Agricultural Water Management 146 (2014) 105–114

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Numerical simulation of water flow in tile and mole drainage systems

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ARTICLE INFO

Article history:
Received 17 December 2013
Accepted 16 July 2014

Keywords:
Tile drainage
Mole drainage
Numerical simulation
Heavy soil
Three-dimensional modeling

ABSTRACT

Tile drainage systems are sometimes not sufficient to provide favorable unsaturated conditions in the rootzone. These drainage systems then need to be supplemented with an additional high conductivity material in the trenches above the tiles or by implementing mole drainage. The HYDRUS (2D/3D) model was used to evaluate the impact of such additional measures for heavy clay soil. Three types of drainage systems were simulated: (i) tile drains, (ii) tile drains with gravel trenches, and (iii) tile drains with gravel trenches and mole drains, using either two-dimensional (the former two systems) or three-dimensional (the latter one) transport domains. Three scenarios were considered to test the efficiency of each system: (i) time to drain an initially saturated system, (ii) high intensity rainfall, and (iii) a real case scenario. Different horizontal spacings between tile drains with or without gravel trenches were also compared with the system which included mole drainage. The results showed that the drainage system that included mole drains and gravel trenches was the most efficient. This system provided the largest drainage rate, was the first to reach steady-state in the time to drain scenario, and also efficiently reduced surface runoff. Adding mole drains to a system with tile drains and gravel trenches resulted in a large reduction of surface runoff (75%). Simulations showed that the spacing of tile drains with or without gravel trenches would have to be 40% or 55% smaller, respectively, in order to reproduce the same water table levels as those observed for the drainage system with mole drains. Therefore, introducing mole drains in drainage systems is an efficient practice for reducing waterlogging and runoff.

1. Introduction

Soil drainage systems aim at limiting saturated conditions in the soil profile that can arise due to hydrological processes from above (downward water percolation) and from below (elevated groundwater). The main goal of drainage systems is to remove excess water and maintain favorable unsaturated conditions in the rootzone. The most common agricultural drainage system consists of perforated PVC tile drains installed in soil at various spacings and depths, depending on soil hydraulic properties, climatic conditions, and cultivated crops. When designing drainage systems, it is crucial to increase the hydraulic functioning of the entire system. These systems are mostly installed in soils with high clay content, i.e., heavy soils with very low hydraulic permeability (Tuli et al., 2005). In such soils, subsurface drainage systems can substantially reduce surface runoff, shorten periods of surface ponding, and lower water table (Konyha et al., 1992; Skaggs et al., 1994). Under certain conditions, including high groundwater table, large and intensive precipitation, and heavy-textured soils, the installation of tile drains may not be sufficient to provide favorable conditions for growing crops. Additional measures may then be needed, such as using a backfill material (gravel) with a high hydraulic conductivity above tile drains or performing *mole drainage*. The presence of a gravel layer above tile drains up to the tilled layer may increase the efficiency of the entire system by promoting by-pass flow of water from the tilled layer directly into the drains. Mole drains are closely-spaced unlined channels of limited duration that are formed in clay subsoil using a ripper blade with a cylindrical foot, often with an expander, which helps to compact and stabilize the channel walls. Mole drainage has been recommended for heavy soils with low

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http://dx.doi.org/10.1016/j.agwat.2014.07.020
0378-3774/

permeability, which would otherwise require a small drain spacing (Hudson et al., 1962). During the construction of the mole channels the foot and expander create a 'leg slot' directly above the mole as well as fissures in the soil upwards from the mole toward the plough layer. These cracks and fissures can promote preferential flow toward mole drains (Leeds-Harrison et al., 1982). Mole drains are intended to improve lateral flow to tile drains and are usually used only in soils with a high clay content (>35%). If established properly and under the right conditions, they may still be operating after five years (Harris, 1984). Tile and mole drains are nonconductive under unsaturated conditions because positive pressure must occur before water can start flowing into them (Stormont and Zhou, 2005).

In recent years, numerical models have been developed to simulate water flow in tile-drained soils. One-dimensional (1D) models (e.g. MACRO, Larsbo and Jarvis, 2003) use an approximate analytical solution of Darcy's equation to account for water loss through the drainage system (e.g., Hooghout, Ernst, or Boussinesq's equations), while two- or three-dimensional (2D or 3D) models (e.g. HYDRUS (2D/3D), Šimůnek et al., 2006) use the Richards equation to explicitly model the dynamics of the water table. In 1D models, the flow to tile drains is implemented as a sink term in the mass balance equation. The Houghoudt's equation is based on the Dupuit–Forchheimer assumptions with corrections for convergence of radial flow near the tiles. When combining the Houghoudt's equation (for the saturated zone) with the Richards equation (for the unsaturated zone), the Houghoudt's equation gives instant lateral fluxes to tile drains, while the Richards equation gives transient fluxes in the unsaturated zone, leading to a rise or drop of the water table. An example of such model is DrainMod, which has been used in many applications. For example, Skaggs et al. (2012) used DrainMod to simulate water flow in a subsurface-drained agricultural field in eastern North Carolina. The performance statistics indicated that the model with calibrated input data accurately predicted daily water table depths, daily drainage rates, and monthly drainage volumes. Singh et al. (2006) calibrated and tested DrainMod on two types of soils in Iowa and used it to simulate the impacts of different designs of subsurface drainage systems. Simulation results suggested that a drainage system designed for a drainage intensity of 4.6 mm d^{-1} with a drain depth of 1.05 m and a drain spacing of 25 m was sufficient to maximize crop production under the prevailing local agricultural conditions.

Water flow and solute transport to tile drains has been also evaluated using the HYDRUS family of codes (Šimůnek et al., 2008). For example, the HYDRUS-2D software package was used by De Vos et al. (2000, 2002) to simulate nitrate transport in a tile-drained layered silt loam soil in a reclaimed Dutch polder, or by Castanheira and Serralheiro (2010) to evaluate the impact of mole drains on salinity of a vertisol under irrigation.

Numerical modeling of drainage systems involving both tile and mole drains is much more limited. Snow et al. (2007) used the APSIM-SWIM model to predict drainage rates and runoff in a mole-tile drained silty loam soil of New Zealand. There was an excellent agreement between simulated and measured drainage, as well as a reasonable agreement between measured and simulated cumulative surface runoff. Armstrong et al. (2000) performed a modeling study on a macroporous clay soil with mole and tile drains, in which they compared four "preferential flow" models (MACRO, CRACK-NP, SIMULAT and PLM) in their ability to simulate isoproturon leaching. MACRO model gave the best results, although globally the simulations showed the difficulty of deriving adequate parameters, even where relatively complete soil physical data were available. A similar study was performed by Besien et al. (1997) on a structured heavy clay soil with tile (0.75 m depth and 50 m spacing) and mole drains (0.5 m depth and 3 m spacing) in which the MACRO model was calibrated and used to investigate the leaching of isoproturon. Madvar et al. (2007) used the SEEP/W model to simulate the hydraulic performance of mole and tile drains in heavy-textured soil. Based on their numerical study the combination of mole and tile drains resulted in economical and hydraulic improvement of the agricultural system.

Most of modeling studies considered water flow in one- or two-dimensional soil profiles, either taking into account only tile drainage without mole drainage or mole drainage without tile drainage (e.g., Castanheira and Serralheiro, 2010), but not both in a fully three-dimensional system. This is mainly because mole drains, being installed in a perpendicular direction to tile drains, make the entire system three-dimensional. Since we could not identify any study that simulated water flow in systems with tile and mole drains as a three-dimensional problem, we conducted 3D numerical experiments to evaluate the performance of these systems. In our numerical simulations we considered environmental conditions that are typical for the eastern part of Croatia. Hydromorphic soils in Croatia cover an area of 1618,500 ha, which is approximately one third (29%) of the total area occupied by agricultural soils (Husnjak, 2007). Subsurface tile drainage systems are installed on 161,530 ha (Petošić et al., 2004), with mole drainage often used to improve drainage efficiency.

The main objective of this paper was to numerically evaluate the performance of different subsurface drainage systems of increasing complexity in hydromorphic soils using a three-dimensional model that can explicitly account for any drainage system. (i) The simplest system to be considered consists of a layered soil profile with parallel tile drains. Such system can be simulated using a two-dimensional simulation domain that is perpendicular to tile drains. (ii) In the second set of simulations it is assumed that a backfill material (gravel) of higher hydraulic conductivity than the original soil is placed above the drains. Such system can also be evaluated assuming a two-dimensional simulation domain perpendicular to drains. (iii) Finally, the most complex system consists of tile drains with backfilled gravel above drains, combined with perpendicular mole drains. Such system has to be analyzed using a fully three-dimensional flow model.

2. Materials and methods

2.1. Theory

Subsurface water flow in the unsaturated and saturated zones is governed by the mass balance equation and the Darcy–Buckingham's law:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial J_{wi}}{\partial x_i} - S(h) \quad (1)$$

$$J_{wi} = -K(h)K_{ij}^{A}\frac{\partial H}{\partial x_j} = -K(h)\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{ij}^{A}\right) \quad (2)$$

respectively, where θ is the volumetric water content [L^3L^{-3}], J_{wi} is Darcy's flux [LT^{-1}] in the i-th direction, S is a sink/source term [T^{-1}], $K(h)$ is the saturated/unsaturated soil hydraulic conductivity function [LT^{-1}], ${K_{ij}}^A$ are the components of the dimensionless anisotropy tensor for hydraulic conductivity K^A [–], H is the total hydraulic head [L] defined as the sum of the pressure head and the gravitational head, $H = h + z$, x_i are the spatial coordinates [L], with x and y being horizontal coordinates and z the vertical coordinate directed upwards, and t is time [T]. The governing flow equation for these conditions, resulting from combining (1) and (2), is given by the following modified form of the Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{ij}^{A}\right)\right] - S \quad (3)$$