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An analytical solution for predicting the transient seepage from a subsurface drainage system

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ABSTRACT

Subsurface drainage systems have been widely used to deal with soil salinization and waterlogging problems around the world. In this paper, a mathematical model was introduced to quantify the transient behavior of the groundwater table and the seepage from a subsurface drainage system. Based on the assumption of a hydrostatic pressure distribution, the model considered the pore-water flow in both the phreatic and vadose soil zones. An approximate analytical solution for the model was derived to quantify the drainage of soils which were initially water-saturated. The analytical solution was validated against laboratory experiments and a 2-D Richards equation-based model, and found to predict well the transient water seepage from the subsurface drainage system. A saturated flow-based model was also tested and found to over-predict the time required for drainage and the total water seepage by nearly one order of magnitude, in comparison with the experimental results and the present analytical solution. During drainage, a vadose zone with a significant water storage capacity developed above the phreatic surface. A considerable amount of water still remained in the vadose zone at the steady state with the water table situated at the drain bottom. Sensitivity analyses demonstrated that effects of the vadose zone were intensified with an increased thickness of capillary fringe, capillary rise and/or burying depth of drains, in terms of the required drainage time and total water seepage. The analytical solution provides guidance for assessing the capillary effects on the effectiveness and efficiency of subsurface drainage systems for combating soil salinization and waterlogging problems.

1. Introduction

Soil salinization and waterlogging are common problems around the world, which negatively impact on agricultural productivity [1–3]. Globally a total area around 9.55 million km^2 is affected by soil salinization [4]. Salt leaching, among various methods developed, is often applied to ameliorate saline soils. This method uses freshwater to flush excessive salts out of the upper soil layer through drainage systems. Free drainage systems based on open ditches and subsurface drains have been used for this purpose [1,5]. Similar drainage systems have also been applied for controlling the groundwater table to reduce the threat of waterlogging in low-relief areas [2].

While various analytical solutions [6–10], laboratory experiments [11,12], field investigations [13–15] and numerical simulations [16–20] have been conducted to examine the flow and salt transport behavior within drainage systems, most of these studies focused on steady-state conditions [6,21]. For salt leaching, flushing is mainly examined with consideration of continuous surface ponding. Under this condition, a relatively high hydraulic head remains near the drain, resulting in low hydraulic gradients from the midsection (i.e., interior area between two drains) to the drain. Considerable amounts of time and freshwater may thus be required to flush some interior area that is far away from the drains [20]. As such, under the steady-state condition, leaching requirements would be more excessive compared with those under transient conditions [21]. Therefore, transient drainage systems should be considered for salt leaching in practice and in research. In the waterlogging problem, the drainage process is also transient as the groundwater table is lowered in order to aerate the root zone. As a well-designed subsurface drainage system is expected to drain quickly excess water, total water seepage and drainage time are two widely adopted metrics for evaluating the performance of a drainage system [22,23].

Analytical solutions provide directly mechanistic insight into the physical process and assist greatly the design of subsurface

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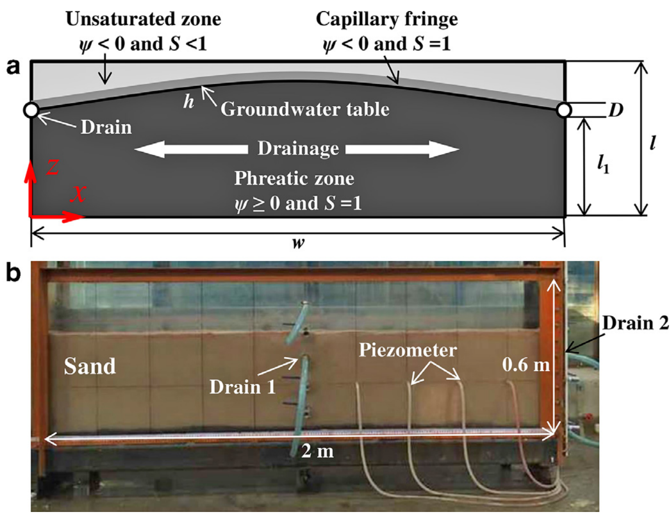

Fig. 1. (a) Schematic diagram of a drainage system laterally bounded by two parallel subsurface drains. ψ is the pore-water pressure head and S is the soil-water saturation. (b) Photo of the experiment setup. The drain was, respectively, set in the middle (Drain 1 for Cases 1 and 2) and on the right side (Drain 2 for Cases 3 and 4. Note that only half of the drainage system was considered) of the flume for different experimental cases.

drainage networks. However, as mentioned above, existing analytical solutions largely focused on steady-state conditions (see the review in Barua and Alam [6]). The exception is the work of Barua and Alam [6], who developed an analytical solution for predicting time-dependent seepage into an array of equally-spaced and parallel ditch drains in a homogeneous and anisotropic soil. While this solution took into account transient effects, it considered only surface ponding conditions and saturated flow, thus limiting its possible engineering applications.

To achieve a better leaching outcome, subsurface drainage systems, particularly those with subsurface drains (Fig. 1(a)), are applied with the drain closed initially to allow the soil flooded first. Subsequently, the drain is opened to dewater the soil. The transient flow that takes place during the soil drainage is also likely to minimize the bypassing effect caused by macro-pores [1]. As shown in Xin et al. [24], vertical macro-pores play a negligible role in affecting soil drainage as long as the soil surface is not flooded. Since, a vadose zone will develop between the groundwater table and soil surface. Note that the vadose zone, situated above the phreatic surface, includes both a capillary fringe (nearly with a full water saturation but pressure less than the atmospheric pressure) and an unsaturated zone (partly saturated zone with pressure also less than the atmospheric pressure). Most salt-affected soils are composed of sandy loam and silt loam. These types of soils are of low permeability but have a high capillary rise up to the order of meters [25]. This allows the vadose zone to play an important role in affecting water seepage from the drainage system. Youngs [8], and Mirjat et al. [26] derived analytical solutions for models with soil capillarity considered under steady-state conditions. They found that the unsaturated flow in soil can lower considerably the groundwater table in comparison with the predictions of analytical solutions based on saturated models.

In general, the vadose zone has been found to play a considerable role in affecting groundwater flow in unconfined aquifers with relatively shallow groundwater tables. Xin et al. [27] and Kong et al. [28] showed that the water stored in the vadose zone is remarkably variable in aquifers with shallow groundwater tables. This favors transient groundwater table fluctuations in coastal unconfined aquifers subjected to low-frequency oscillations such as tides. The effect of vadose zone is particularly important in unconfined aquifers with high capillary rise and/or shallow water table. Dan et al. [29,30] examined the effects of vadose zone on steady and transient flows in a drainage layer of highway pavement and demonstrated the strong need to integrate saturated and unsaturated zones in the design of pavement drainage systems.

To our best knowledge, there is no existing analytical solution for describing transient flows in subsurface drainage systems subjected to the influence of vadose zone. While Dan et al. [30] considered capillarity in their analytical solution for predicting the transient seepage in a drainage layer of highway, the capillary fringe was neglected. As will be shown in this study, the capillary fringe would significantly alter the predicted water seepage from the soil. Assuming that the pore-water pressure in the soil follows approximately a hydrostatic pressure distribution, we introduce here a 1-D model and derive an analytical solution for predicting the transient water seepage from a subsurface drainage system. The rest of the paper is organized as follows: in Section 2, we describe the conceptual and mathematical models as well as the analytical solution. In Section 3, the analytical solution is tested against laboratory experiments and a 2-D Richards equation-based model. In Section 4, a sensitivity analysis is conducted to examine the effects of soil properties and drain depth on the drainage process. Conclusions are drawn in Section 5.

2. Conceptual and mathematical models

2.1. Conceptual model

Here, we consider a drainage system with equally-spaced and parallel subsurface drains. For such a system, the flow is symmetrical in the lateral direction with respect to either the drain or the midsection between drains [9,17]. As such, our model focuses on a vertical two-dimensional (2-D) soil section of width w [L] in the lateral direction, bounded by two parallel subsurface drains (Fig. 1(a)). The flow in the along-drain direction (y [L]) is assumed to be negligible. The soil is assumed to be homogeneous and isotropic. An impervious layer is assumed to be laid below the soil with a thickness of l [L]. The x–z coordinate origin is set at the impervious layer and under the left drain (Fig. 1(a)). Both the soil surface and impervious layer are assumed to be flat and horizontal. Two subsurface drains with inner diameters of D are set in the drainage system. The center of the drains is at the height of l_c [L] from the impervious base, giving the lower bound (l_1 [L]) of the drain at $l_c - D/2$.

2.2. Governing equation

The pore-water flow in the modelled soil section can be described by the 2-D Richards equation, i.e.,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\psi)\frac{\partial \Phi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\psi)\frac{\partial \Phi}{\partial z}\right] \quad (1)$$

where θ is the soil-water content [-], $= \phi S$ with ϕ being the soil porosity [-] and S being the soil-water saturation [-]; t is the time [T]; x is the distance from the left drain [L] (Fig. 1(a)). Φ is the total hydraulic head, $= \psi + z$ [L] with z being the elevation [L] and ψ being the pore-water pressure head (negative in the vadose zone and also referred to as matric potential. $|\psi|$ gives the suction head). $K(\psi)$ is the soil hydraulic conductivity [LT^{-1}].

It is not trivial to derive an analytical solution directly for the 2-D Richards equation. Thus a simplified model is needed. For most subsurface drainage systems, the ratio of the soil thickness to width (i.e., l/w) is relatively small. With no soil surface ponding, the horizontal flow is dominant across the soil, particularly in the midsection. Given such a condition, the vertical flow can be