Agricultural Water Management 192 (2017) 244–256

Contents lists available at ScienceDirect

Agricultural Water Management

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

Simulation of soil water movement under subsurface irrigation with porous ceramic emitter

Yaohui Cai[a], Pute Wu[a,b,*], Lin Zhang[b], Delan Zhu[a], Junying Chen[a], ShouJun Wu[a], Xiao Zhao[a]

[a] College of Water Resources and Architecture Engineering, Northwest A&F University, Yangling, Shaanxi, 712100, PR China
[b] Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling, Shaanxi, 712100, PR China

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 29 June 2017
Accepted 10 July 2017

Keywords:
Ceramic emitter
Hydrus-2D
Wetting pattern
Structure parameters
Buried depth
Installation method

ABSTRACT

Subsurface irrigation has been achieved by using ceramic emitters, pitchers, pots and ceramic tubes, which have gained a certain degree of interest in arid regions due to their efficient use of water. Research on the formation of wetting patterns around the ceramic emitter is essential for the design of irrigation system. In this study, numerical simulations were carried out to investigate the effects of emitter installation method, emitter buried depth, emitter structural parameters, irrigation doses and initial soil water content on the wetting patterns in clay loam with Hydrus-2D. Finally, two field application experiments were conducted to test the practicality and reliability of simulation results. The simulation results were in good agreement with the experimental data. Results showed, emitter installation method had the least effect on the wetting pattern. A 25 cm buried depth would be suit for irrigating vegetables, a 45 cm deep buried depth would suit for irrigating fruit trees. The structure parameters had a significant effect on cumulative fluxes and horizontal wetting front, the structural parameters (emitter length is 7.00 cm, emitter external diameter is 1.25 cm, and emitter inner diameter is 0.60 cm) would be a better fabricate parameters for ceramic emitter. Wetting front increased with increasing irrigation doses and initial water content. To prevent percolation, when the initial water content was high, it should be better to cut down the irrigation duration of ceramic emitter. The field results indicated that Hydrus-2D could be used to investigate the suitable parameters for ceramic emitter in subsurface irrigation systems and determine the suitable arrangement and operation mode of ceramic emitter.

1. Introduction

Sub-surface irrigation is an efficient traditional irrigation method, which gains extensive interests in arid regions due to its low manufacturing cost and high water use efficiency (Sheng, 1974; Bainbridge, 2001; Sammis, 1980; Ayars et al., 1999; Batchelor et al., 1996). Sub-surface irrigation has been practiced commonly by buried pots, pitchers and porous pipes which were made of unglazed porous ceramics (Mondal, 1974; Siyal et al., 2013; Abu-Zreig and Atoum, 2004; Stein, 1997). Porous ceramic emitter is an improved version of the traditional method of subsurface irrigation, with good performance and low cost (Cai et al., 2015). In porous ceramics, well-connected micro-pores form large amounts of water transfer channels so that water permeating into the porous ceramics can seep out and arrive into soils by the well-connected pore channels (Simonis and Basson, 2011; Salamon et al., 2010). Compared with drip fertigation, the consecutive and stable water supply of negative pressure fertigation with ceramic emitter improved tomato fruit yield and water use efficiency (WUE) by 1.6–8.2% and 9.9–30.5% in the North China Plain, respectively (Li et al., 2017). Similarly, Zhang et al. (2009) found that tomato irrigated by ceramic emitter under the working pressure of 0 cm got the highest yield, about 1.17 kg pot^{-1}, but the lowest WUE, about 24.9 kg m^{-3}.

In order to minimize wetting of soil surface (evaporation losses) and deep percolation, increase the WUE, the proper design of irrigation system with ceramic emitters as the core component requires information of the soil wetting patterns around the ceramic emitters. Furthermore, the size of the wetting pattern is an essential factor governing the distribution of emitters along the pipelines. Ordinarily, the soil wetting pattern under a ceramic emitter is affected by soil hydraulic properties, emitter working pressure and other factors. In the past two decades, several researchers have

* Corresponding author at: College of Water Resources and Architecture Engineering, Northwest A&F University, Yangling, Shaanxi, 712100, PR China.
E-mail address: gjzwpt@vip.sina.com (P. Wu).

http://dx.doi.org/10.1016/j.agwat.2017.07.004
0378-3774/

studied the factors affecting soil water movement of ceramic emitter. Kato and Tejima (1982) researched the soil water movement under a porous ceramic tube with different hydraulic conductivity in a condition of constant working pressure, which showed a positive correlation between the wetting pattern and tube length. Das Gupta et al. (2009) found that the discharge of porous clay pipe was a function of the soil texture and the applied hydraulic head in the soil. So as to effectively design, assessment, and use of ceramic emitters, it is necessary to consider parameters as much as possible to predict the soil wetting pattern accurately.

Hydrus-2D is a well-known computer software package that could accurate and efficient analysis of water flow and solute transport in variably saturated porous media (Naglič et al., 2014; Abou Lila et al., 2013; El-Nesr et al., 2014), such as subsurface irrigation and pitcher irrigation. The soil wetting patterns under a porous ceramic pipe were investigated by Siyal et al. (2009a), they showed that predictions of the soil water content made with Hydrus were in good agreement with the observed data, and the depth of wetting pattern increased with installation depth, installation depth also affected the upper position of wetting front. In addition, the effect of pitcher sizes on the zone of wetting, water content distribution was also demonstrated by Siyal et al. (2009b), they found that the volume of small pitcher was near half of the large one, but with double hydraulic conductivity, would produce approximately the same wetting front as large one. However, there are two differences between porous ceramic emitter and pitcher or clay pipe. One is ceramic emitter is much smaller than traditional pitcher and clay pipe, the other is installation method, pitchers were all buried in the soil down to their neck, the clay pipe was all buried in the soil and water was conveyed and applied through the same pipe. Therefore, the soil water movement of the ceramic emitters may be different from that of the pitchers and the clay pipes.

In this study, the wetting patterns obtained by Hydrus-2D simulation were compared with the experiments data from soil tank experiments. And then Hydrus-2D model was used to investigate numerically the effect of installation method, buried depth, structural parameters, irrigation doses and initial soil water content on wetting pattern of porous ceramic emitter. And thus, the suitable installation method, buried depth and structural parameters were given out. In addition, field application experiments were conducted to valid the practicality and reliability of simulation results.

2. Materials and methods

2.1. HYDRUS simulations

2.1.1. Numerical modelling theory

Soil water from the porous ceramic emitter into the soil was simulated using HYDRUS-2D software package (version 2.03) (Šimůnek et al., 2006, 2016). Assuming a homogeneous and isotropic soil, the governing two-dimensional flow equation is described by Richards equation (Richards, 1931; Celia et al., 1990), and the equation is solved by the Galerkin finite-element methods:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}[K(h)\frac{\partial h}{\partial x}] + \frac{\partial}{\partial z}[K(h)\frac{\partial h}{\partial z}] + \frac{\partial K(h)}{\partial z} \quad (1)$$

where θ is the volumetric water content [L^3L^{-3}], t is the time [T], x is the horizontal coordinate [L], z is the vertical coordinate that is positive upward [L], h is the pressure head [L], $K(h)$ is the unsaturated hydraulic conductivity [LT^{-1}].

The soil water retention, $\theta(h)$, and hydraulic conductivity, $K(h)$, were described using the analytical functions of van Genuchten (1980) as follows:

$$S_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \frac{1}{(1+|\alpha h|^n)^m}(m = 1\text{-}1/n) \quad (2)$$

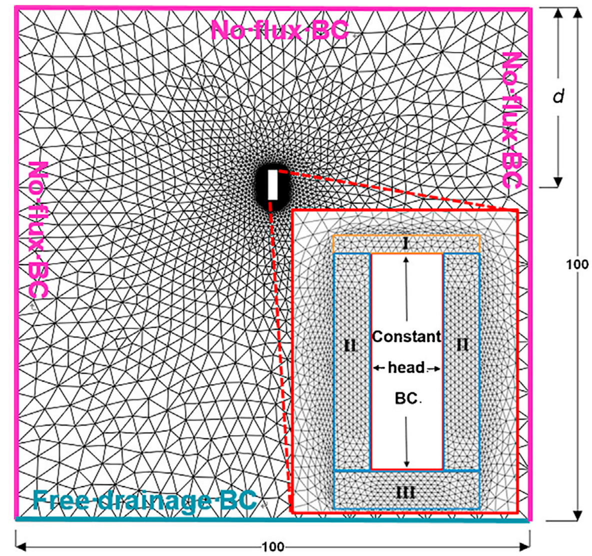

Fig. 1. Location of the ceramic emitter and the transport domain with applied boundary conditions (I, Lip; II, Emitter-circular tube; III, Emitter-bottom).

$$K(h) = K_s S_e^{0.5}[1-(1-S_e^{1/m})^m]^2 \quad (3)$$

where S_e is the relative saturation; K_s is the saturated hydraulic conductivity; θr and θs are the residual and saturated water contents [L^3L^{-3}], respectively; and α is an empirical parameter [L^{-1}] inversely related to the air entry value, n and m are all van Genuchten-Mualem shape parameters.

The HYDRUS model inputs for simulating water flow included flow domain geometry, soil hydraulic parameters and initial and boundary conditions. Geometry and boundary conditions for defining the physical problem of this study are shown in Fig. 1.

2.1.2. Modeling domain geometry

In actual situation, the emitter spacing is large than 50 cm, so the simulated domain for water flow was rectangular, 100 cm wide and 100 cm deep, i.e., large enough so that an overlap in water content profiles from neighboring emitters do not have to be considered. The ceramic emitter with a lip is located in the central of the domain (buried deep was d). The domain was discretized into 9978 finite triangular elements with a very fine grid within the ceramic emitter wall and in the soil near the ceramic emitter (0.2 cm), and gradually increasing elements farther from ceramic emitter (up to 5 cm in the bottom boundary, up to 2 cm in the surface boundary).

2.1.3. Boundary conditions

The ceramic emitter internal boundary nodes were assigned a constant pressure head (0 cm), were identical to the pressure head implemented in the soil tank laboratory experiments. The left and right boundary was set as a "zero flux" condition. The bottom boundary was set as a "free drainage boundary condition". The surface boundary condition was also set as a "zero flux boundary condition" when compared the results of measuring and simulating, the water evaporates rate was considered to be 0 mm d^{-1}, because when compared the results of measuring and simulating, the test duration is only 5 h, and the surface of soil is cover with plastic sheeting, so the evaporates rate is negligible. In order to simulate the situations closer to the real situation, an "atmospheric boundary condition" was used when the simulation duration was 120 h, the water evaporates rate was considered to be 0.4 mm d^{-1}, daily variations of evaporates rate were not considered.