesses (0.25 m, 0.30 m, and 0.40 m) and the positions of sensors used in the embankment. During the studied period, the soil temperature and volumetric water content were measured every three hours using TDR for points I1 to I3, and S1 to S3. For the measurement of soil slope surface temperature at point A1, sensor PT100 was adopted. It is worth noting that during construction, a 20 cm soil layer was added on the slopes. Soil temperature probe ST1-05 was set at point A2 for monitoring the temperature of soil surface at the top of the embankment. More information of this embankment construction can be found in the report by Froumentin [24].

3. Soil-atmosphere interaction

The soil-atmosphere interaction happened at soil surface [7]. For bare soils, as rainfall happens, some water infiltrates into the soil mass, the rest goes away by runoff on soil surface. Meanwhile, evaporation happens at soil surface because of energy transfer and vapor pressure gradient exiting near the soil surface. For the heat