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Measured and simulated soil wetting patterns under porous clay pipe sub-surface irrigation

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ABSTRACT

Sub-surface irrigation with porous clay pipe can be an efficient, water saving method of irrigation for many less developed arid and semi-arid regions. Maximizing the efficiency of clay pipe irrigation requires guidelines and criteria for system design and operation. In this study, experimental and simulated (with HYDRUS (2D/3D)) soil wetting patterns were investigated for sub-surface pipe systems operating at different water pressures. Predictions of the soil water content made with HYDRUS were found to be in good agreement ($R^2 = 0.98$) with the observed data. Additional simulations with HYDRUS were used to study the effects of various design parameters on soil wetting. Increasing the system pressure increased the size of the wetted zone. The installation depth affects the recommended lateral spacing as well as the amount of evaporative water loss. For a given water application, the potential rate of surface evaporation affected the shape of the wetted region only minimally. Soil texture, due to its connection to soil hydraulic conductivity and water retention, has a larger impact on the wetting geometry. In general, greater horizontal spreading occurs in fine texture soils, or in the case of layered soils, in the finer textured layers.

1. Introduction

Improving agricultural water use efficiency is vitally important in many parts of the world that have limited water resources. Sub-surface irrigation, in which water is applied below the soil surface, can help conserve water by reducing evaporative water losses in agricultural systems. Sub-surface irrigation has been practiced in various forms since ancient times, including pitcher or pot irrigation (e.g. Bainbridge, 2001; Siyal et al., submitted for publication) and perforated or porous clay pipe irrigation (e.g. Ashrafi et al., 2002; Qiaosheng et al., 2007). The development of plastic micro-irrigation technology in the last century led to increased use of sub-surface irrigation. Today, sub-surface micro-irrigation is used throughout the world to irrigate field crops, vegetables, and fruits (Camp, 1998). However, in many parts of the world, plastic drip tubing and emitters are cost-prohibitive, and traditional methods such as clay pipe irrigation remain an important technique for irrigation and water conservation.

In traditional sub-surface pipe irrigation systems perforated or porous pipes are buried in the soil. Water seeps from the pipe into the soil and spreads out in the root zone due to capillary forces. Batchelor et al. (1996), Hegazi (1998), and Bainbridge (2001) found that traditional sub-surface irrigation methods have high water use efficiency, i.e., high crop production per amount of applied water. The efficiency may be affected by the water application rate and by system design parameters such as the size, depth, and spacing of pipes, etc., which determine the extent of deep percolation water losses and soil saturation problems. Also, evaporation losses are minimized when the wetting front is kept below the soil surface. Hence, an ability to predict the geometry and moisture distribution of the wetted zone for different soils, pipe compositions, and system designs can be very useful for developing guidelines and criteria for optimizing the performance of traditional sub-surface irrigation systems (e.g. Zur, 1996).

Soil wetting patterns under surface and sub-surface micro-irrigation have been measured and/or analyzed theoretically by a number of authors, including Bresler (1978), Assouline (2002), Cote et al. (2003), Skaggs et al. (2004), Gärdenäs et al. (2005), Singh et al. (2006), Wang et al. (2006), and Lazarovitch et al. (2007), to name only a few. Among these studies, several of the more recent ones (e.g. Assouline, 2002; Cote et al., 2003; Skaggs et al., 2004; Gärdenäs et al., 2005) have used HYDRUS-2D (Šimůnek et al., 1999) to simulate soil wetting. For example, Skaggs et al. (2004) demonstrated that HYDRUS-2D simulations of drip irrigation were in agreement with detailed field measurements. Nevertheless, not much work has been done focusing specifically on traditional sub-surface systems. Analyzing traditional systems differs in that it is generally necessary

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to explicitly model the geometry and hydraulic properties of the pitcher or pipe, whereas modern drip equipment can often be modeled as an idealized object such as a line source (Ashrafi et al., 2002). Previous analyses of traditional systems include numerical modeling of infiltration and water distributions under sub-surface clay pipe (Ashrafi et al., 2002) and pitcher (Siyal et al., submitted for publication) irrigation, and dimensional analysis of the wetted region under sub-surface porous pipe irrigation (Qiaosheng et al., 2007).

The objective of this study was to simulate with the HYDRUS (2D/3D) software package (Šimůnek et al., 2006) soil wetting under sub-surface porous pipe irrigation and to investigate relationships among the hydraulic and physical parameters and soil wetting patterns as affected by irrigation design and management practices. HYDRUS (2D/3D), also known simply as HYDRUS, was released in 2006 and is an update of the HYDRUS-2D code. Ashrafi et al. (2002) previously presented numerical simulations of infiltration from clay pipe irrigation and compared the results with data obtained in a laboratory using a soil-bin measuring 124 cm × 124 cm × 15 cm. In our work, the simulations are compared with data obtained under field conditions.

2. Methods and materials

2.1. Field experiment

A sub-surface irrigation experiment featuring baked clay pipes was carried out in the experimental field of the Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, Pakistan. The site is located at 25°25′28″N, 68°32′25″E and is at an elevation of about 26 m above sea level. Trenches 20 m long and 0.43 m deep were excavated for burying clay pipes.

In Pakistan, clay irrigation pipes are made by hand. A local skilled potter was asked to prepare clay pipes for the experiment. Pipes longer than 40 cm in length and smaller than 10 cm in diameter were difficult for the potter to shape. Additionally, the potter indicated that larger pipes have a higher likelihood of cracking. Therefore, pipes with approximately 10 cm diameter and 40 cm length were prepared using clay soil and baked in a kiln. The pipe wall thicknesses and outside diameters were measured with a Vernier Calliper and found to be 1.5 ± 0.11 cm and 13.1 ± 0.20 cm, respectively. So that the pipes could be joined, one end of the pipes tapered to a 15-cm diameter. Pipes for the terminal end of the laterals were made with a closed end, whereas pipes for the beginning of the laterals tapered on one end to a 6.2 ± 0.12 cm outside diameter so that it could be connected to the steel main line using rubber pipe and hose clamps (Fig. 1). The porosity of the pipes was determined to be 0.36 ± 0.01 based on the difference in weights of dry and saturated pipes.

Longer pipe segments were formed by cementing together four pipes. These segments were then placed in the trench and cemented together to form 20 m long pipes (Fig. 1). The pipes were buried with soil that was removed during excavation at a depth of 30 cm (measured to the top of the pipe). Water was fed to the irrigation system from an aboveground storage tank. A water meter and pressure gauge were installed at the beginning of the

Fig. 1. Baked clay pipes and their installation at the experimental field.

irrigation laterals, as were valves for modifying water flow and pressure. In total, 25 clay pipe lateral lines were installed at a spacing of 1 m.

Water was supplied continuously to one of the laterals for 5 days at a hydraulic head of 200 cm. At the end of the 5 days, soil samples were taken from the depths 0, 15, 30, 45, 60, 75 and 90 cm, at distances 15, 30 and 45 cm on both sides of the pipe. The gravimetric water contents of the samples were determined by recording the weight loss of the samples after oven drying at 105 °C for 24 h. Due to the presumed symmetry of the wetted zone, the two water contents for the same depths and distances on opposite sides of the pipe were averaged for data analysis. Wetting patterns after 5 days of irrigation with hydraulic heads of 100, 50 and 25 cm were subsequently obtained on different laterals. In each case, the soil around the lateral was initially dry.

The hydrometer method was used to determine the soil particle size distribution. The texture of the soil according to the USDA system was found to be loam, with the sand content ranging from 40 to 46%, silt from 30 to 45%, and clay from 15 to 24%. Soil bulk density was determined at several locations down to a depth of 90 cm using a core sampler with 1.5 cm diameter. The density measurements ranged from 1.25 to 1.30 g cm^{-3}. No obvious trend in the bulk density was observed, so the average value of 1.27 g cm^{-3} was used to convert the gravimetric water content data to volumetric water content.

The saturated hydraulic conductivity of the clay pipes was measured in the laboratory using the falling head method described by Abu-Zreig and Atoum (2004). This procedure involved first submerging a pipe in water for 3 days. To seal the ends of the pipe, clay disks, made from the same clay baked at the same temperature, were attached with plaster of Paris. The pipe was submersed down to its neck in a container in which the water level was kept constant by an overflow (Fig. 2). A graduated manometer tube with 0.5 cm diameter was inserted into a hole drilled in the upper disk. The manometer tube (and thus the irrigation pipe) was filled with water, creating a hydraulic head drop across the wall of the pipe equal to the height of water in the manometer above the water surface in the bucket (Fig. 2). The decline in the water height in the manometer over time was monitored and recorded. The hydraulic conductivity of the saturated pipe was then determined according to:

$$\ln\left(\frac{h_o}{h}\right) = K_s \frac{At}{aL} \tag{1}$$

where h_o is the initial height of water in the manometer above the free water surface (L), h is the height of water in the manometer at time t (L), A is the surface area of the clay pipe (L^2), a is the cross-sectional area of the manometer tube (L^2), L is the average wall thickness of the pipe (L), K_s is the hydraulic conductivity at saturation (L T^{-1}), and t is time (T).

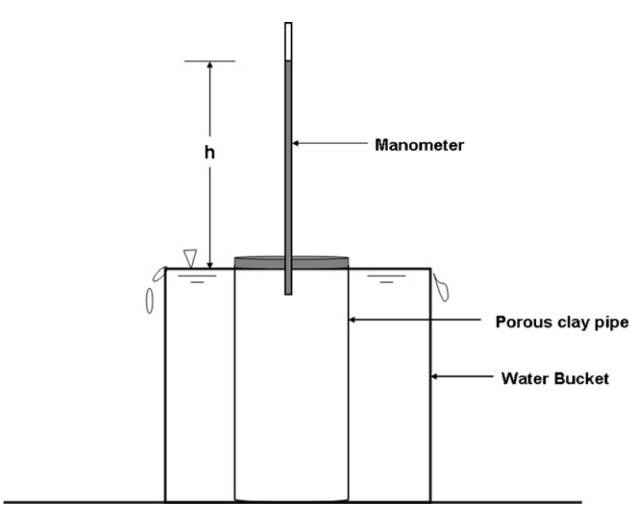

Fig. 2. Diagram illustrating the falling head method used to measure the saturated hydraulic conductivity of the clay pipes.

2.2. HYDRUS simulations

The HYDRUS (2D/3D) software package (Šimůnek et al., 2006) simulates variably saturated water flow in porous media by solving the mixed form of the Richards equation (Celia et al., 1990) using a Galerkin finite-element method. We used HYDRUS to simulate water infiltration and redistribution from a sub-surface porous clay pipe source. The soil hydraulic properties in HYDRUS are based on the van Genuchten (1980) model:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{-\theta_r}{(1+|\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{2}$$

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

where θ_r and θ_s are the residual and saturated water contents ($L^3\,L^{-3}$), respectively; K_s is the saturated hydraulic conductivity (L T^{-1}); α is an empirical constant that is inversely related to the air-entry pressure value (L^{-1}); n is an empirical parameter related to the pore-size distribution (unitless); l is an empirical shape parameter; $m = 1 - 1/n$ (unitless); and S_e is the effective saturation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4}$$

Only the right side of the vertical cross-section was simulated, with the clay pipe located on the left side of an otherwise rectangular computational domain (Fig. 3). Similar to the approach of Ashrafi et al. (2002), the pipe wall was included in the flow domain, represented in our case by a half circular wall with a

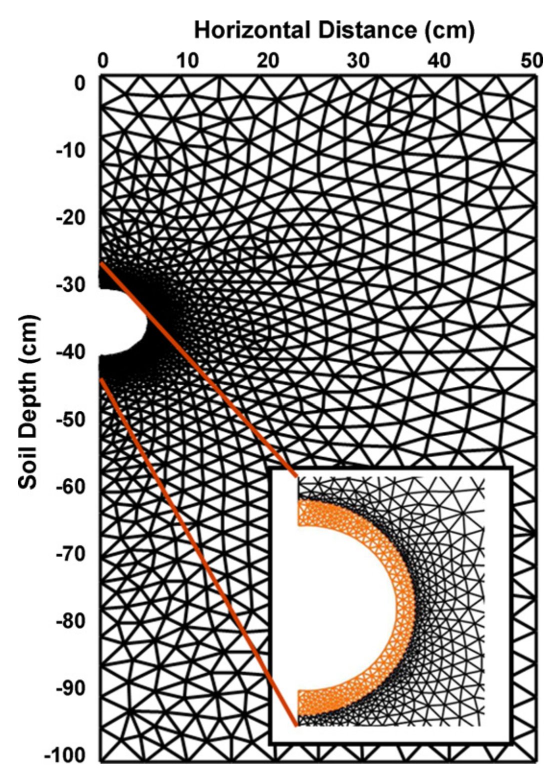

Fig. 3. Typical geometry and finite-element mesh used in the HYDRUS (2D/3D) simulations.

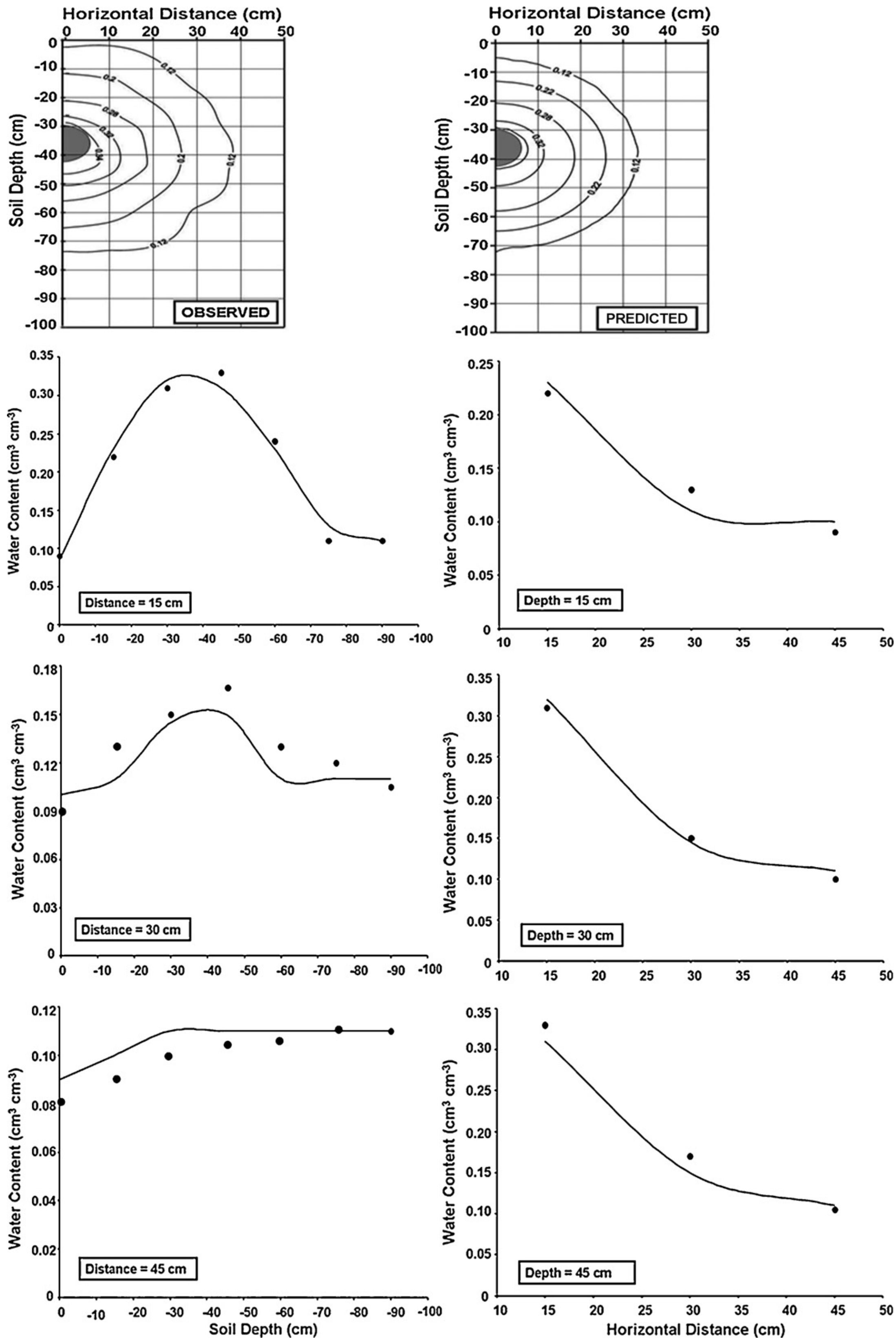

Fig. 4. Measured and predicted water contents after 5 days of irrigation with a constant pipe pressure head of 25 cm. The upper plots show the observed and predicted water content contour maps, while the lower plots compare measured (solid circles) and predicted (solid line) water contents along selected transects.

thickness of 1.5 cm (Fig. 3 inset). The flow domain was discretized with 1333 nodes and 2553 triangular elements, using smaller spacing within the pipe wall and in the soil near the pipe (Fig. 3). The finite-element mesh was generated using the automatic triangulation algorithm that is implemented in HYDRUS (Šimůnek et al., 2006).

Hydraulic parameters (θ_r, θ_s, α, n and l) for nodes representing soil material were determined with the Rosetta pedotransfer

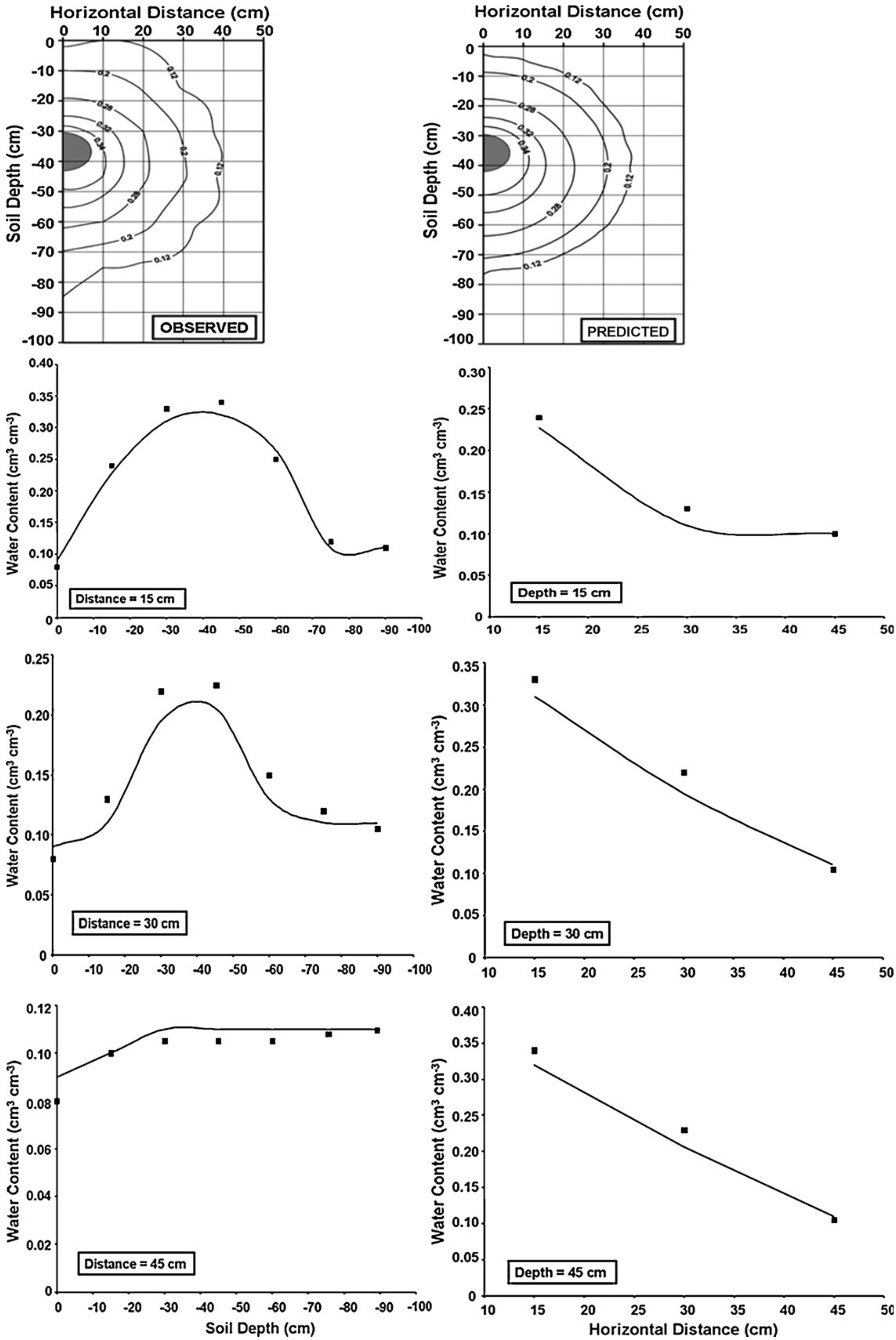

Fig. 5. Measured and predicted water contents after 5 days of irrigation with a constant pipe pressure head of 50 cm.

function model (Schaap et al., 2001) that is provided in HYDRUS. Based on data for the bulk density and percentages of sand, silt and clay, parameters for the loam soil were estimated to be θ_r = 0.078, θ_s = 0.43, K_s = 24.96 cm d^{-1}, α = 0.036 cm^{-1}, n = 1.56 and l = 0.5. For the pipe material, the laboratory measured K_s values for four randomly selected pipes were 0.051, 0.046, 0.055, and 0.048 cm d^{-1}. The average K_s value of 0.05 cm d^{-1} was used in the simulations. Other hydraulic properties for the clay pipe were

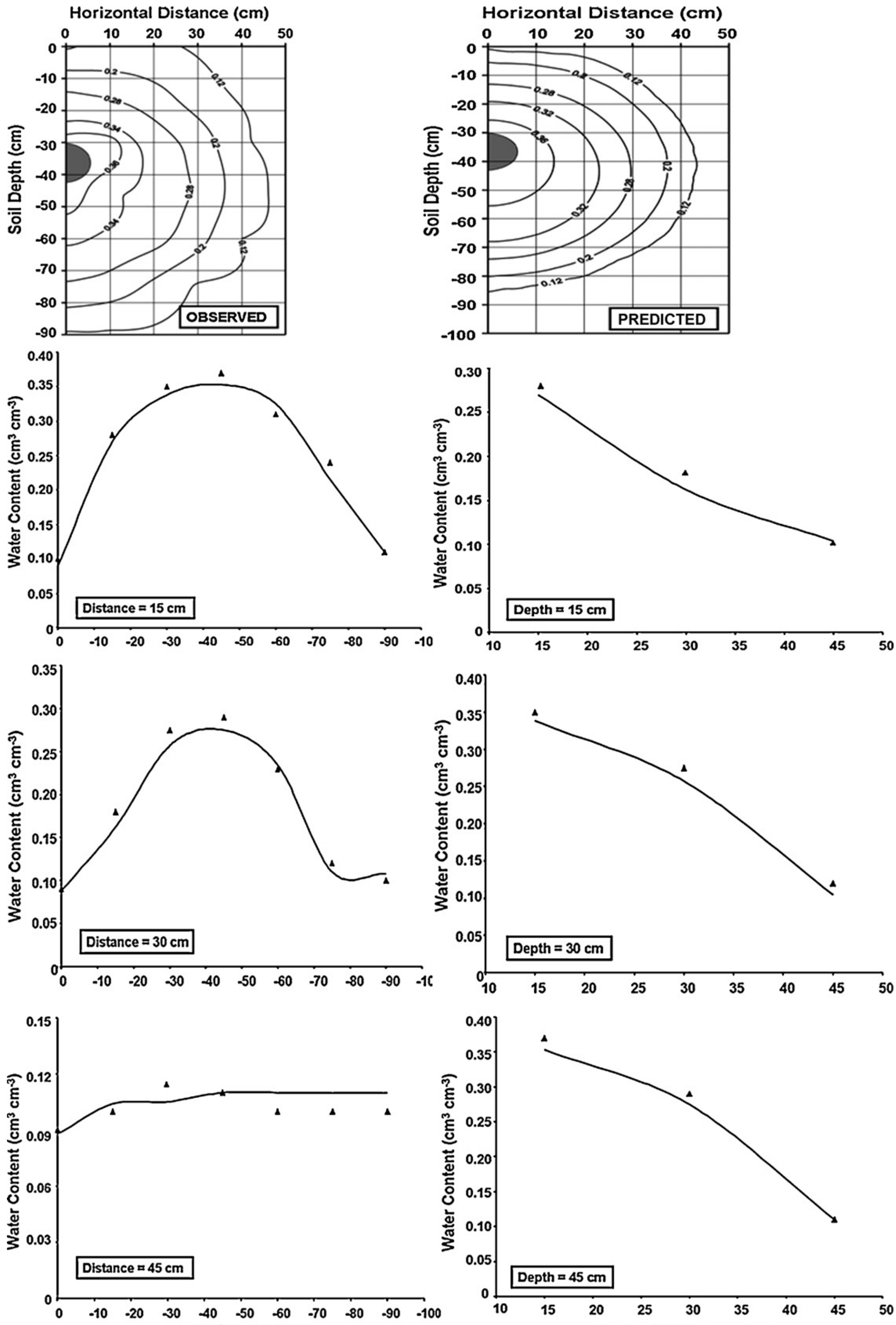

Fig. 6. Measured and predicted water contents after 5 days of irrigation with a constant pipe pressure head of 100 cm.

taken to be θ_s = 0.35, θ_r = 0.042, α = 0.000001 cm^{-1}, n = 1.3 and l = 0.5. The small value of α was chosen so that the pipe wall would remain saturated throughout the simulations, and thus the assumed unsaturated parameter (θ_r, θ_s, n and l) values for the pipe wall material were of no consequence. To test the sensitivity of our results to this assumed α value, we additionally made simulations with α = 0.0016 cm^{-1}, a value that would be appropriate given the estimated soil hydraulic parameter values and an assumption that the soil and pipe materials were similar in the sense of Miller and Miller (1956). We found that simulated soil

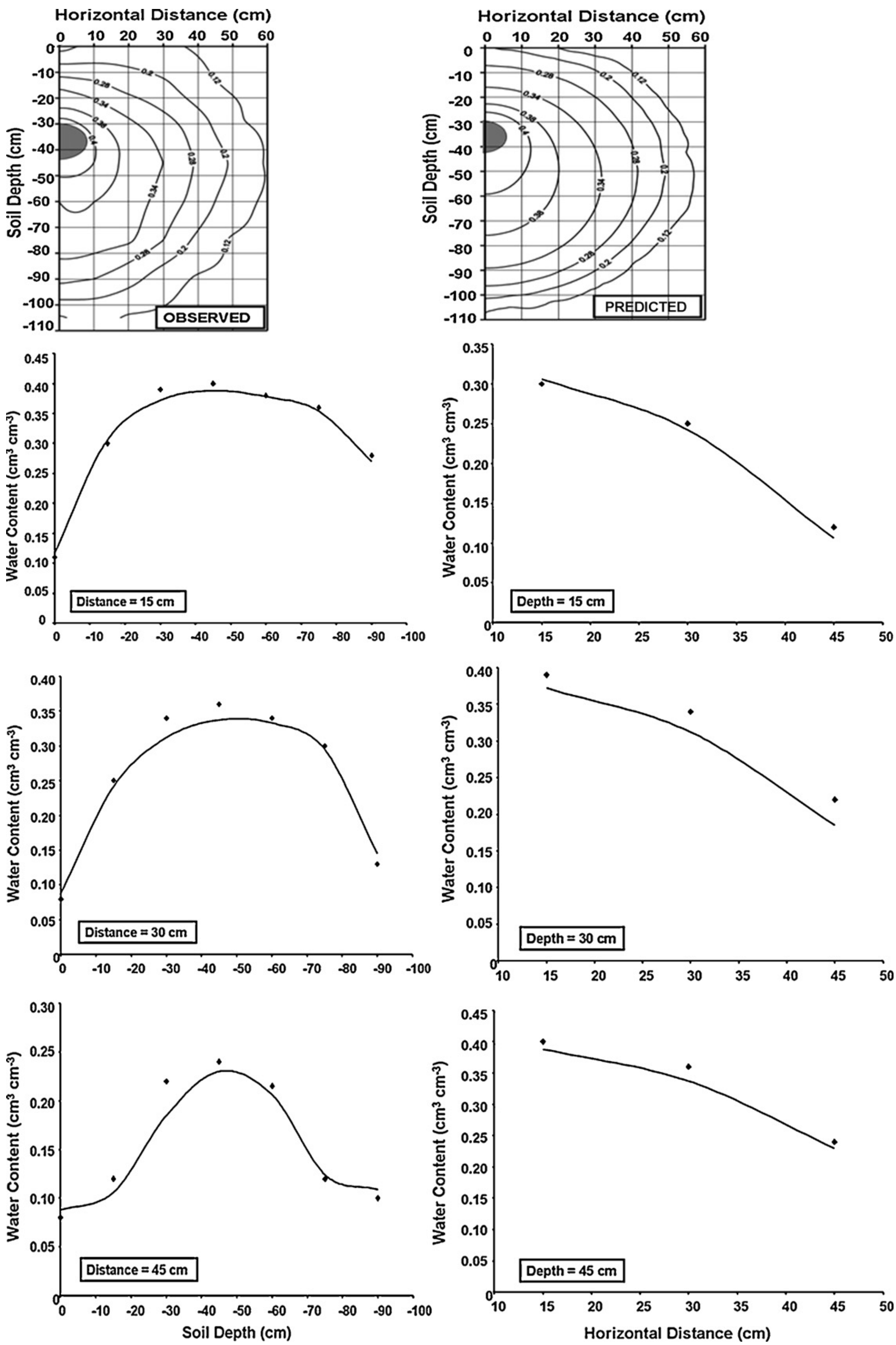

Fig. 7. Measured and predicted water contents after 5 days of irrigation with a constant pipe pressure head of 200 cm.

wetting was not substantially different using the two α values, and thus we discuss below only results obtained with the smaller α value.

The clay pipe internal boundary nodes were assigned a constant pressure head equal to the pressure head imposed in the experimental trial. The remaining portion of the left boundary was set as a zero flux condition (due to the symmetry of the profile). The surface boundary condition was specified as an "atmospheric boundary condition" (Šimůnek et al., 2006), such that water evaporates from the surface at a constant potential

Table 1
Goodness-of-fit parameters for different pipe pressure heads. (ME = mean error; RMSE = root mean square error; R^2 = coefficient of determination).

Pressure head (cm)	ME ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)	R^2
25	−0.001	0.011	0.974
50	−0.004	0.013	0.970
100	−0.004	0.012	0.984
200	−0.006	0.014	0.983

rate = 0.4 cm d^{-1} when the surface soil water pressure head is above a threshold value = −15,000 cm, and switches to a constant pressure head condition = −15,000 cm if the soil dries down the threshold value. In this way, water evaporates at the potential rate when the surface is wet, and at a lower, soil controlled rate when the soil is dry. The bottom boundary was specified as a "free drainage boundary condition" (unit hydraulic gradient) while the right boundary was a zero flux condition. The computational domain was made sufficiently large such that the right hand and bottom boundaries did not affect water flow (50 cm × 100 cm or 60 cm × 110 cm depending on the imposed pipe pressure head).

The initial soil profile was specified based on the measured water content of soil samples taken when the irrigation pipe was buried. These water content measurements were converted to pressure head values using the soil water retention characteristic given by Eq. (2) with the loam soil parameter values given above. Consistent with these observed values, the initial conditions were specified such that the pressure head increased linearly with depth in the profile, from −3000 cm at the top (z = 0) to −2000 cm at the bottom (z = 100 cm). The initial profile was assumed uniform in the horizontal direction. The clay pipe wall was assumed to be initially saturated (Ashrafi et al., 2002).

2.3. Evaluation of simulation model predictions

The agreement of the HYDRUS simulations with the measured data was quantified with three statistical measures, the mean error (ME), root mean square error (RMSE), and coefficient of determination (R^2). These parameters are defined as (Willmott, 1982)

$$\mathrm{ME} = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \quad (5)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (6)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (7)$$

where N is the total number of data points; P_i is the ith simulated data point; O_i is the ith observed data; and $\bar{O}$ is the mean of observed data. The ME can potentially identify the presence of bias, i.e. under estimation and overestimation, in the predicted values, whereas RMSE gives an overall measure of the amount by which the data differ from the model predictions. Values of ME, RMSE, and R^2 were determined for the water content along various transects in soil profiles.

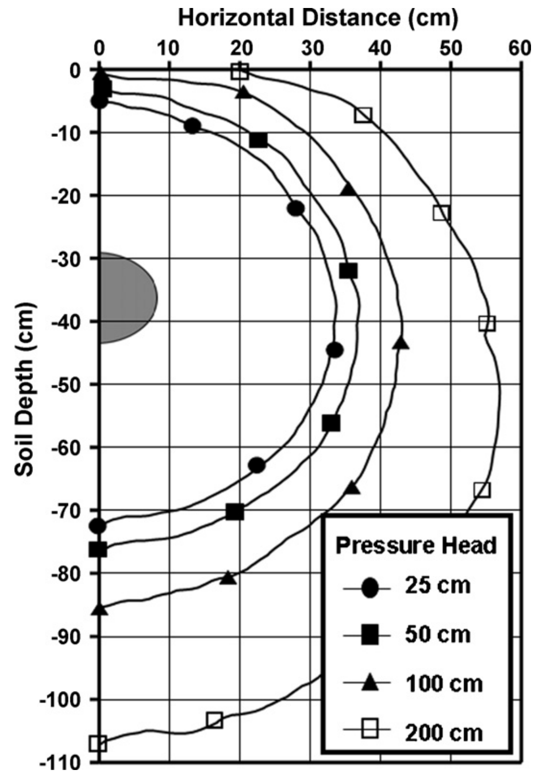

Fig. 8. Predicted wetting fronts after 5 days of irrigation for different pipe pressure heads.

3. Results and discussions

3.1. Comparison of measured and simulated wetting

Figs. 4–7 show measured and simulated water content distributions for sub-surface clay pipe irrigation with line pressure heads of 25, 50, 100, and 200 cm, after 5 days of irrigation. Each figure shows measured and predicted water contents along selected profile transects, as well as contour plots of the observed and simulated water content profiles. The contour plots were drawn using a kriging interpolation algorithm.

It is clear from the contour plots shown in Figs. 4–7 that in general the predicted soil water distribution is in good agreement with the observed; the depths and widths of the wetted area are very close as are the spatial distributions of the water content. The transect plots also indicate good agreement between the experimental and simulated results.

To further evaluate quantitatively the accuracy of the model predictions, the mean error, the root mean square, and the coefficient of determination (R^2) were calculated for observed and predicted water contents. Table 1 contains the calculated values for

Table 2
Parameters used in HYDRUS-2D simulations.

Case	Pressure head (cm)	Soil type	Installation depth (cm)	Evaporation rate (cm d^{-1})	Duration of simulation (days)
I	25, 50, 100, 200	Loam	30	0.4	5
II	100	Loam	20, 30, 40	0.4	5
III	100	Loam	30	0, 0.4, 1, 1.5	5
IV	100	Loam, Sandy loam, Silt, clay loam	30	0.4	5
V	100	Layered	30	0.4	5

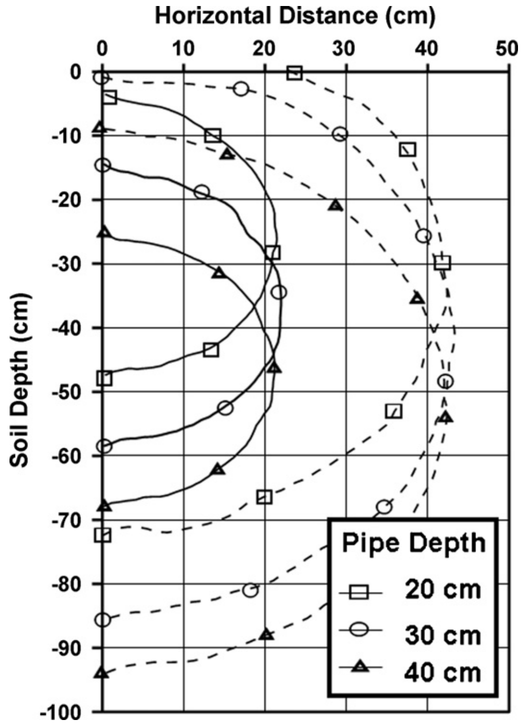

Fig. 9. Predicted wetting fronts for different pipe installation depths and irrigation durations. The pipe pressure head is 100 cm. Solid and broken lines are results for 1 and 5 days of irrigation, respectively.

each pipe pressure head. The absolute value of ME is indicative of model performance. A positive or negative value of ME indicates that the model overestimates or underestimates the experimental results, respectively. The ME values in Table 1 shows that HYDRUS

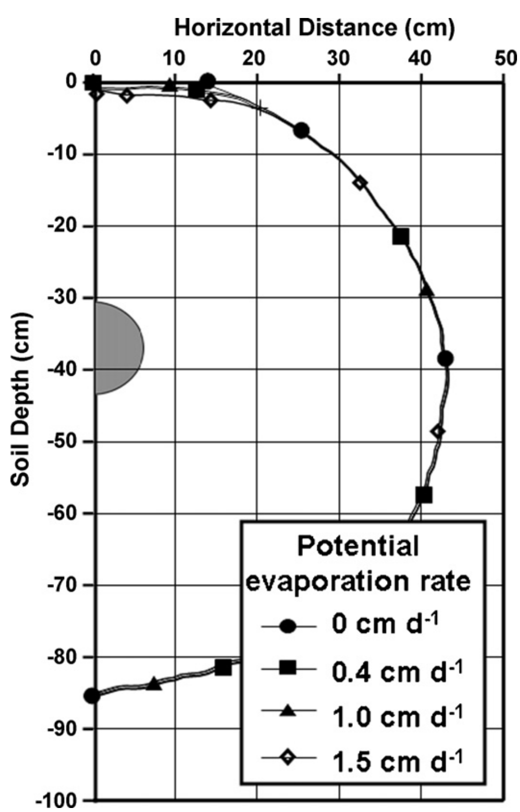

Fig. 10. Predicted wetting fronts after 5 days of irrigation for different potential evaporation rates.

Table 3
Hydraulic parameter values typical of particular soil textural classes (Carsel and Parrish, 1988).

Textural class of soil	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	K_s (cm d^{-1})	A (cm^{-1})	n	l
Sandy loam	0.065	0.410	106.100	0.075	1.890	0.500
Silt	0.034	0.460	6.000	0.016	1.370	0.500
Silty clay loam	0.089	0.430	1.680	0.010	1.230	0.500

underestimated the water content values, with ME being negative for all experimental treatments. However, the underestimation was slight, with the average value of ME being only 6.9% of the mean measured water content across all depths and treatments. The average value of RMSE was 0.012, which corresponds to a very small spread in the data when observed values are plotted against predicted values. The coefficient of determination (R^2) ranged between 0.97 and 0.98, indicating a good model fit. Overall, the observed level of accuracy for the model predictions confirms that HYDRUS is suitable tool for investigating the design of sub-surface clay pipe irrigation systems.

3.2. Effects of various parameters on the wetting pattern

The geometry of the wetted zone may be affected by various parameters, including the pressure head applied in the system, the depth of pipe installation, the potential rate of surface evaporation, and soil texture and layering. Thus HYDRUS simulations were carried out in which these parameters were varied to determine their effect on the geometry of wetted zone. The input data used in these simulations are presented in Table 2.

3.2.1. Pressure head

Fig. 8 shows predicted wetting fronts, after 5 days of irrigation, for different pipe pressure heads (Table 2, Case I). The wetted soil volume increases as the pipe pressure head increases because the higher pressure head increases the water flux through the pipe wall. The effect of increasing pressure head can also be seen by comparing Figs. 4–7, where an increasing wetted region is shown for both model predictions and experimental data.

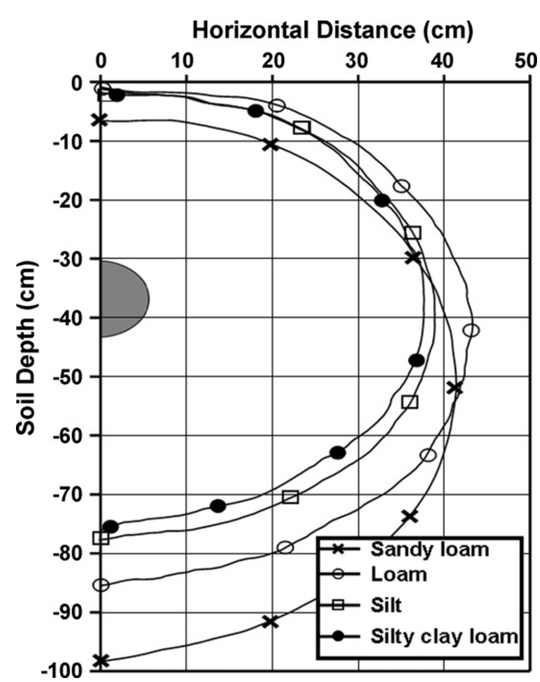

Fig. 11. Predicted wetting fronts after 5 days of irrigation for different soil textures.

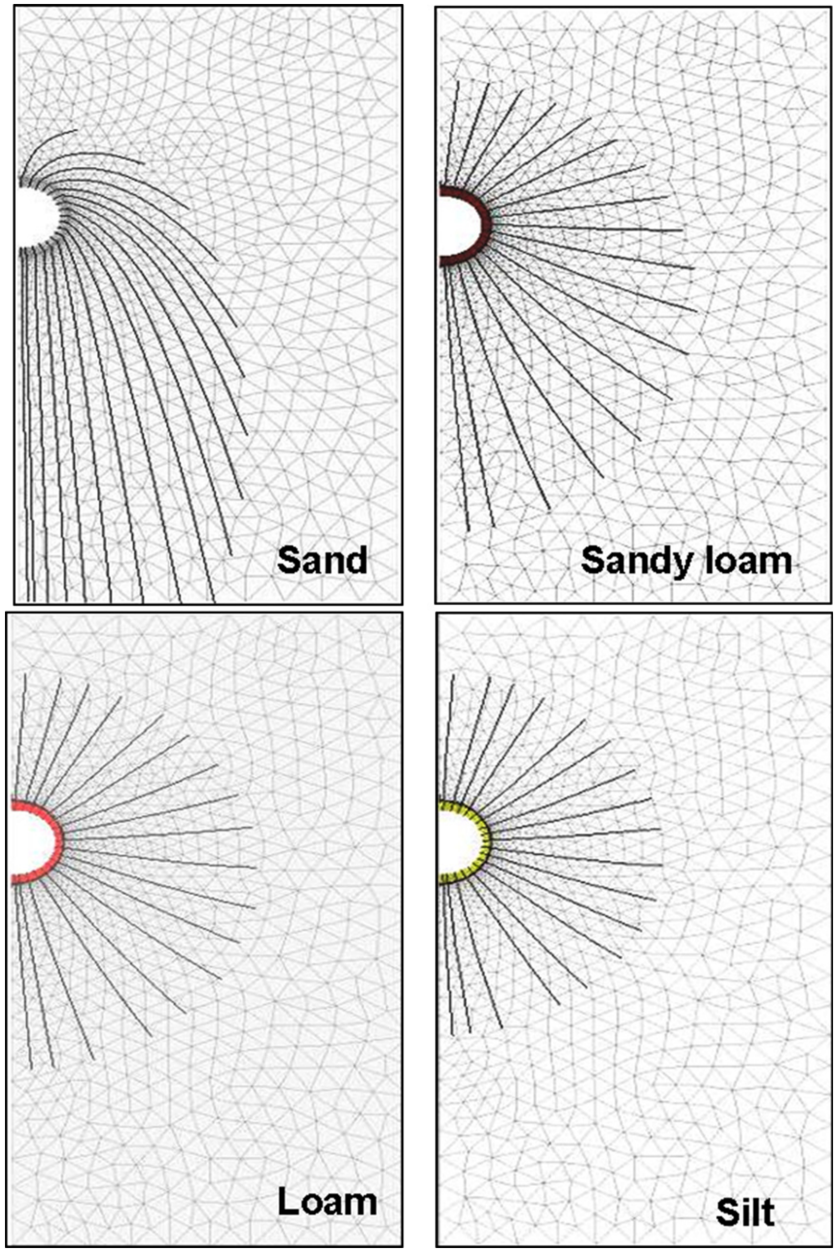

Fig. 12. Paths of flowing particles after 5 days of irrigation for different soil textures.

3.2.2. Depth of pipe installation

The effect of pipe installation depth on the geometry of the wetted zone (Table 2, Case II) is demonstrated in Fig. 9. The figure shows that, as expected, the depth of wetting increases with installation depth, consistent with the observations of Singh et al. (2006). The depth of installation also affects the upper position of wetting front along the soil surface but it has little or no effect on the extent of horizontal wetting deeper in the soil profile. For a given pressure head and irrigation duration, shallower installation depths allow the wetting front to reach the soil surface, where it undergoes increased horizontal spreading. Ashrafi et al. (2002) observed this feature and noted that it implies an inverse relationship between the installation depth and the recommended spacing between laterals, with shallower installations allowing for larger spacings. Shallower depths also minimize installation costs. On the other hand, allowing the water to come to the surface in this manner increases evaporative losses, countering what is potentially a primary benefit of sub-surface irrigation. In our simulations, after 5 days irrigation in a loam soil with a constant potential evaporation rate of 0.4 cm d^{-1}, negligible surface evaporation occurred for pipes installed at 40 cm depth whereas approximately 5.2 and 25.8 cm^2 of water per unit length of pipe was lost for 30 and 20 cm installations, respectively. Thus, for the conditions of our simulations, a 30-cm deep installation might require more laterals and would be more expensive to install, but those costs would be offset by water savings. Deeper installations are also less likely to be damaged by tillage operations.

3.2.3. Evaporation

The previous section noted the evaporative losses that occur for different installation depths. Here we look closer at the effects that evaporation may have on the geometry of soil wetting (Table 2, Case III). Fig. 10 shows that the effect of the potential evaporation rate on wetting geometry is minimal, with the shape of the wetting front near the soil surface changing only slightly as the evaporation rate is increased from 0 and 1.5 cm d^{-1}.

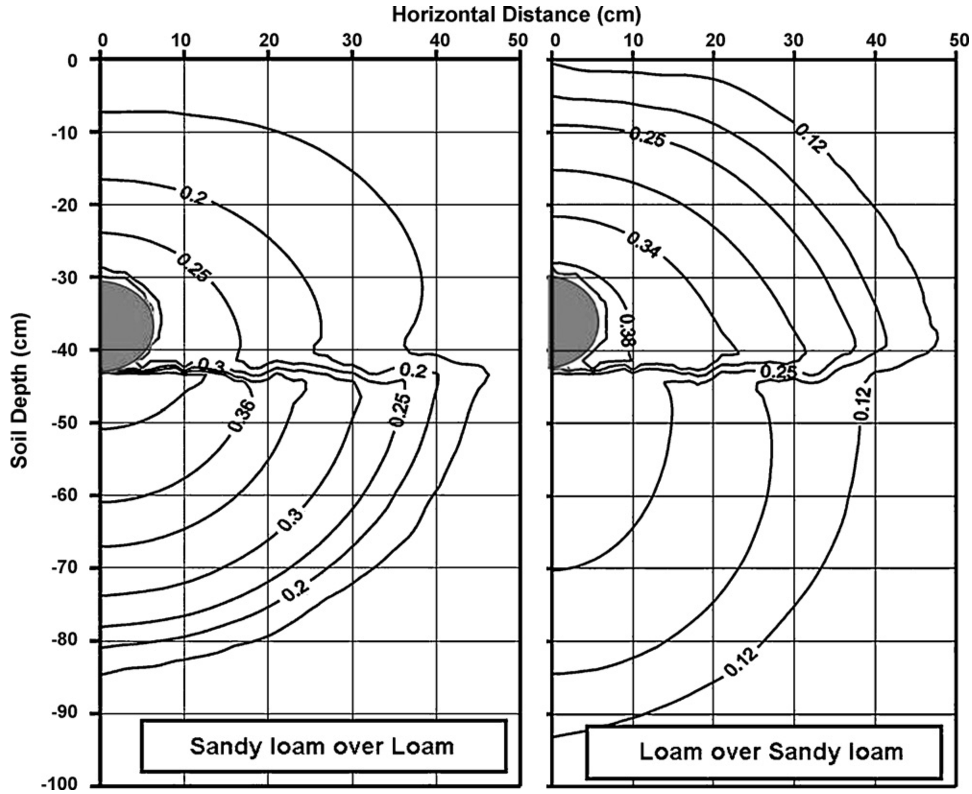

Fig. 13. Contour map of predicted volumetric water contents after 5 days of irrigation in layered soil.

3.2.4. Soil texture

The effect of soil texture on the geometry of the wetted zone (Table 2, Case IV) was investigated using the soil hydraulic parameter values given in Table 3, which are typical values for particular soil texture classes (Carsel and Parrish, 1988). The predicted wetting fronts after 5 days of irrigation are plotted in Fig. 11. The figure shows that the water penetrated deeper in the sandy loam (coarse soil) soil than in the finer textured soils. This is due to the larger hydraulic conductivity of the sandy loam soil. For all the considered soil textures, the vertical spread of the water was greater than the horizontal due to the pull of the gravity. The horizontal spread varied among the textures, with the greatest horizontal spreading occurring in the loam. The flow patterns leading to this varied wetting are illustrated in Fig. 12, which shows paths of water "particles" originating at the pipe after 5 days of irrigation. The figure was constructed using the particle tracking options in HYDRUS. In sand, almost all of the streamlines point downward, whereas in sand loam the directions of the streamlines are more uniformly distributed but the downward velocities are larger. In the loam and silt, both the streamline directions and velocities are distributed fairly uniformly, with larger velocities being shown in the loam. Clearly, the required spacing for laterals depends on the soil texture, with smaller spacings required in coarse textured soils.

3.2.5. Soil layering

Fig. 13 shows contour maps of predicted volumetric water content for two layered soils (Table 2, Case V). One soil is sandy loam over loam (coarse over fine) while the other is loam over sandy loam (fine over coarse). The layer boundary is at the depth of the bottom of the pipe such that the entire pipe is in the top layer. Fig. 13 shows that more horizontal spreading occurs in the loam (finer textured) layer regardless of whether it is on top or bottom. In layered soils, it may be desirable to account for such variability in horizontal spreading when determining lateral spacing.

4. Summary and conclusions

In many less developed parts of the world, traditional methods of sub-surface irrigation can help conserve scarce water resources. In this work, experimental and simulation studies were carried out to investigate soil wetting patterns during sub-surface porous clay pipe irrigation. Soil water distributions predicted with HYDRUS (2D/3D) were in good agreement (R^2 = 0.97–0.98) with experimental measurements made under field conditions. Based on the calculated mean error of the prediction, it was concluded that the model slightly underestimated the soil water content. Overall, the observed accuracy of the model predictions clearly provides support for using HYDRUS (2D/3D) to investigate and design sub-surface porous pipe irrigation systems.

Computer simulations with HYDRUS (2D/3D) showed that as pressure head in the irrigation pipe increases, the size of the wetted zone also increases. The depth of pipe installation affects the recommended spacing between laterals, although the use of shallow installations can lead to higher evaporative losses. For a given water application, the potential rate of surface evaporation affected the shape of the wetted region only minimally. Soil texture, due to its connection to soil hydraulic conductivity and water retention, has a larger impact on the wetting geometry. In general, greater horizontal spreading occurs in fine texture soils, or in the case of layered soils, in the finer textured layers.

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