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Effects of macro-pores on water flow in coastal subsurface drainage systems

Pei Xin[a,*], Xiayang Yu[a], Chunhui Lu[a,b], Ling Li[a,c]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China
[b] Monash Water for Liveability, Civil Engineering Department, Monash University, Victoria, Australia
[c] School of Civil Engineering, The University of Queensland, Queensland, Australia

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ABSTRACT

Leaching through subsurface drainage systems has been widely adopted to ameliorate saline soils. The application of this method to remove salt from reclaimed lands in the coastal zone, however, may be impacted by macro-pores such as crab burrows, which are commonly distributed in the soils. We developed a three-dimensional model to investigate water flow in subsurface drainage systems affected by macro-pores distributed deterministically and randomly through Monte Carlo simulations. The results showed that, for subsurface drainage systems under the condition of continuous surface ponding, macro-pores increased the hydraulic head in the deep soil, which in turn reduced the hydraulic gradient between the surface and deep soil. As a consequence, water infiltration across the soil surface was inhibited. Since salt transport in the soil is dominated by advection, the flow simulation results indicated that macro-pores decreased the efficiency of salt leaching by one order of magnitude, in terms of both the elapsed time and the amount of water required to remove salt over the designed soil leaching depth (0.6 m). The reduction of the leaching efficiency was even greater in drainage systems with a layered soil stratigraphy. Sensitivity analyses demonstrated that with an increased penetration depth or density of macro-pores, the leaching efficiency decreased further. The revealed impact of macro-pores on water flow represents a significant shortcoming of the salt leaching technique when applied to coastal saline soils. Future designs of soil amelioration schemes in the coastal zone should consider and aim to minimize the bypassing effect caused by macro-pores.

1. Introduction

Soil salinization is a major problem in many arid and semi-arid regions worldwide [1]. According to [2] published in 2003, the total area of salt-affected lands in the world was around 9.55 million km^2, approximately 10% of the total land area. The problem has worsened dramatically due to global climate change and anthropogenic activities over the last decade [3,4].

Excess of salts in soils can alter significantly the physical and chemical soil properties, and decrease the agricultural productivity [5]. To cope with this global issue, various physical, chemical, biological and ecological methods have been developed for ameliorating saline soils (see the review by Qadir et al. [1]). Among these methods, leaching is a traditional and still globally adopted one. This method flushes excessive salts from upper to lower soil depths using good quality water and removes the salts through drainage systems. Commonly, surface flushing is accomplished by continuous ponding, intermittent ponding and sprinkling, while salt discharge is performed by using pumping wells, subsurface drains and open ditches [1,6]. As subsurface drains are easy to set up, workable with no requirement for power and land saving, they are prevailingly used in these drainage systems.

The salt leaching method has been studied extensively via analytical solutions [7-10], laboratory experiments [11,12], field investigations [13-15] and numerical simulations [16-19]. It was found that in a drainage system with complete and continuous ponding, the surface water infiltration rate decreases from the drain location to midway between drains (hereinafter, referred to as interior). It takes much longer time to flush the interior area far away from the drains. To remove salts over a particular crop rhizosphere depth across the whole area, the method with continuous ponding would lead to significant waste of good quantity water. Therefore, various alternative methods, such as drip irrigation (an irrigation method that allows water to drip slowly to the roots of plants through narrow tubes) and progressive ponding, have been proposed to improve the efficiency of salt leaching. Based on analytical solutions, Youngs and Leeds-Harrison [10] provided a framework for analyzing the progressive ponding condition. This method divides the whole soil area into different strips

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* Corresponding author: Tel.: +86 18751985592.
E-mail address: pei.xin@outlook.com (P. Xin).

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separated by bunds. Ponding starts from the midway area between drains and progresses towards the drains until the whole area is flooded. This method was tested against laboratory experiments and found to be significantly more effective than the complete ponding method [11, 20]. Progressive ponding enhances the local hydraulic head gradient in the interior. The leaching efficiency can be thus improved by up to 4 times with respect to the amount of water needed to drain the soil to the required soil depth [16, 17]. While salt transport in the soil is affected by both advection and diffusion/dispersion processes, all these studies suggested that increasing the hydraulic head gradient between the drain and interior is the key to improving the efficiency of salt leaching.

While these studies provide a theoretical basis for performing salt leaching analysis, it remains a challenge to apply the leaching method in the field. The area of salt-affected soils in China is around 0.35 million km^2, a quarter of which are coastal saline soils. This figure is still increasing due to intensive land reclamation being carried out in the coastal zone [3]. How to effectively utilize these coastal saline soils is now critically important to relieving the population pressure and ensuring food safety in eastern China [21]. Adjacent to the coastal sea, these soils are typically of high salinity and have to be ameliorated to satisfy the needs of agricultural use. Salt leaching is prevailingly adopted in China and a significant amount of good quality water is consumed every year for this purpose despite severe water shortage in China [22]. This study was firstly motivated to test the efficiency of the leaching approach widely adopted in China's coastal areas. We conducted a couple of field surveys in these areas, including the Chongming Dongtan wetland (Shanghai) and the reclaimed land from the Jiangsu coastal wetlands. The former is a natural marsh wetland linked to the sea and the latter is isolated from the sea in terms of surface water connection. For the latter shortly after the reclamation, no agricultural activities are presently carried out as sufficient soil amelioration is still needed to meet the condition for crop growth. In these two coastal areas, we observed the following two typical types of soil heterogeneity:

(1) Macro-pores produced by invertebrates, such as crab burrows, are commonly found in coastal saline soils (Fig. 1a). Using polyester resin casting (Fig. 1b), Xin et al. [23] found that the depth of these burrows can reach 70 cm (Fig. 1c). The density of burrows with diameters ranging from 1 to 4 cm can be up to 8/m^2. Macro-pores, as preferential flow paths, can significantly affect the flow in various groundwater systems [24, 25]. Akay et al. [12] conducted a laboratory study to examine the effect of a single vertical burrow on flow in a soil column overlying a drain. The finding revealed that the open macro-pore collected the surface water significantly and enhanced water infiltration.

(2) Coastal sediments possess a layered soil stratigraphy. Commonly, low-permeability silt loams are found to overlie sandy deposits. The high-permeability sandy deposits, combined with macro-pores, can create preferential flow paths affecting the pore-water flow in coastal groundwater systems. In particular, the lower higher-permeability layer is likely to favor drainage as long as the horizontal hydraulic gradient exists [17, 26, 27]. In a drainage system, this kind of soil configuration is likely to lead to a more uniform flow field and increase water infiltration in the midway area between drains [17].

It should be noted that these two typical types of soil heterogeneity are not only just commonly encountered in the coastal zone of China but also in other coastal areas around the world. Macro-pores created by plant roots, soil cracks, and soil fauna are found in most of soils and have attracted increasing attention over the recent decades [24, 25, 28-31]. Coastal sediments are often lay down by layers and lead to distinct soil strata [28, 32-34]. Therefore, amelioration strategies for coastal saline soils need to carefully take these effects into account. There are speculations about the effect of macro-pores on various groundwater systems. However, the macro-pore effects have not yet been adequately understood [25, 35, 36]. To the best of the authors' knowledge, no quantitative analysis on the effect of macro-pores on pore-water flow in coastal subsurface drainage systems has been conducted to date.

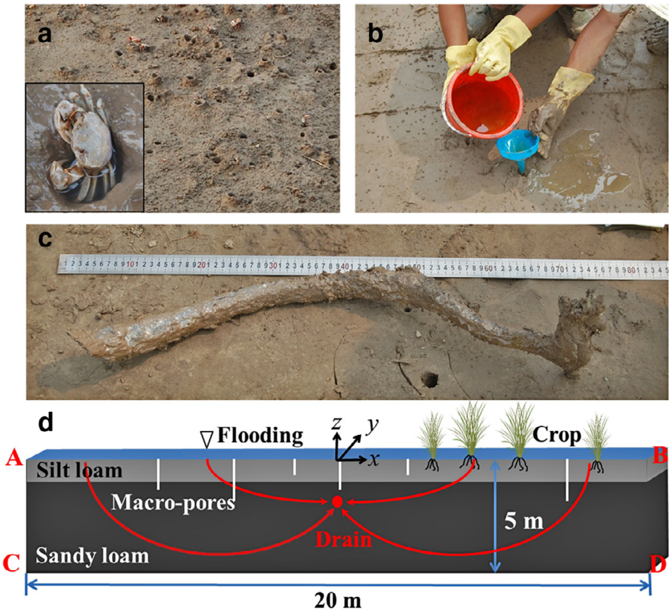

Fig. 1. (a) Illustration of coastal soils with macro-pores (crab burrows) distributed (picture taken in the Chongming Dongtan wetland, Shanghai, China). A crab is shown at the lower left corner. (b) Illustration of using polyester resin casting to measure the structure of burrows. (c) Morphology of a casted crab burrow. A ruler is placed for comparison. (d) Three-dimensional schematic diagram of a drainage system subjected to continuous and complete surface ponding. The elevation datum is set at the soil surface. Soil configuration and macro-pores are also illustrated.

In this study, we developed a three-dimensional (3-D) model to investigate water flow in coastal subsurface drainage systems affected by macro-pores. Firstly, we examined the effect of regularly distributed macro-pores on uniform and layered drainage systems. Velocity flow fields, and time and water needed for leaching were examined in detail. Secondly, we conducted Monte Carlo simulations to better represent the field conditions and examine the uncertainty caused by randomly distributed macro-pores.

2. Conceptual and numerical model

The model domain, with a simplified 3-D cuboid geometry, is representative of the drainage systems commonly adopted in China's coastal areas. The model is assumed to be laterally bounded by two hydraulic divides in the middle between the simulated subsurface drain and adjacent parallel drains (one on each side). The model domain is thus centred by the simulated drain and extends in the along-drain (y [L]) direction by a width of 1 m (Fig. 1d). **AB** shows the soil surface and **CD** is an impermeable base. The thickness of the aquifer is set to 5 m and the distance between two parallel subsurface drains is set to 20 m. The drain with a diameter of 8 cm is set up at the 1 m soil depth. The soil stratigraphy is set up to represent the field condition investigated by Xin et al. [23]. The domain is divided vertically into two zones (Fig. 1d, the upper silt loam zone and lower sandy loam zone) separated by a horizontal interface at the depth of 0.6 m from the soil surface.

To focus on the effect of macro-pores on the water flow in the first instance, the study considered steady-state flow in the subsurface drainage system with complete and continuous ponding. Therefore, only steady-state and water saturated (no air trapped) pore-water flow occurred in the soil. The hydraulic head is be governed by the