Annual Journal of Hydraulic Engineering,
JSCE VOL. 41 (1997)

Tow-Dimensional Radial Flow Pattern Under Trickle Irrigation Subjected To Evaporation

BY: Gamal ABOUZEID*, Kunio WATANABE**, Mohamed ASHOUR***, Nashaat ALI*** and Ali MOHAMED***

Abstract

With the increasing economic growth in the arid regions, and with the growing need for new water resources, the demand of new water supply systems for irrigation are becoming high. One of the most water-safe method for irrigation is the trickle method. In this method, water for irrigation must be supplied just on root zone with the help of emitters. The problem associated with the trickle irrigation is the salinization, this leading to such problem as threatens irrigated agriculture, slow infiltration, water logging and crusting. Gypsum has been shown to be effective in reducing the sodium content in soil, but it is inconvenient for trickle irrigation and currently too costly. The dynamics of soil salinization is strongly affected by evaporated water and by plant water uptake. Therefore, any hydraulic solution for reducing the salinization needs a good understanding of the flow pattern and moisture content and their relationship with the evaporation and water uptake by plants under the use of trickle irrigation. The flow pattern and the moisture distribution under trickle irrigation was simulated numerically and experimentally. The hydraulic properties of the studied soils were estimated in this study. To maintain high water content in the upper part of the soil under trickle irrigation, a sub-layer was used beneath the top soil layer and its hydraulic properties were examined.

Keywords: Downs Regions, Evaporation, Infiltration, Radial Flow Pattern, Trickle Irrigation, Unsaturated Hydraulic Properties.

1. Introduction

Downward infiltration of water into a uniform soil profile ponded at the surface has been studied intensively, especially since the theoretical work of Philip (1954). Also, attention has been devoted to infiltration into layered soil. Takagi (1960) analyzed the steady state down flow of water through a two layer profile into a free water table beneath. Brandt et al. (1971) were able to simulate the flow pattern of wetting under line source by calculating the matric flux potential from diffusivity and water content. Van der Ploeg and Benecke (1974) based their numerical analysis on Darcy's low and the continuity equation to simulate the wetting pattern under line sources. In the surveying of the previous studies, there is a defect in analyzing the unsaturated flow beneath a point source trickle irrigation with evaporation from the soil surface. This may be due to the difficulty in the measurement of the spatial evaporation rates and the complexity in the three dimensional simulation of the flow pattern of infiltration under trickle source. The estimation of the unsaturated hydraulic properties of soils are indispensable in analyzing the unsaturated flow. In the present study, the Garlekin approach for the finite element method is used for solving the basic unsaturated radial flow equation in two dimensional aiming to define the flow pattern under trickle source where the soil surface is subjected to evaporation, also to define the relation

*Student Member of JSCE, Egyptian Ph. D. Channel System Student, Civil Eng. Dept., Saitama Univ.
** Associate Prof., Civil Eng. Dept., Saitama Univ. 255 Shimo-Okubo, Urawa-Shi, 338 Saitama, Japan.
*** Egyptian supervisors of the Ph.D. Channel system student, Civil Eng. Dept., Assiut Univ., Egypt.

between evaporation and the surface moisture content and how we can reduce the evaporation. The unsaturated hydraulic properties can be estimated using the inverse solution of unsaturated flow. The analysis of unsaturated flow pattern through layered soil under trickle source with unsteady evaporation from soil surface and how we can maintain high moisture content beneath the soil surface is the second aim of this study.

2. Laboratory Tests.

Experiments were conducted in plexiglass column (30 cm. dia. & 60 cm. height) packed with soil in 2- cm increments and mechanically compacted to the top tip of the plexiglass column. The column was not thermally isolated because the difference between the outside temperature and inside one was not high and the time of test was not so long. The column rested on a steel angles frame with its base. The plexiglass column has a small hole (2.5 cm dia.) through which the water can enter to the bottom of the soil column from a constant head tank as in Fig. 1. This constant head is taken as a bottom boundary condition. The trickle irrigation was applied at the center of the surface with the help of an emitter at a rate of 0.035 l / h for a 12 hours "on" during the day time. Evaporation from the soil column was allowed. The evaporation sensors were used for measuring this evaporation (See Watanabe, 1991). The evaporation sensors used were (Tokyo Keisoku ETH2101). These sensor types are used in laboratory under a certain climatic conditions, but in the in-situ measurements, the box type sensors (Watanabe and Tsutsui, 1994) are in developing to be used with drip irrigation. The sensors were intervally installed on the soil surface (3 cm apart) as in Fig. 1 to measure the distribution of evaporation rate as in Fig. 2. This distribution and water drip from the emitter are the boundary flux condition on the top surface. Experimental data on moisture content distributions were generated in duplicates over the soil profile in the both radial and vertical directions. The moister measurements were carried out just after each "on" operation using the gravitational method, where the soil samples were weighted before and after drying in an oven has 110°C and by measuring the porosity and specific weight of solids, the saturation could be calculated.

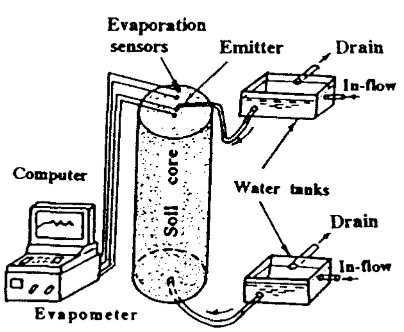

Fig. 1 Schematic view of the laboratory test

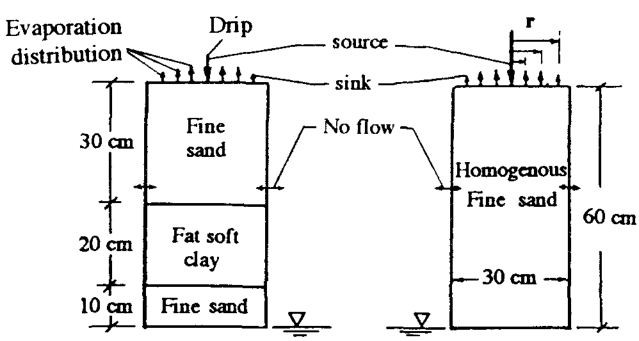

Fig. 2 Soil texture and boundary conditions

The experiments were performed in two categories. *First,* the experiments were carried out on homogenous fine sand with a depth of 60.0 cm, a constant water head was given at the bottom and the evaporation rate was measured at the top surface (Figs. 1 and 2). After that, the radial and vertical saturation distributions were measured over the soil column. *Second,* a surface fine sand layer with a depth 30.0 cm was underlied by a 20.0 cm thick fat soft clay soil (sub-layer), the remainder 10.0 cm till the water table was fine sand as in Fig. 2. Soil samples were taken for the measurements of the saturation.

3. Unsaturated Hydraulic Properties of The Tested Soils

Most soil-water transport process, such as infiltration, evaporation, and uptake by plant roots, involve flow in an unsaturated soil. The need to describe such flow processes quantitatively in context of the soil-plantatmosphere continuum requires the precise assessment of the parameters entering the governing flow equation. The most important relationships upon which the successful simulation of unsaturated flow depends are the hydraulic conductivity and the capillary head as functions of moisture content, h(θ) and K(θ) respectively.

In this study we used the inverse solution technique of the water flow in unsaturated soil core (Watanabe et al., 1995 and Abouzeid et al., 1996) for estimating the unsaturated hydraulic properties. The van-Genuchten model (1980) was adopted in this technique for representing the hydraulic properties of unsaturated soils. Small soil specimens of 5 cm diameter and 7 cm height subjected to evaporation on the surface and constant water table at the bottom were used. The unsaturated flow were created in these specimens.

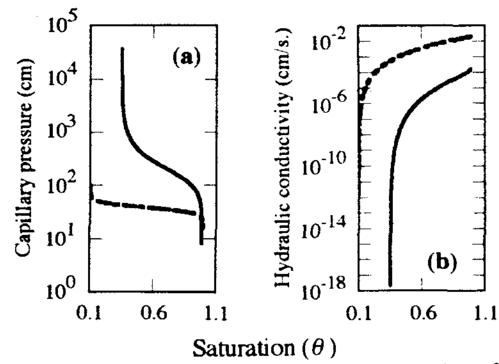

Fig. 3 The estimated hydraulic properties of ------Fine sand and —— Fat soft clay

The estimated parameters included in the van-Genuchten model with the porosity and saturated hydraulic conductivity for the tested soils are summarized in Table 1. Figures 3a and 3b shows the estimated water retention function and hydraulic conductivity function drawn by using those estimated parameters.

4. Unsaturated Radial Flow Model

Under the assumption that, the tested soil are homogenous in radial directions around point (trickle source), the flow pattern under trickle irrigation can be approximated as a two dimensional radial flow instead of three dimensional. When the hydraulic properties of the studied soils are known, the moisture distribution and capillary pressure can be calculated by solving the following unsaturated radial flow equation;

$$C(\theta)\frac{\partial h}{\partial t} = \frac{K(\theta)}{r}\left\{\frac{\partial}{\partial r}\left[r\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[r\frac{\partial h}{\partial z}\right]\right\} \pm q \qquad (1) \qquad \text{and} \qquad h = \psi + z \qquad (2)$$

where; θ is the saturation, C(θ) is the specific moisture capacity, K(θ) is the hydraulic conductivity as a function of the saturation, q is the sink or source term, z is the height from a reference level, r is the radial distance and ψ is the capillary pressure head.

The van-Genuchten model was adopted for presenting the hydraulic properties of the tested soils .This model can be written as follow;

$$K(\theta) = K_s S_e^{1/2}\left\{1 - \left(1 - S_e^{1/m}\right)^m\right\}^2 \qquad (3)$$

$$C(\theta) = \alpha(n-1)(\theta_s - \theta_d) S_e^{1/m}\left(1 - S_e^{1/m}\right)^m \qquad (4)$$

where;

$$S_e = \frac{\theta - \theta_d}{\theta_s - \theta_d} \qquad (0 \le S_e \le 1) \qquad (5)$$

$$S_e = \left\{1 + |\alpha\psi|^n\right\}^{-m} \qquad (\alpha > 0) \qquad (6)$$

$$n = \frac{1}{1-m} \qquad (0 < m < 1, n > 1) \qquad (7)$$

Table 1. The estimated parameters in the van-Genuchten model

Soil type	Fine sand	Fat soft clay
Ks (cm/s)	2.0E-2	1.6E-4
Porosity	0.445	0.6
α (cm-1)	0.02664	0.006
m	0.89684	0.6
θ_d	0.1	0.35
θ_s	0.995	0.99

where, K_s is the saturated hydraulic conductivity (cm/sec.), S_e is the effective saturation, θ_d (L^3/L^3) and θ_s (L^3/L^3) are the residual and saturated water contents and α (L^{-1}), n and m are empirical parameters. The estimated values of K_s, θ_s, θ_d, α, and m are as shown in Table 1. When the unsaturated hydraulic properties are modeled, Eq. (1) can be solved for θ and h using the finite element method on the basis of Galerkin approach with an appropriate boundary conditions.

The given boundary conditions were; an unsteady evaporation rate, which was experimentally measured in mg/m^2/sec. by evaporation sensors, it was approximated at the surface boundary of the finite element mesh and input as unsteady sink at points from the soil surface with the emitter flow rate 0.035 l/ h as a steady source in the center point of the soil surface (Fig. 2), all together each one hour time interval. The bottom boundary conditions were kept constant at bounded constant water table for the soil texture shown in Figs. 1 and 2.

5. Results and Discussion

From the laboratory tests, the evaporation rate from the sandy soil which was subjected to trickle irrigation was measured during the test time (from 9 a.m. to 9 p.m.) 12 hours "on". Fig. 4 shows the transient change of the evaporation rate under the shown air temperature and relative humidity. Laboratory air temperature was about 24.7 °C morning and evening and about 26.3 °C at the noon period and the relative humidity was higher than 60%. Whereas the rate of evaporation may small but it is effective, then what about the rate in the arid regions!. Watanabe et al. (1996) found more than 60% of water poured on the ground surface in a day time was rapidly evaporated during 3 hours after the water was supplied in Sahele in the vicinity of Nara city of Republic of Mali. From Fig. 4, we can say the evaporation rate from soil surface under trickle irrigation much affected by the soil surface moisture content, the relative humidity and the air temperature. When the air temperature is low and the relative humidity is high, the evaporation rate is low as shown in Fig. 5. So, it is recommended to irrigate through these conditions (night time) to reduce the evaporation rate, especially in the downs regions where the differences in the relative humidity and temperature between the day time and night time is very high and the trickle irrigation is recommended in this regions.

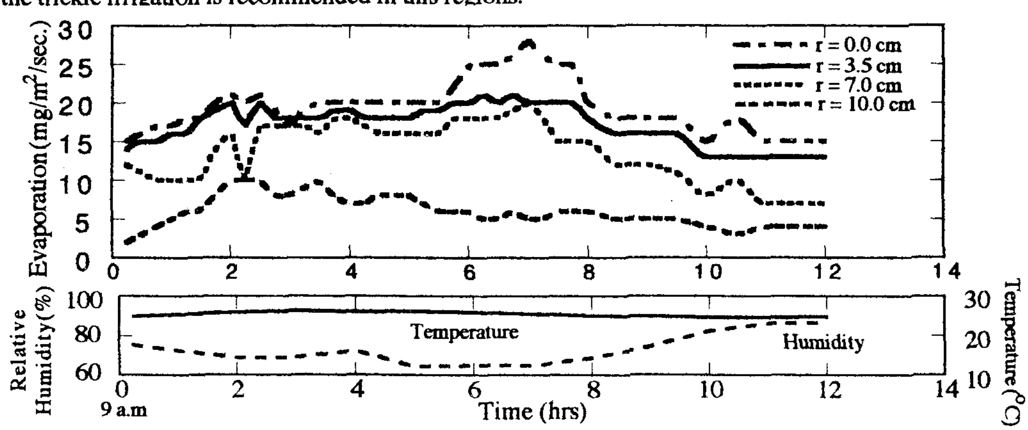

Fig. 4 (Upper) Transient change of the measured evaporation from fine sandy soil under trickle irrigation at different radial distance (r) from the emitter. (lower) The climatic condition (Relative humidity & temperature) during the test

Moisture content distributions under steady point source trickle irrigation subjected to unsteady evaporation were computed numerically and measured experimentally. The computed distribution was compared with the measured one for the homogenous sand and layered soils. Figure 5 shows a good agreement between measured and calculated saturation for the upper part of soil profile, but for the lower part there is a slight difference. This difference may due to the effect of hystersis in the water retention function due to the difference between the estimated technique of hydraulic properties (drying case) and the infiltration due to irrigation (imbibtion case). Also, the effect of trickle water source are clearly shown in this figure.

Because of the climatic condition was same for the two categories, the surface evaporation rate was same from the surface, consequently the soil surface moisture condition calculated are almost same as in Figure 6. For the part just over the second layer in the surface layer (fine sand), the moisture content are higher than in case of homogenous sand column. This is due to the effect of the hydraulic properties of the second layer (fat soft clay). From these results one can say that to maintain a high moisture content in the lower part of the upper sand layer, under trickle irrigation, a soil layer has high permeability and know hydraulic properties presenting the required moisture content with the used emitter flow rate can be used underneath this upper layer as in Fig. 2 (left).

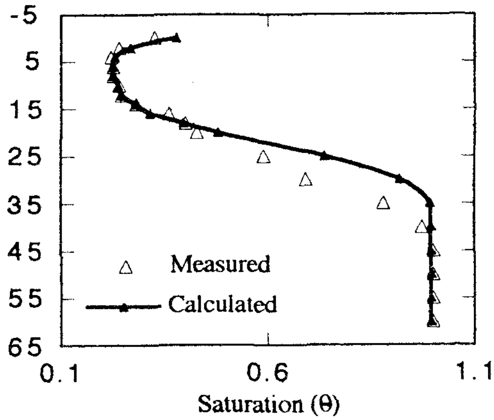

Fig. 5 Measured and calculated vertical saturation distribution for fine sand under trickle irrigation after 12 hrs "on" r= 0.0 cm, q= 0.035 l/h

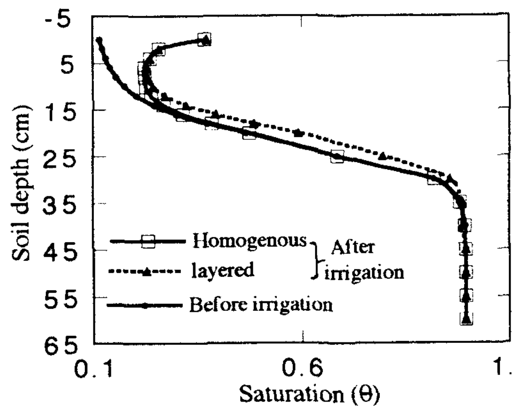

Fig. 6 Vertical moisture distribution calculated just before and after 12 hrs trickle irrigation "on" for homogenous and layered soils r= 0.0 cm, q= 0.035 l/h

The radial distribution of the measured evaporation rate and the moisture content distribution of the soil surface after 5 hours "on" are shown in Fig. 7. From this figure, under constant air temperature and relative humidity , the evaporation rate increases with the increase of the soil surface moisture content. This confirm the need to a solution for reducing the evaporation from the soil surface. From the practical point of view, an artificial coarse gravel thin layer can be used on the soil surface to reduce the evaporation rate from soils and to make useful from the dewdrop in dew the soil surface in the downs regions and also to reduce the grow of strange and harmful herbage.

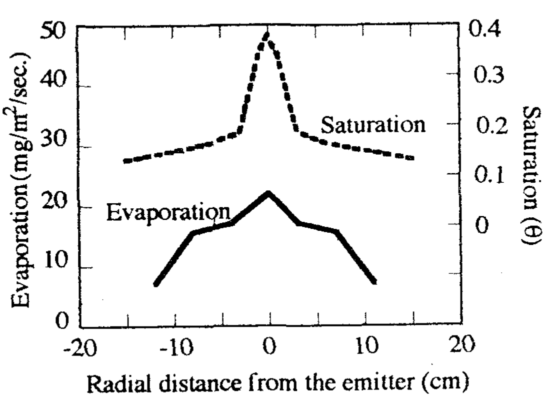

Fig. 7 Measured evaporation rate and the surface moisture content changes with the distance from the emitter (r) under trickle irrigation after 5 hrs.

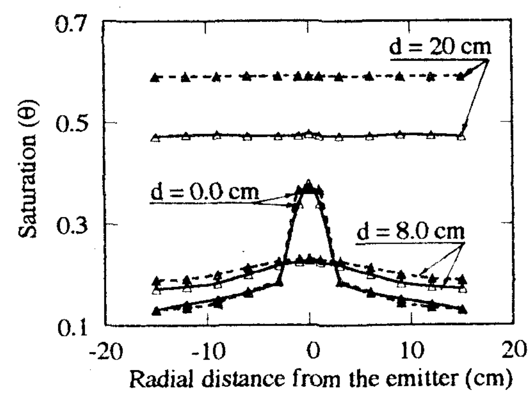

Fig. 8 Radial saturation distributions under trickle irrigation calculated for different soil depths 'd' for —△— homogenous profile and ---▲--- layered soil profile.

Figure 8 shows a comparison between the radial moisture distributions through three depths under trickle source for homogenous and layered soils. From this figure, we can observe that the moisture content above the second layer for the case of layered soil is much higher than the homogenous soil and the difference increases with the increase of soil depth till the second layer. Also from this figure, the effect of the emitter flow and the evaporation on the soil surface moisture content are clearly shown, where the moisture distribution was decreased rapidly with the radial distance (r) from the emitter. From the observation during experimental performance period, the wetting surface area was increasing with the time. This increase of the wetted surface area increases the evaporation area.

Conclusions

The findings from this study may have practical applications particularly where it is desirable to reduce the evaporation rate and improve the soil moisture content artificially under trickle irrigation, and the following conclusions may be drawn;

1) Unsaturated flow near the trickle irrigation was well simulated by the two-dimensional radial flow analysis.
2) Evaporation around drip point can be well measured by using evaporation sensors under laboratory condition.
3) Spatial evaporation rate decreases with the decrease of moisture content of the soil.
4) The use of an artificial sub-layer to improve the surface soil (shallow root zone) moisture content are presented
5) According to the soil hydraulic properties and emitter flow rate, the time required for "on" and "off" cycle of trickle irrigation can be estimated from the desired moisture content after irrigation and evaporation during "off" cycle.
6) Because the evaporation rate decreases with the increase of air relative humidity and with the decrease of the temperature, it is recommended to irrigate in these conditions (night time) in the downs regions.

References

1) Abouzeid, A., K. Watwnabe, M. Ashour, A. Nashaat, and M. Ali, (1996): In situ determination of the hydraulic properties of unsaturated soil. Proc. of the 51th National conference of the Japan Society of Civil Engineering, Nagoya, JAPAN.
2) Brandt, A., E. Bresler, N. Diner, I. Ben-Asher, J. Heller and D. Goldberg, (1971): Infiltration from a trickle source: 1. Mathematical models. Soil Sci. Soc. Am. Proc. 35:675-682.
3) Philip, J.,(1954): An infiltration equation with physical significance. Soil Sci.. 77: 153-157.
4) Takagi, S., (1960): Analysis of the vertical downward flow of water through a two-layer soil. Soil Sci. 90: 98-103.
5) Van der Ploeg, R., and P. Benecke, (1974): Unsteady, unsaturated, n-dimensional moisture flow in soil: A computer simulation program. Soil Sci. Soc. Am. Proc. 38:881-885.
6) van-Genuchten, M. T., (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898.
7) Watanabe, K., (1991): Evaporation measurement in validation drift. Part 1, Stripa Technical Report, 1-131.
8) Watanabe K. and Y. Tsutsui (1994): Anew equipment used for measuring evaporation in a field. Proc. 7th. Congr. IAEG: 309-313.
9) Watanabe, K., S. Hamada, T. Sakai, and Y. Hoshino, (1995): In-situ and laboratory tests for estimating the hydraulic properties of unsaturated rock. Proc. Inter. Congr. on Rock Mech., JAPAN.
10) Watanabe, K., Y. Morita, M. Fujita and M. Keita, (1996): Field measurement of evapo-transpiration in the Sahele area of repuplic of Mali, west Africa. Jour. of The Japan Society of Eng. Geology, 37-2: 33-42.