Analysis Of Drip irrigation Uniformity By Numerical Simulation

T.S. Tsay[a]; S.-H. Ju[b]; and C.C. Huang[c]

[a]The Overseas Chinese Institute of Technology, Taichung, Taiwan.

[b]Department of Civil Engineering, National Cheng-Kung University, Tainan, Taiwan.

[c]Agricultural Engineering Research Center, Chung-Li, Taiwan.

Abstract: Water supply is important for crop growth and production. In arid and semi-arid area, high profit upland crops are frequently chosen because water supply is usually unstable. Management and controls of irrigation are keys to achieve farm profitability and water saving. In many irrigation methods, drip irrigation is popular for upland irrigation because water can be irrigated effectively to the root zone of the crop. As infiltration of drip irrigation is an unsaturated flow problem, it has drawn much attention because of the complex relations among the unsaturated hydraulic conductivity, piezometric head and moisture content. It is obvious that direct simulation of unsaturated flow using 3-dimensional numerical model requires huge memory and consuming time. An axial symmetric unsaturated flow model was presented to reduce the computation time and required memory. In addition to the unsaturated flow complexity, flow uniformity of drip irrigation was concerned because it is related to the irrigation efficiency. This paper presents a uniformity analysis by simulating the unsaturated flow of drip irrigation using axial symmetric model. A coefficient of uniformity for drip irrigation is proposed in this study. The objectives of this research are to establish an axial-symmetric unsaturated flow model and to analyze uniformity of drip irrigation *in situ*.

Keywords: *unsaturated flow; drip irrigation; uniformity*

1. INTRODUCTION

In the arid and semi-arid areas, drip irrigation and sprinkle irrigation are frequently used to reach the maximum water use efficiency (Hamouri *et al.*, 1996; Tarjueo *et al.*, 1999; and Fabeiro *et al.*, 2002). However, sufficient water supply is one of the major factors of obtaining crop production. As demands of water resources are increasing, the water use efficiency is getting more and more important. In many irrigation methods, drip irrigation is popular for upland crops because water can be irrigated directly to the root zone of the crop. If the irrigated water is not enough, crop production can be reduced. On the other hand, it is waste of water. Hence, understanding soil water movement is helpful in drip irrigation design.

Drip irrigation is often used for high efficiency crop and fertilization in Taiwan as well as in many other places. The economic feasibility of drip irrigation was carefully evaluated (Tiwari *et al.*, 1998). The application of drip irrigation was found to increase in yields compared to that of furrow irrigation. As measurement of drip irrigation water flow is easier than other irrigation methods, this irrigation method is used to evaluate crop evapotranspiration and crop coefficient for various plants such as eggplant and sweet lime (Chartzoulakis and Drosos, 1995；Sepaskhah and Kashefipour, 1995). The wetting pattern of drip irrigation was studied using neutron moisture meter and the results can be applied to drip irrigation design (Vidhana Arachchi, 1998). It can be concluded from the literature review that drip irrigation was popular for a water supply method in most arid and semi-arid areas. It is interesting to visualize the soil water distribution from a dripper to obtain useful information in designing drip flow rate and dripping time. However, *in situ* measurement of soil moisture content is feasible but time consuming and expensive. Numerical modeling of unsaturated flow has been extensively studied for the complex relation among the unsaturated hydraulic conductivity, piezometric head and moisture content. Because direct unsaturated flow simulation using 3-dimensional numerical model requires huge computer memory and CPU time, an axial symmetric unsaturated flow model was proposed in this study to simulate the 3-dimensional problem. The axial symmetric unsaturated flow model is efficient in computation time and memory because it implements computations by 2-dimensional method to achieve the 3-dimensional results. In addition to the unsaturated flow complexity, flow uniformity of soil water from dripper was concerned because it is related to the irrigation efficiency. A coefficient of uniformity for drip irrigation is proposed in this study. The objectives of this research are to establish a numerical model for simulating flow pattern of drip irrigation and to analyze uniformity of drip irrigation.

2. FLOW CONCEPTUAL MODEL

Figure 1 illustrates the flow conceptual model of drip irrigation. The irrigated water can be visualized as a “point” source which injecting to the ground surface. The injected water flows vertically and horizontally into the soil. Soil moisture content near the source is greater than that away from the source. The moisture content contour’s shapes are axial symmetric bulbs. Hence, the axial symmetric flow pattern can be modeled by a 2-dimensional simulation instead of a 3-dimensional one.

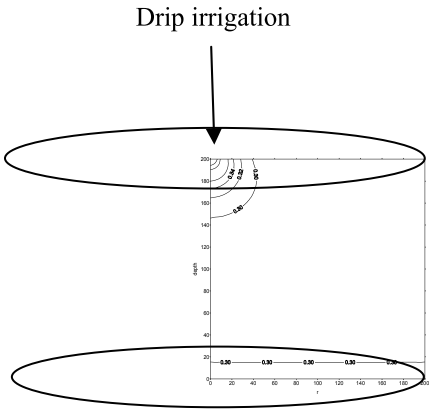

Figure 1. The conceptual flow model of drip irrigation.

3. GOVERNING EQUATION

3.1. Introduction

Literatures about infiltration of unsaturated flow were reviewed in order to develop a model for simulating soil water flow of drip irrigation. The infiltration problem of unsaturated flow has drawn much attention for its importance in approximating groundwater recharge (Parlange *et al.*, 1985; Allison *et al.*, 1994; and Nimmo *et al.*, 1994). The mathematical model of unsaturated flow was developed by Richards (1931). However, the non-linear relation among soil moisture content, piezometric and unsaturated hydraulic conductivity was not well defined until van Genuchten’s function (van Genuchten, 1980).

3.2. Richards equation and van Genuchten’s function

The unsaturated flow is mostly described by Richards equation:

$$F\frac{\partial h}{\partial t} = \nabla \cdot \left[K_r \underline{\underline{K_s}} \cdot \left(\nabla h + \nabla z\right)\right] + q' \qquad (1)$$

where $F = \alpha'\frac{\theta}{n_e} + \beta'\theta + \frac{d\theta}{dh}$ = water capacity, h = pressure head, z = potential head, $\underline{\underline{K_r}}$ = relative hydraulic conductivity, $\underline{\underline{K_s}}$ = saturated hydraulic conductivity tensor, t = time , q' =internal source/sink, n_e = effective porosity, θ = moisture content, α' = modified compressibility of soil, and β' = water modified compressibility of water.

In unsaturated flow, the effective hydraulic conductivity ($\underline{\underline{K}}$) is a function of pressure head, the relationship between the effective hydraulic and the saturated hydraulic conductivity ($\underline{\underline{K_s}}$) is

$$\underline{\underline{K}} = K_r \underline{\underline{K_s}} \qquad (2)$$

The relation between of K_r and effective moisture content (θ_e) can be expressed by van Genuchten functions (van Genuchten, 1980)

$$K_r = \theta_e^{0.5}\left[1 - \left(1 - \theta_e^{1/\gamma}\right)^{\gamma}\right]^2 \qquad (3)$$

where,

$$\text{when } h < 0,\ \theta_e = \left[1 + \left(|\alpha h|\right)^{\beta}\right]^{-\gamma} \qquad (4)$$

$$\text{when } h \geq 0,\ \theta_e = 1 \qquad (5)$$

and

$$\theta_w = \theta_r + \theta_e\left(\theta_s - \theta_r\right) \qquad (6)$$

$$\gamma = 1 - \frac{1}{\beta} \qquad (7)$$

where θ_w = moisture content, θ_s = saturation moisture content, θ_r =residual moisture content, β, γ : soil-specific exponents, α : soil-specific coefficient.

3.3. Domain transform

It can be seen that numerical simulation of Equation (1) is time consuming and requires huge memory. In order to reduce the computation time and memory, Richards equation was transformed to the cylindrical coordinate according to the conceptual model. The 3-dimensional flow problem in the rectangular coordinates (x, y, z) can be simulated by 2-dimensional method in the cylindrical coordinates (r, θ , z) since the flow pattern is symmetric to the axis z. The $\nabla -$operator in the cylindrical coordinates can be obtained by

$$\nabla = \underline{\delta}_r \frac{\partial}{\partial r} + \underline{\delta}_\theta \frac{1}{r}\frac{\partial}{\partial \theta} + \underline{\delta}_z \frac{\partial}{\partial z} \tag{8}$$

where $\underline{\delta}_r$, $\underline{\delta}_\theta$ and $\underline{\delta}_z$ are unit vectors of cylindrical coordinates (Bird *et al.*, 1987). Finite element method is used to solve the transformed Richards equation. Index method and conjugate-gradient-like methods (Tsay and Ju, 1998) were applied to store and solve matrices.

4. SOIL WATER UNIFORMITY

The problem of uniformity was discussed in sprinkle irrigation since it depends upon many factors such as sprinkle type, nozzle number, size, and operating pressure. Highly uniform sprinkle irrigation would result in water saving and farm profitability (Tarjueo *et al.*, 1999). The uniformity problem of drip irrigation is also concerned because flow pattern of dripped water is expected to cover crop's root zone by using limited water. An optimum time of irrigation couple with irrigation strength can be obtained for the best irrigation efficiency. This paper assumes that soil's field capacity θ_f is the optimum moisture content for crop growth. A drip irrigation coefficient of uniformity, CUD (%), is proposed in this study:

$$\text{CUD} = \left[1 - \frac{\sum_{i=1}^{n} |\theta_i - \theta_f|}{n\theta_f} \right] \times 100 \tag{9}$$

which follows Christiansen's coefficient of uniformity. Where θ_i is the moisture content of computed grid number, θ_f is the expected moisture content and n is the total number of grid in the computation domain. CUD deviates from 1 when the water is irrigated more or less than the expected moisture content.

5. SOIL SAMPLING AND PROPERTIES

Simulation of the drip irrigation flow pattern was applied to a pineapple farm in Taidong, Taiwan to exam the designed irrigation flow rate. The area of the selected pineapple farm is 79 meters long and 23 meters wide. Five soil samples from the field were obtained to approximate the parameters in equations (4) and (6) by soil tests. The relations between pressure head and moisture content of the samples is shown in Figure 2. It is found from the figure that θ_r =0, θ_s =0.42, α =0.00976, β =1.29, and Ks = 10^{-2} cm/sec.

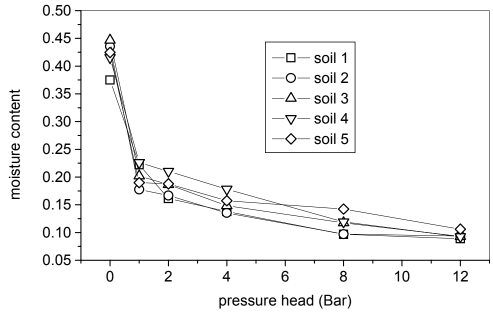

Figure 2. Relations between soil suction and moisture content of five soil samples in the selected pineapple farm.

6. PINEAPPLE ROOT ZONE INVESTIGATION

The pineapple root distribution is sparse and shallow. The maximum root develops to the depth of no more than 1 meter and most roots distribute between of 30-60 cm. The maximum evapotranspiration of pineapple is more likely to be 5-6 mm per day. In this research, the root development was investigated by delving pineapples randomly in the field after they were grown for 7 months. It is found that (1) the root depth of pineapples ranges from 45 cm to 60 cm from a sample size of 80 and (2) soil property is very critical to pineapple root development.

7. SIMULATIONS AND UNIFORMITY ANALYSIS

7.1. Assumptions

The numerical simulation of flow pattern due to drip irrigation assumes:

1. the soil is homogeneous and isotropic;
2. van Genuchten function is valid for estimating the nonlinear relations between soil pressure, moisture content and unsaturated hydraulic conductivity;
3. the irrigated water is infiltrated to an area with the radius of 5 cm;
4. no ponding happens during irrigation; and
5. pineapple root effect of water is neglected.

7.2. Infiltration simulation

According to the conditions of the pineapple farm *in situ* and the above assumptions, the initial result of the simulation appears to be reasonable.

Figure 3 shows that when water is dripped from the left upper corner for a period of time, the moisture content contour's value is getting larger near the irrigation source.

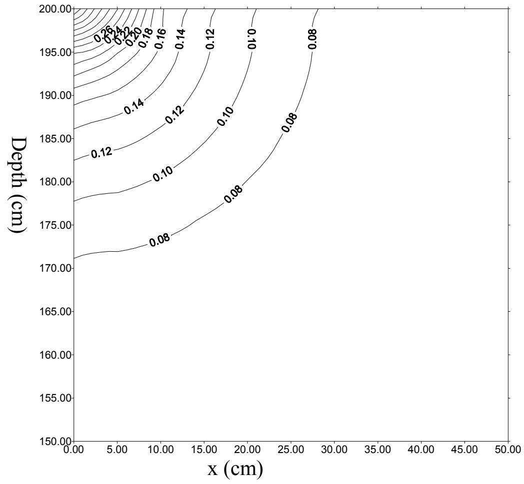

Figure 3. The moisture content contour of drip irrigation after 3,000 second when the irrigation strength is 0.8×10^{-6}cm/sec

Figure 4 indicates that higher initial moisture content is better for water flow. The moisture content contour of 0.3 reaches 29 cm depth after 5 hours of irrigation at irrigation flow rate of 0.01768 cm/sec for a barely dry soil when the initial moisture content is 0.21. Using the same irrigation time and flow rate, the moisture content contour of 0.3 reaches 34 cm depth when the initial moisture content is 0.25.

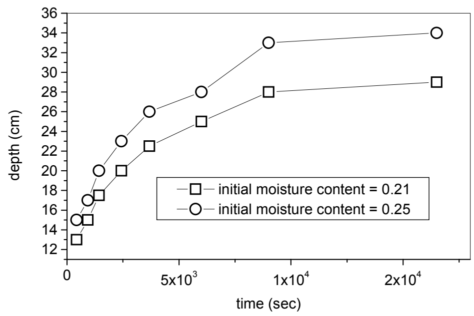

Figure 4. Relations of irrigation time and the moving depth when moisture content reaches 0.3

7.3. Uniformity analysis

The uniformity analysis is implemented by simulating flows in the pineapple farm. A soil column with height of 2 meters and radius of 2 meters is used in this simulation. The designed irrigation rate of the pineapple is 0.8×10^{-6}cm/sec, and θ_f =0.35 and initial θ =0.27. This analysis suggests Equation (9) to present the uniformity of flow of drip irrigation. However, there is not any significant difference between the results from the irrigation time of 500,000 sec and 2,000,000 sec (Figure 5). Some possible reasons include: (1) the domain calculated for CUD is much larger than the irrigated domain since most part of the soil moisture content did not changed much owing to small irrigation strength, and (2) the initial θ is very close to θ_f and the total absolute difference comparing to $n\theta_f$ becomes a very small value.

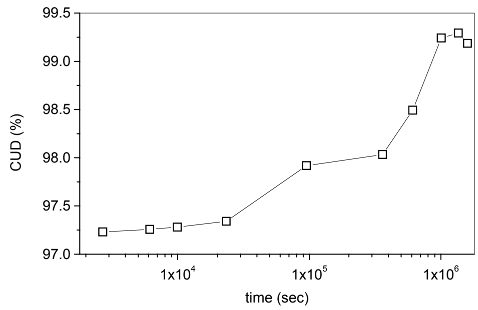

Figure 5. Uniformity verse time of drip irrigation flow pattern in a soil column with a height of 2 meter and a radius of 2 meter when the irrigation strength is 0.8×10^{-6}cm/sec

8. CONCLUSIONS AND DISCUSSIONS

Abundant water supply is very important to crop growth. As drip irrigation can be irrigated directly to crop root zone, it is a popular irrigation method in arid and semi-arid area. It can be concluded from this study that:

1. irrigation intervals between each irrigation schedule should be close enough since over dry soil is not good for water conveyance;
2. according to the infiltration phenomena from drip irrigation, the axial symmetric unsaturated flow model can reduce the required computation memory and time of a three dimensional model;
3. the simulated flow pattern of the pineapple farm using the axial symmetric unsaturated flow model showed reasonable results; and
4. the uniformity analysis could be modified by restricting the irrigation domain to the most effected boundary in order to get more significant comparing results.

The future work of this research suggests sand tank experiment to verify the axial symmetric unsaturated flow model.

9. ACKNOWLEDGEMENTS

This research is supported by Council of Agriculture, Executive Yuan, Taiwan. Project no.: 91AS-1.3.3-FC-R1(29).

10. REFERENCES

Allison, G. B.; Gee, G. W. and Tyler, S. W.: Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions, Soil Sci. Soc. Am. J., 58, 6-14, 1994.

Bird, R.B.; Armstrong, R.C. and Hassager, O.: *Dynamics of Polymeric Liquids*, John Wiley & Sons, New York, 1987.

Chartzoulakis, K. and Drosos, N.,: Water use and yield of greenhouse grown eggplant under drip irrigation, Agricultural Water Management, 28, 113-120, 1995.

Fabeiro, C.; de Santa Olalla, F. Martin and de Juan, J.A.: Production of muskmelon (Cucumis mela L.) under controlled deficit irrigation in a semi-arid climate, *Agricultural Water Management*, 54, 93-105, 2002.

Hamouri, B.E.; Handouf, A.; Mekrane, M. Touzani, M.; Khana, A.; Khallayoune, K. and Benchokroun, T.: Use of wastewater for crop production under arid and saline conditions: yield and hygienic quality of the crop and soil conditions, *Wat. Sci. Tech.*, 33(10-11), 327-334, 1996.

Nimmo, J. R.; Stonestrom, D. A. and Akstin, K. C.: The feasibility of recharge rate determinations using the steady-state centrifuge method, Soil Sci. Soc. Am. J., 58, 49-56, 1994.

Parlange, J.-Y.; Haverkamp, R. and Touma, J.: Infiltration under ponded conditions: 1. Optimal analytical solution and comparison with experimental observations, Soil Sci. Soc. Am. J., 139, 305-311, 1985.

Richards, L. A.: Capillary conduction of liquids through porous mediums, physics, 1, 318-333, 1931.

Tarjuelo, J.M.; Montero, J.; Honrubia, F.T.; Ortiz, J.J. and Ortega, J.F.: Analysis of uniformity of sprinkle irrigation in a semi-arid area, *Agricultural Water Management*, 40, 315-331, 1999.

Sepaskhah, A.R. and Kashefipour, S.M.: Evapotranspiration and crop coefficient of sweet lime under drip irrigation, Agricultural Water Management, 27, 331-340, 1995.

Tiwari, K.N.; Mal, P.K.; Singh, R.M. and Chattopadhyay, A.: Response of okra to drip irrigation under mulch and non-mulch conditions, *Agricultural Water Management*, 38, 91-102, 1998.

Tsay, T.S. and Ju, S.-H.: Application of a general index method to finite difference in the curvilinear coordinate, Journal of Chinese Agricultural Engineering, 44(4), 1998.

van Genuchten, M. Th.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, pp. 892-898, 1980.

Vidhana Arachchi, L.P.: Preliminary requirement to design a suitable drip irrigation system for coconut in gravelly soils, *Agricultural Water Management*, 38, 169-180, 1998.