

Research Paper

Modelling water content redistribution during evaporation from sandy soil in the presence of water table

Jidong Teng^{a,*}, Noriyuki Yasufuku^b, Sheng Zhang^a, Yi He^c^a Natural Engineering Laboratory for High-Speed-Railway Construction, Central South University, Changsha 410075, China^b Department of Civil and Structural Engineering, Kyushu University, Fukuoka 819-0395, Japan^c Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 610031, China

ARTICLE INFO

Article history:

Received 11 August 2015

Received in revised form 17 February 2016

Accepted 17 February 2016

Available online 27 February 2016

Keywords:

Evaporation

Water content redistribution

Initial condition

Climate control apparatus

ABSTRACT

An analytical model based on Richards equation is presented to describe water content redistribution during evaporation. Exponential functions are utilized to describe the relation of hydraulic conductivity and water content on pressure head. The water content at any given depth z and time t , together with the evaporation rate at the soil surface are outputs of this model. The proposed is capable of modelling the transformation of the constant rate stage into a falling rate stage of evaporation, moreover it extends the use of analytical model to arbitrary initial conditions. Detailed parametric analysis was carried out to investigate the effect of six governing factors. The main findings are as follows: hydraulic conductivity (K_s) and desaturation coefficient (α) affect the water content profile more than the storage capacity ($\theta_s - \theta_r$) does; the relation between the duration of the constant rate stage and the dimensionless evaporation rate γ can be expressed by a negative power function; the initial conditions are the most influential factor for the soil water profile among all factors examined. Finally, two evaporation tests conducted on K-7 sand and Fontainebleau sand were introduced to validate the proposed analytical model. Results showed that this model could reasonably predict the temporal water content profile during evaporation process, but some discrepancies still existed in some cases. Nevertheless, the analytical model provides a useful tool for predicting the vertical distribution of water content during evaporation.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Evaluating evaporation processes on soil surfaces is of great importance in addressing many practical problems in geotechnical and geoenvironmental engineering. Examples include the design of soil cover systems in mining and landfill applications [49,52,53], modelling surface fluxes of saturated–unsaturated ground [2,3,10,12], soil salinization in arid and semi-arid regions [32,17], assessment of the long-term performance of expressway or railway embankments [16,9,31], and the recent geotechnical greening system for preventing desertification [54]. These examples highlight the need for experimentally and theoretically investigating the mechanism of soil evaporation.

Evaporation can be described by both macroscopic and microscopic mechanisms. The former describes the change in the phase of water from liquid to vapour, whereas the latter describes how

water molecules overcome attractive forces to escape into the atmosphere. Both experimental data and theoretical schemes have shown that two distinct stages of soil evaporation exist, a constant rate stage and a falling rate stage, referred to as Stages 1 and 2, respectively. Fig. 1 presents a schematic illustration of these two stages. Evaporation in Stage 1 is governed by external atmospheric conditions as soil is sufficiently conductive to satisfy the evaporative demand, whereas in Stage 2 the soil is partially saturated or dried such that the atmospherically determined potential evaporation rate cannot be maintained; thus, soil water transport is the rate-determining process [4,40]. Soil evaporation is affected by various factors, such as soil texture, initial water content, hydraulic conductivity, water retention ability, and water table level [37]. These factors do not function as independent variables but rather act as a closely coupled system. Because of this relationship, a comprehensive description of the mechanism of evaporation is still lacking.

Many previous researchers have reported steady-state solutions to the evaporation problem using soil profiles [13,47,30,29,17,33], but these solutions usually cannot reflect reality because evaporation typically occurs under transient conditions [56]. Studies on

* Corresponding author at: Railway Campus of Central South University, Shaoshan South Road No. 68, Changsha 410075, China. Tel./fax: +86 0731 82656193.

E-mail address: jdteng@csu.edu.cn (J. Teng).

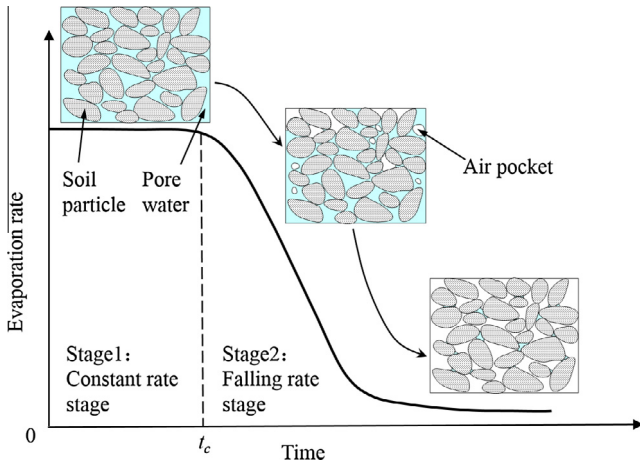


Fig. 1. Schematic illustration of the soil evaporation curve, where t_c represents the critical time between Stage 1 and Stage 2.

transient evaporation can be divided into those formulating numerical solutions and those formulating analytical solutions with various initial and boundary conditions. In reality, many numerical schemes have been developed for analyzing evaporation or water flow problems in porous media [6,48,45,38,15,19,11]. For example, adaptive time stepping schemes and adaptive spatial meshing schemes have been studied to solve the nonlinear governing equation [23,20]. Besides, some numerical codes have been established including where Richards equation was built into small and large scale groundwater/environmental models [34,18,35]. Those numerical solutions range in complexity and applicability, and some of them require sophisticated algorithms to overcome convergence and mass conservation problems. On the other hand, analytical solutions often offer better accuracy and are relatively easy to implement in many ways [55]. Thus, this paper elect to focus on the analytical approach. Although, several researchers have presented analytical or quasi-analytical solutions to the Richards equation for soil evaporation in the presence or absence of a water table [27,51,24,56,26,41], these solution are not sufficient to clarify the evaporation mechanism. One of the reasons for this deficit is that these studies have mainly focused on an initial uniform soil profile by considering saturated conditions without taking into account variations in water content or suction distribution. Furthermore, evaporative fluxes have usually been treated as a constant [40] or as a variable involving a basic function [24] to determine water content redistribution, whereas few analytical studies have addressed the transformation of the actual evaporation rate when Stage 1 transitions to Stage 2. Moreover, a comparison between theory and field or laboratory observations is lacking in some studies, such as Novak [27] and Nasser et al. [26]. As a result, it is difficult to determine the accuracy of these models. This study was performed aiming to overcome the shortcomings in current models, which are confining in uniform initial water content, neglecting the transformation of two evaporation stages, and rarely comparing with measured data.

In this study, an analytical model was developed to model water content redistribution during evaporation. Specific to sandy soil, exponential water retention and hydraulic conductivity relationships were utilized to linearize the Richards equation. In this model, arbitrary initial conditions were taken into account together with the transformation of Stage 1 into Stage 2 during the evaporation process. By using quadratic functions to fit the water content profiles at the initial time and the ending time of Stage 1, respectively, clear formulations of the water content redistribution and surface evaporation rate were obtained. Thereafter, parametric analysis was carried out to investigate the individual

effects of six governing factors on the water content redistribution and evaporation rate. Finally, the proposed analytical model was validated based on the results of laboratory evaporation tests of sandy soil under a climate control apparatus and the test results reported in the literature for Fontainebleau sand.

2. Theory

2.1. Assumptions and the Richards equation

To derive an analytical solution, the following assumptions are made: (1) Evaporation takes place in homogeneous soil under isothermal conditions; (2) vapour transmission of water through the soil profile is not considered, that is to say, moving water occurs in liquid form, Gardner's [14] analysis has shown good agreement between the analytical prediction that the vapour transport is negligible and laboratory measurements of a drying column, which supports this assumption; (3) the flow of liquid water in soil is due to a gradient in the piezometric head or water content, and osmotic pressure is neglected; (4) hysteresis in the relations between matric suction and soil water content is not taken into account.

The Richards equation is a general partial differential equation describing water flow in unsaturated, non-deformable soils. By invoking Darcy's law and the continuity equation, the partial differential equation governing the one-dimensional movement of water in the vertical direction is derived as follows:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} \left(K(\psi) \frac{\partial \psi}{\partial z} \right) + \frac{\partial K(\psi)}{\partial z} \quad (1)$$

where θ is the volumetric water content, t is time, z is the downward-facing vertical coordinate pointing, and $K(\psi)$ is hydraulic conductivity as a function of matric suction ψ .

Yanful et al. [53] stated that evaporation processes in which the gradient of the gravitational head is negligible compared to the strong matric suction gradient may also occur. In addition, an analytical solution to the Richards equation with a gravitational term is challenging to obtain due to the difficult forms of integrals or series involved. Even if the solution did possess a clear formulation, it would somehow diverge from the mechanism established by the boundary conditions [39,1,7,8,26]. Therefore, the fundamental differential equation without a gravitational term in unsaturated soil is formulated as follows:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} \left(K(\psi) \frac{\partial \psi}{\partial z} \right) \quad (2)$$

Because Eq. (2) contains two related parameters, it is possible to eliminate either θ or ψ by including the concept of specific water content, which is defined as the slope of the soil–water characteristic curve:

$$s(\theta) = -\frac{d\theta}{d\psi} \quad (3)$$

where a negative sign is used to account for the fact that an increase in volumetric water content, θ , leads to a decrease in suction ψ . Now, the flux expression in Eq. (2) can be written as

$$K(\psi) \frac{\partial \psi}{\partial z} = K(\theta) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial z} = -\frac{K(\theta)}{s(\theta)} \frac{\partial \theta}{\partial z} \quad (4)$$

By adopting the diffusivity term, which is defined as the ratio of the hydraulic conductivity $K(\theta)$ to the specific water capacity $s(\theta)$, the new form of the Richards equation can be obtained. The diffusivity can be expressed as

$$D(\theta) = \frac{K(\theta)}{s(\theta)} \quad (5)$$

Download English Version:

<https://daneshyari.com/en/article/6710461>

Download Persian Version:

<https://daneshyari.com/article/6710461>

[Daneshyari.com](https://daneshyari.com)