Simulations of in situ water content and temperature changes due to ground-atmospheric interactions

Simulation des variations de la teneur en eau et de la temperature dues aux interactions sol - atmosphère

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ABSTRACT

A series of numerical analyses has been carried out to investigate the sensitivity of water content, pore-water pressure and temperature changes to the variations of the soil albedo value (i.e., the ratio of reflected to incident solar radiation) and the initial temperature profiles (ITP). The soil-atmosphere interface model is used to calculate the evaporation rate and heat flux on the soil surface; the water transport equations (liquid - Darcy's law and vapor - Fick's law) coupled to heat flow equation (de Vries 1987) are solved to determine the profiles of temperature, water content or pore water pressure. The results show that it is important to know the atmospheric water balance for predicting soil temperature and water content (or pore water pressure) profiles. The results also suggest that the ITP can affect the temperature profiles but its influence of the considered changes on the pore water pressure and volumetric water content profiles is very small. During the cold season, precise albedo values are not very important nor very sensitive in influencing the water balance.

RÉSUMÉ

Une série d'analyses numériques a été effectuée pour étudier la sensibilité des variations de la teneur en eau, de la pression d'eau et de la température aux profils de température initiale (PTI). Le modèle sol-atmosphère est utilisé pour calculer le taux d'évaporation et du flux de chaleur en surface du sol ; les équations de transfert d'eau (liquide – loi de Darcy et vapeur – loi de Fick) couplées à l'équation du flux de chaleur (de Vries 1987) sont résolues pour déterminer les profils de température, de la teneur en eau ou de la pression d'eau. Les résultats montrent qu'il est important de connaître le bilan d'eau dans l'atmosphère pour déterminer différents profils dans le sol. Les résultats suggèrent également que le PTI peut influencer sur les profils de température mais son influence sur la pression d'eau et sur le teneur en eau volumique est faible.

Keywords: soil temperature profiles; water content profiles; ground-atmospheric interactions; numerical analysis.

1 INTRODUCTION

The vast majority of civil infrastructure systems are founded on and in soils above the groundwater table, involving unsaturated soils. The importance of understanding and predicting in situ soil water content (or suction) and temperature changes due to ground-atmospheric interactions in the unsaturated region have become more evident (Blight 1997). The spatial variation of soil water content in a drying soil sample is mainly dependent on the local environmental conditions, initial water content and temperature, hydromechanical properties of the soil, and on the boundary conditions at the soil-atmosphere interface. This paper presents results of a series of numerical analyses aiming to predict temperature, water content, and pore-water pressure changes due to climatic effects in a soil profile during a given period by considering the soil-atmosphere interface interaction. It is applied the principle of mass and energy conservation to describe one-dimensional water (liquid and vapour) and heat flow in unsaturated soil and the surface energy balance approach to evaluate the evaporation fluxes from a soil surface. A one dimensional explicit finite difference program developed at Ecole Nationale des Ponts et Chaussees by Gao (2006) is used for numerical simulations. The program models the coupled water flow and heat flow in unsaturated soil and uses an energy estimation method for determining the evaporation rate of water from a wet soil (Choudhury et al. 1986 or Xu and Qiu 1997). The model was validated with several data sets and able to satisfactorily predict the behaviour and volumetric water content profiles for non-cohesive and cohesive soils by Gao (2006).

This study analyses data from field measurements in Mormoiron, France, carried out from 2004 to 2005. A water deficit is observed in most of time throughout the investigated years. Thus, the years of 2004 and 2005 correspond to drier conditions where the recharge of the water table did not take place. In this case, rates of evaporation of water from the soil surface must be known in order to assess the water balance accurately. The most direct method of estimating evaporation or evapotranspiration is by considering the surface energy balance.

The observations on soil temperature at 0.5m, 1.5m, and 2.5 m depth are compared to the predicted soil temperature profiles based on modeling the ground-atmosphere interaction using the measured meteorological data. In order to model the changes in soil temperature and water content (or suction) profiles due to climatic effects during a given period, it is necessary to determine the soil albedo value (i.e., the ratio of reflected to incident solar radiation). It is a function of several surface parameters including soil color, water content, roughness and vegetation cover. Since the soil albedo value is not known, the sensitivity of predicted temperature changes due to ground-atmospheric interactions to the variations of the soil albedo is investigated. It is also discussed the influence of the initial soil temperature profile (ISTP) on the predicted soil temperature and water content (or suction) profiles.

Although the model is restricted to a consideration of pure water (chemically inactive) and no vegetated soil surfaces without pounded water, it forms the basis of a more general formulation which could incorporate the effects of these changes on the rate of evaporation of water from soil surfaces.

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2 SOIL-ATMOSPHERE INTERFACE MODEL

The model computes the evaporation rate from soil by solving the water transport equations (liquid - Darcy's law and vapor - Fick's law) coupled to heat flow equation (de Vries 1987). The surface energy balance is used for defining a reliable boundary setting method for extended periods of evaporation. The energy estimation method proposed by Choudhury et al. (1986) or Xu and Qiu (1997) is used for determining the evaporation rate of water from a wet soil. Details of the used method are discussed in Gao (2006). To solve the governing equation the suction-volumetric water content and suction-unsaturated hydraulic conductivity relationships must be known. The relationships are (Juarez-Badillo 1992):

$$\theta_w = \frac{\theta_{ws} - \theta_r}{1 + \left(\frac{\theta_{ws} - \theta_r}{\theta_{w1} - \theta_r} - 1\right)\left(\frac{s}{s_1}\right)^{\varsigma}} + \theta_r \quad (1a)$$

$$k_w = \frac{k_s}{1 + \left(\frac{k_s}{k_{w1}} - 1\right)\left(\frac{s}{s_1}\right)^{\xi}} \quad (1b)$$

where θ_{ws} is the volumetric water content at saturate state, θ_r is the residual volumetric water content, θ_{w1} is the value of water content corresponding to suction s_1, and ς is the parameter that controls the shape of the s-θ_w curve, k_s is the water permeability at s = 0, and k_{w1} is the hydraulic conductivity corresponding to suction s_1.

The thermal conductivity of soil, λ, is (de Vries 1963):

$$\lambda = \frac{f_s\theta_s\lambda_s + f_w\theta_w\lambda_w + f_a\theta_a\lambda_a}{f_s\theta_s + f_w\theta_w + f_a\theta_a}$$
$$\lambda_a = \lambda_{dry-air} + \lambda_{water-vapor} \quad (2)$$

where the thermal conductivity of solid, λ_s = $(k)^q\,(k^*)^{1-q}$ (Johansen 1975), q = the quartz volume fraction, for q = 0, λ_s = 2.0 W/mK and q = 100 %, λ_s = 7.7W/mK, the thermal conductivity of water λ_w (0.57 W/m ^{0}C), $\lambda_{dry-air}$ (0.025 W/m ^{0}C), $\lambda_{water-vapor}$ (0.608 θ_w), f_s, f_w and f_a are the weight coefficient for solid, water and air respectively and $f_w = 1.0$,

$$f_s = \left[1 + \left(\frac{\lambda_s}{\lambda_w} - 1\right)\right]^{-1}$$

$$f_a = \frac{1}{3}\sum_{i=1}^{3}\left[1 + \left(\frac{\lambda_a}{\lambda_w} - 1\right)g_i\right]^{-1}$$

where g_i are called shape factors ($g_1 + g_2 + g_3 = 1$) (Gao 2006):

for $\theta_w > 0.121$

$$g_1 = g_2 = \frac{0.333 - 0.105}{0.236 - 0.121}(\theta_w - 0.121) + 0.105$$

for $\theta_w < 0.121$

$$g_1 = g_2 = \frac{0.105 - 0.015}{0.121}\theta_w + 0.015)$$

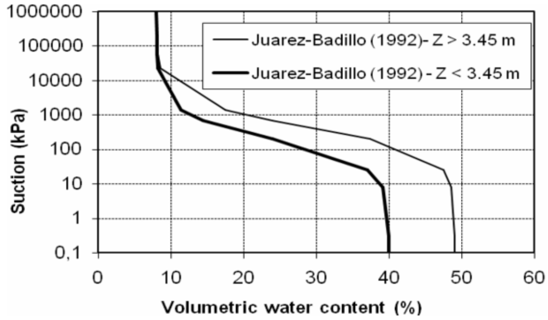
3 NUMERICAL SIMULATIONS

A one-dimensional computer program developed at ENPC by Gao (2006) using an explicit finite difference method was used for numerical simulations. The coupled water flow and heat flow equations are solved assuming that the soil skeleton is rigid. The input data are θ_{ws} = 0.49-0.4, θ_r = 0.08, θ_{w1} = 0.24, s_1 = 700-200 kPa, ς =1.1, k_{sat} = 1.2 x 10^{-11}-2.4 x 10^{-10}m/s and k_{w1} = 1.2 x 10^{-14}m/s, s_1 = 40 kPa, ς'' = 1.25 (see Figure 1). The thermal coefficients C_w (4.15x10^6 J/m^3 ^{o}C), C_s (2.24x10^6 J/m^3 ^{o}C), and q = 50% and λ_s = 3.92. The climatic data measured at Mormoiron, France, from December 2003 to December 2005 (i.e., solar radiation (0.05 to 0.35 $kW.m^{-2}$), energy, precipitation, runoff, wind speed (2 to 14 m/s), air temperature (0 to 25 ^{o}C), and air humidity) were used in the numerical simulations. The analyses performed employed the same values of the depth of the analysis (ZMAX = 5.25 m), the constant spacing (Δz = 0.005-0.05 m), the time step (Δt = 0.5 s), the runtime, TMAX (s), bottom volumetric water content boundary (θ_b = 0.30), bottom temperature boundary (T_b= 14^{o}C), and initial volumetric water content profile (Figure 3).

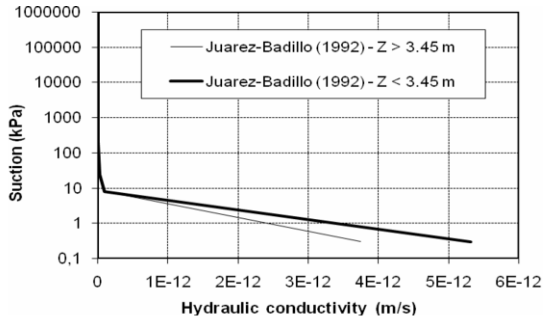
Figure 2 shows the atmospheric water balance from December (D) 2003 and December (D) 2004 and January (J) 2005 to December (D) 2005 A water deficit is observed in most of time throughout the studied years except for a brief period in December 2003, October 2004, April 2005 and October 2005. Thus, the years of 2004 and 2005 correspond to drier conditions where the recharge of the water table did not take place.

Since the initial temperature profile (ITP) is not known, we investigate the sensitivity of predicted water content, pore-water pressure and temperature profiles to the variations of the ITP (Figure 3). The insensitivity of the results (Cases B and D) presented in Figures 4 and 5 is visible. The volumetric water content and pore water pressures at depth higher than 1.5 m are almost constant. Figure 6 presents the predicted temperature profiles from January to July 2004 considering the ITP for Cases B and D. As can be seen from this comparison, the value of the ITP can affect the temperature spatial distribution. The influence is more accentuated for the near surface layers, where more extreme variations in temperature occur. The results show that the temperatures increase with the depth during the cold season (January to March 2004) and decrease with the depth during the warm season (April to July, 04/2004 to 07/2004).

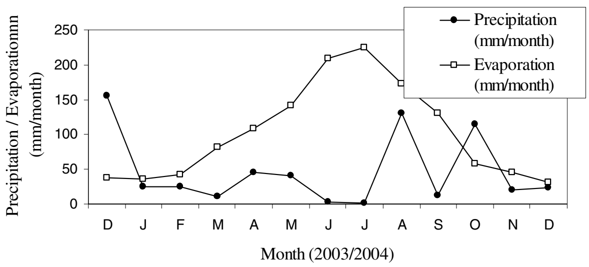
The changes in soil temperature and water content (or suction) due to climatic effects in a soil profile during a given period depend on the ratio of reflected to incident solar radiation (i.e., the soil albedo value). It is a function of several surface parameters including soil color, water content, roughness and vegetation cover, usually being lower for wet and rough conditions. The albedo value ranges from 0 to 1. The value of 0 refers to a blackbody, a theoretical media that absorbs 100% of the incident radiation. Albedo ranging from 0.1-0.2 refers to dark-colored, rough soil surfaces, while the



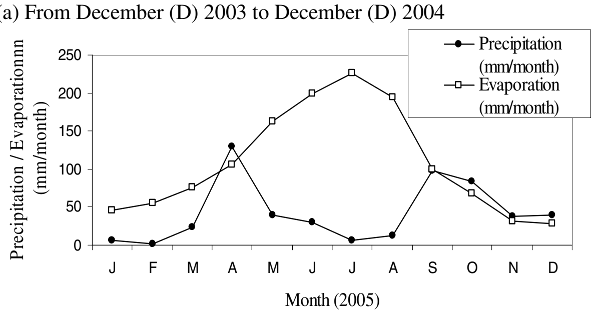
(a) Suction-volumetric water content functions



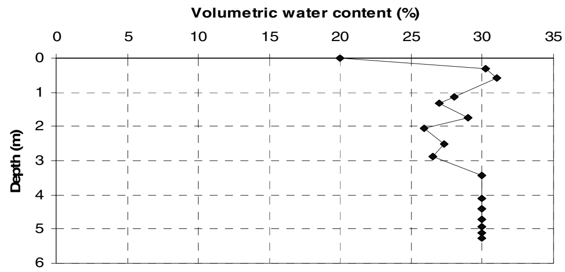
(b) Suction-unsaturated hydraulic conductivity functions
Figure 1: The considered constitutive functions



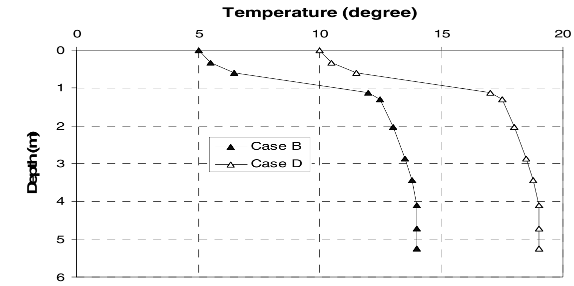
(a) From December (D) 2003 to December (D) 2004



(b) From January (J) to December (D) 2005
Figure 2. Atmospheric water balance for the investigated region



(a) Volumetric water content profile



(b) Soil temperature profiles
Figure 3. The considered initial soil profiles

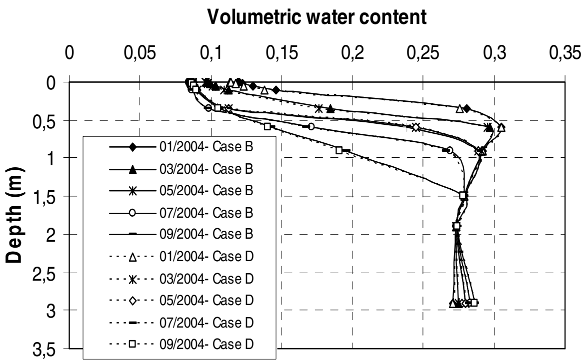


Figure 4. Influence of Initial temperature profiles on the volumetric water content profiles

values around 0.4-0.5 represent smooth, light-colored soil surfaces. The value of 1 refers to an ideal reflector surface (an absolute white surface) in which all the energy falling on the surface is reflected. Since the soil albedo value is not known, the sensitivity of predicted temperature changes due to ground-atmospheric interactions to the variations of the soil albedo is investigated in Figure 7, where case B (soil albedo = 0.15) and case C (soil albedo =0.05). The insensitivity of the results (Cases B and C) during the cold season (January to March 2005) is shown in Figure 7. Small changes in the temperature values (increase) due to the variation (decrease) of the soil albedo (case C) are observed during the warm season (April to August 2005).

Figure 8 presents the comparison of predicted and measured changes in temperature profiles (at 0.5m, 1.5m, and 2.5 m depth) during 2005 in Mormoiron, France. The results suggest that in the near the surface layers the simulations were less satisfactory due to probably vegetation effects or other mechanical phenomena (i.e., soil cracking). A sensitivity analysis of temperature and water content profiles to the changes to the variations of other unknown parameters (i.e., soil water content that depend on the soil temperature) should also be investigated. Cui et al. (2005) proposed to consider the superficial zone independently, using different values of the soil parameters.

4 CONCLUSIONS

The numerical analyses carried out to investigate the sensitivity of water content, pore-water pressure and temperature changes to the variations of the initial temperature profiles (ITP) suggest that the value of the ITP can affect the temperature profiles and the influence of the considered changes on the pore water pressure and volumetric water content profiles is very small. The results also show that it is important to know the atmospheric water balance for predicting the temperature, pore water pressure and volumetric water content profiles. During the cold season, precise albedo values are not very important nor very sensitive in influencing the water balance. The comparison of predicted and measured changes in temperature profiles suggest that in near the surface layers the simulations are less satisfactory due to probably vegetation effects or other mechanical phenomena (i.e., soil cracking).

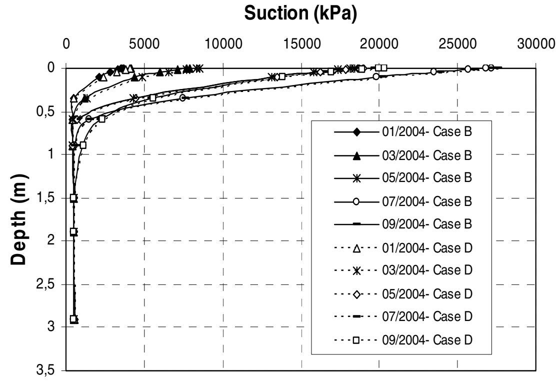


Figure 5. Influence of Initial temperature profiles on the pore water pressure profiles

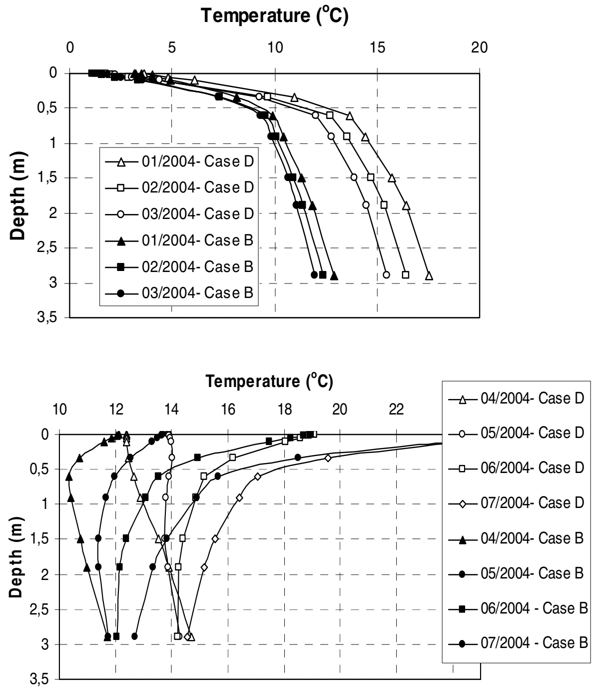


Figure 6. Influence of Initial temperature profiles on the temperature profiles (2004)

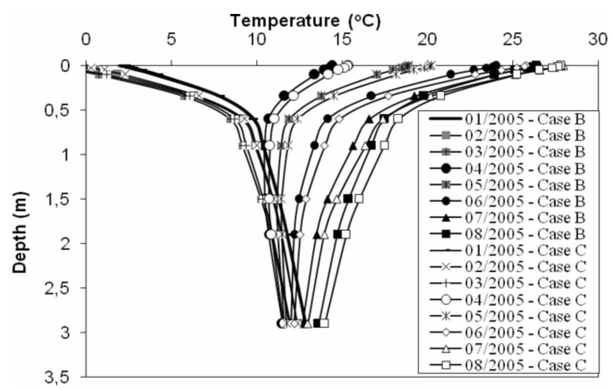


Figure 7. Influence of the soil albedo values on the temperature profiles (2005)

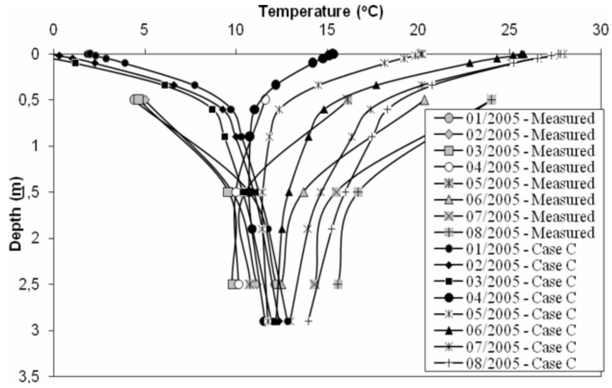


Figure 8. Comparison of predicted and measured changes in temperature profiles during 2005

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