

Utah State University

DigitalCommons@USU

Reports

Utah Water Research Laboratory

January 1977

Water Flow Patterns in Heterogeneous Soils Under Trickle Irrigation

Abdolhossien Nassehzadeh-Tabrizi

Roland W. Jeppson

Lyman S. Willardson

Follow this and additional works at: https://digitalcommons.usu.edu/water_rep



Part of the [Civil and Environmental Engineering Commons](#), and the [Water Resource Management Commons](#)

Recommended Citation

Nassehzadeh-Tabrizi, Abdolhossien; Jeppson, Roland W.; and Willardson, Lyman S., "Water Flow Patterns in Heterogeneous Soils Under Trickle Irrigation" (1977). *Reports*. Paper 177.

https://digitalcommons.usu.edu/water_rep/177

This Report is brought to you for free and open access by the Utah Water Research Laboratory at DigitalCommons@USU. It has been accepted for inclusion in Reports by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



WATER FLOW PATTERNS IN
HETEROGENEOUS SOILS UNDER TRICKLE
IRRIGATION

by

A. Nassehzadeh-Tabrizi

Roland W. Jeppson

and

Lyman S. Willardson

Supported by

The National Science Foundation
Grant No. ENG 74-24314

The material herein was presented as paper no.
77-2556 at the 1977 Winter meeting, American
Society of Agricultural Engineers, Chicago, Ill.,
December 13-16, 1977

Utah Water Research Laboratory
Departments of Civil & Environmental Engineering
and
Agricultural & Irrigation Engineering
Utah State University
Logan, Utah 84322
December 1977

PRWG-172-2

WATER FLOW PATTERNS IN HETEROGENEOUS SOILS
UNDER TRICKLE IRRIGATION

A. Nassehzadeh-Tabrizi, R. W. Jeppson, and L. S. Willardson

ABSTRACT

Numerical solutions of the problem of unsteady unsaturated three-dimensional axisymmetric flows from a trickle irrigation source in heterogeneous soils have been obtained. The mathematical model permits any vertical heterogeneity of the soil to be specified and describes the heterogeneity so that the hydraulic properties of the soil vary continuously as a function of depth. The point relationship of saturation and relative hydraulic conductivity to capillary pressure is defined by the Brooks-Corey (1966) parametric equations. At all dimensionless times the distribution of saturation, hydraulic head, and capillary pressure and extent and amount of lateral and vertical water movement and the rate of advance and position of the wetting front in the resultant flow field are determined as parts of the solution. Any one of the factors can be analyzed to define its interrelationships with respect to the magnitude and degrees of heterogeneity of the other hydraulic properties of the soil.

The quality of trickle irrigation system design depends on better definition of shape of the wetting patterns and location of wetting front. Differences in the flow patterns in heterogeneous soils from the patterns in homogeneous soil are provided.

INTRODUCTION

Prediction capability to determine moisture content and soil water tension under a trickle irrigation point source is one of the important research needs at the present time. Knowledge of water movement in the soil is necessary for improvement of trickle irrigation design. Better design of trickle irrigation also depends on better definition of shape of the wetting pattern and the volume of wetted soil.

For a noninteracting single emitter, the ponded area on the soil surface is approximately circular. Since the ponded area is relatively small compared with the total soil surface, water movement is essentially three dimensional and axisymmetric. Considerable lateral spreading occurs at the surface as unsaturated flow.

In the past the unsaturated flow equation has been solved analytically under simplifying assumptions, and for simple boundary conditions. The majority of these closed form solutions are for steady state isothermal flow through saturated isotropic homogeneous media, an idealized case that does not exist in nature. Wooding (1968), Philip (1968, 1969, 1971), and Raats (1971, 1972) linearized the flow equation by using the matrix flux potential and solved for the case of steady infiltration from both circular areas and point sources. Brandt et al. (1971) developed a numerical solution for unsteady infiltration from a trickle source into homogeneous soils.

During the past decade knowledge of soil water flow under unsaturated conditions has advanced rapidly. High speed computers make practical the numerical solution of these difficult and strongly nonlinear initial-boundary-value problems.

PROCEDURE

It is now practical to give more detailed attention to a transient unsaturated flow system in heterogeneous media. Steady state flow conditions exist only in theory and heterogeneity of the soil is the rule rather than the exception. At the present time, mathematical models for transient flow in heterogeneous porous media, with the exception of a model by Watson and Whisler (1972), assume that a heterogeneous soil consists of discrete layers of homogeneous soil. In these models the hydraulic head and pressure head, but not the moisture content, are assumed continuous across the interface of the two layers. The validity of this approach may be questioned because the development of a differential equation describing soil water flow, obtained by substituting Darcy's law into the differential form of the continuity equation, is based on the assumption that all variables and their derivatives are continuous. However, only the integral form of the continuity equation is valid across a true interface since the other variables are discontinuous.

An alternate method is presented in this study that describes soil heterogeneity by specifying that the physical and hydraulic properties of the soil vary continuously as a function of depth. No interfaces are present in the system. Reisenauer (1963), Jeppson and Nelson (1970), Jeppson and Schriber (1972), and Watson and Whisler (1972) used this approach to describe unsaturated flow in a system in which only saturated hydraulic conductivity is allowed to vary. The problem which has been studied herein is for three dimensional axisymmetric unsteady flow through heterogeneous porous media resulting from water being applied on a horizontal soil surface. In this problem, heterogeneity is described by specifying that the hydraulic properties of the soil vary continuously with depth. The Brooks-Corey (1966) parametric equations are used to describe the hydraulic properties. These equations are relatively simple and also provide a reasonably good fit to capillary pressure-saturation and capillary-pressure-hydraulic conductivity data, and involve only three parameters, the residual saturation, S_r , the pore size distribution exponent, λ , and bubbling pressure, P_b^r .

Plotting the Brooks-Corey (1966) equation for degree of saturation and capillary pressure on log-log paper produces a straight line having an intercept, $P_c' = P_b'$ at $S = 1.0$, where S is the effective saturation, P_b' is the bubbling pressure and P_c' is the capillary pressure. For capillary pressures greater than the bubbling pressure, P_b' , (closer to zero), $S = 1.0$. Under trickle irrigation (infiltration processes) the soil never becomes fully saturated and therefore it has been assumed that capillary pressure will always be greater than or equal to the bubbling pressure ($|P_c'| \geq |P_b'|$). Since this problem deals only with the infiltration and not desaturation, in the derivation of flow equation it is assumed that there is a unique relation between the pressure and water content (no hysteresis).

Description of the soil heterogeneity is accomplished by letting the saturated hydraulic conductivity, K_r , the soil porosity, η , the residual saturation, S_r , the pore size distributing exponent, λ , and the bubbling pressure P_b' all be continuous functions of depth. This description allows for specification of an infinite number of different conditions. Different solutions were obtained for different problem specifications. The influence of various degrees of heterogeneity on the amount and distribution of soil moisture, capillary pressure and the extent and amount of horizontal and vertical moisture spreading and the rate of advance and position of wetting front, all of which are of interest in the trickle irrigation, were investigated.

It is not the intent of this paper to describe the detailed mathematical formulation used to obtain the solution. This formulation and solution method would require considerable explanation and is given elsewhere.^{1/} Results from the numerical solutions will be discussed as they affect trickle irrigation design. However, to understand the solution results it is necessary to point out the following:

1. The degree of soil saturation, S , and the relative hydraulic conductivity, K_r , for heterogeneous porous media are described by the following equations, respectively:

$$S = S_r(z) + [1 - S_r(z)] \left[\frac{P_b(z)}{P_c(r,z)} \right]^{\lambda(z)} \quad \text{for } |P_c| \geq |P_b| \quad (1)$$

and

$$K_r = \left[\frac{P_b(z)}{P_c(r,z)} \right]^{2+3\lambda(z)} \quad \text{for } |P_c| \geq |P_b| \quad (2)$$

in which

S = saturation as a function of depth, z

^{1/}Ph.D. dissertation by the first author, Utah State University, also additional professional papers are anticipated to cover this.

S_r = residual saturation as a function of depth, z

$P_b = \frac{P'_b}{\gamma L}$, dimensionless bubbling pressure, with P'_b in lb/ft^2 or N/m^2 ,
function of depth, z

$P_c = \frac{P'_c}{\gamma L}$, dimensionless pressure head, with P'_c in lb/ft^2 or N/m^2 , as
a function of depth, z , and radial coordinate, r

$r = \frac{R}{L}$, dimensionless radial coordinate

$z = \frac{Z}{L}$, dimensionless axial coordinate or depth. Origin is at
bottom of problem.

λ = pore size distribution exponent, function of depth, z

L = scaling length used to nondimensionalize the radial and axial
coordinates and pressure heads

$K_r = \frac{K}{K_o}$, relative hydraulic conductivity at each position where K
is the effective hydraulic conductivity and K_o is the saturated hydraulic
conductivity, which is constant for homogeneous soil. The saturated
hydraulic conductivity, K_o , is defined as the product of a constant,
 K_a , with units of velocity and a dimensionless quantity, K_v , which is
a function of the depth, or

$$K_o(z) = K_a K_v(z)$$

Therefore,

$$K = K_a K_v(z) K_r(P_b, \lambda, P_c)$$

The parenthesis enclose variables upon which that variable is
dependent. With the exception of $P_c(r,z)$ which is a dependent variable
for the formulation, this dependency is specified in equation form a
priori.

2. The unsaturated flow is assumed to be axisymmetric. Figure 1
shows the physical problem and typical assumed boundaries of the flow
field.

3. The outer boundary of the flow field is far enough removed
from the source of water that no flow occurs in its vicinity.

4. The ground surface is horizontal.

5. No evapotranspiration occurs.

6. The initial condition assumes hydrostatic equilibrium, i.e.,
no water movement.

7. The circular surface of water application can be held at any
desired constant water content or receive water at any specified time

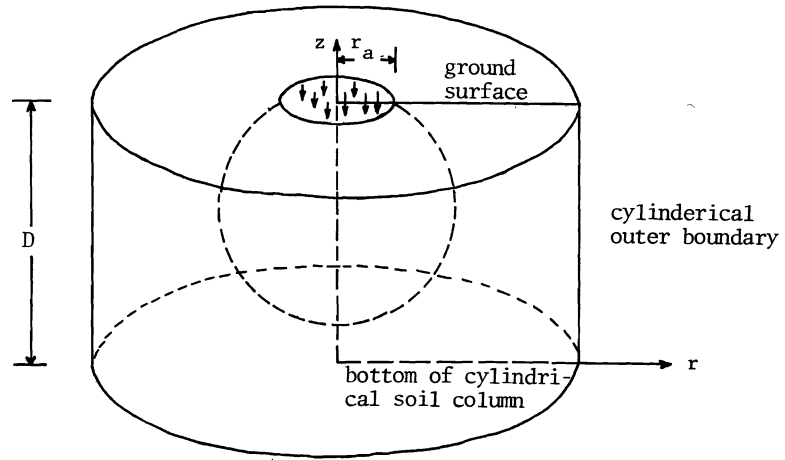


Figure 1. Physical condition for evaluation of transient flow of water from a trickle source at soil surface.

dependent rate. For later conditions, when the intake capacity of the soil is exceeded, the capillary pressure becomes zero and the soil surface becomes fully saturated. When a computed saturation of about 95 percent is reached, the solution continues using the first alternative where the upper boundary condition is a circle of water application.

REPRESENTATIVE SOLUTIONS AND ANALYSIS OF RESULTS

In this study, many solutions have been obtained by varying soil parameters systematically in order to define the trends, solution sensitivity and effect of heterogeneity of the soil on the soil water flow patterns. Herein only one parameter in any given solution is varied. To simplify presentation, these variations have been selected to be linear with depth. Selected items from these solutions are compared to the same item for a homogeneous soil that has parameters P_b , λ , S_r , η , or K_o equal to the average of the varied parameters for the soils in the comparison. Prior to initiation of infiltration, it is assumed that the water in the soil profile is in static equilibrium and that along the soil profile, the hydraulic head, h , is constant and taken as -8.0 feet (2.44 meters). The circular ponded area through which water is infiltrating was assumed to have a constant saturation at all times of 90 percent. For all problems the dimensionless depth of soil was $D = 2.0$ and the dimensionless radius of circular area was taken as $r_a = 0.3$. A dimensionless time increment $\Delta\tau$ of .005 was used to start the solution. Thereafter values of $\Delta\tau$ are periodically multiplied by values larger than 1 to increase the efficiency of computation. The solutions were terminated before the wetting front had penetrated to the cylindrical outer boundary or bottom of soil profile.

Table 1 summarizes the specifications used in obtaining the solutions presented in the various figures hereafter. In the discussions these solutions are referred to by the number contained in the first column of Table 1.

As the water moves into the soil filling a portion of the voids, the capillary pressure is increased (decreased in absolute magnitude) with a resulting increase in hydraulic head, providing the elevation head does not vary. Therefore, an examination of the variation of capillary pressure in the flow field reveals much about the nature of water movement. By noting the extent of the change in initial capillary pressure in the lateral and vertical directions, an indication of the importance of soil heterogeneity effects on the flow pattern can be seen. Lines of constant capillary pressure are shown in Figures 2 through 6 for dimensionless times, $\tau = 0.0$ and $\tau = 1.46$. The Figures were drawn using the solution results from problems number 1 through 11

$\frac{h}{L}$ is defined by $\tau = \frac{K_a}{L} t$.

Table 1. Summary of Specification of Problems

Problem No.	Soil Parameters					Initial Hydraulic Head h_t	Depth D
	P_b	λ	S_r	η	K_v		
1	1.0	1.0	.15	.40	1.0	- 8.0	2.0
2	.70 + .3z	1.0	.15	.40	1.0	- 8.0	2.0
3	1.30 - .3z	1.0	.15	.40	1.0	- 8.0	2.0
4	1.0	.70 + .3z	.15	.40	1.0	- 8.0	2.0
5	1.0	1.30 - .3z	.15	.40	1.0	- 8.0	2.0
6	1.0	1.0	.05 + .1z	.40	1.0	- 8.0	2.0
7	1.0	1.0	.25 - .1z	.40	1.0	- 8.0	2.0
8	1.0	1.0	.15	.18 + .22z	1.0	- 8.0	2.0
9	1.0	1.0	.15	.62 - .22z	1.0	- 8.0	2.0
10	1.0	1.0	.15	.40	.60 + .2z	- 8.0	2.0
11	1.0	1.0	.15	.40	1.40 - .2z	- 8.0	2.0

in Table 1. In each figure, a few of the constant capillary pressure (iso-pressure) lines have been plotted. The computer program defines the wetting front at a position where hydraulic head exceeds the initial hydraulic head by 0.0003 dimensionless units. The vertical position of the wetting front represents the depth of water penetration, and the difference between the maximum radial movement and the radius of the circle of the water application zone, r_a , equals the amount of lateral movement at that time step. Figures 2 through 6 show the effect of soil heterogeneity on the position of wetting front. The distribution of dimensionless capillary pressure prior to the start of the solution (i.e., initial capillary pressure distribution, $\tau = 0.0$) is the same for all problems and is given by horizontal lines consisting of a long line and two dots. In order to find the difference between the results of the heterogeneous condition and the homogeneous condition, three solutions are plotted on the same graph for each varied parameter considered. In all figures presented hereafter, the same parameter has the dashed line and shows that the magnitude of the variable parameter

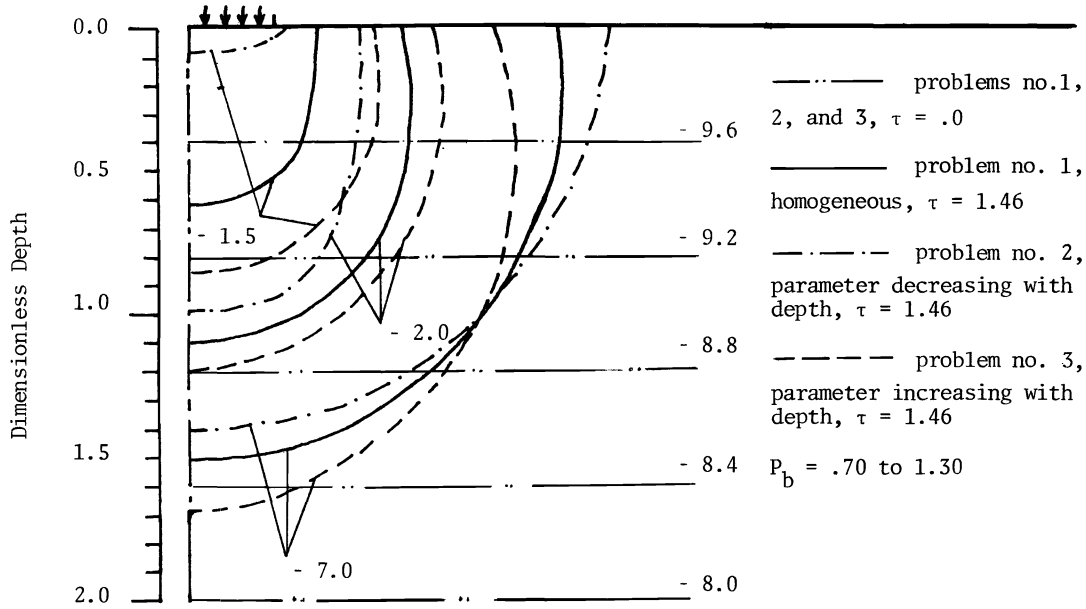


Figure 2. Effect of variation of bubbling pressure, P_b , on distribution of dimensionless capillary pressure P_c prior to infiltration and at dimensionless time $\tau = 1.46$ from maintaining the surface circle of application at 90% saturation for problems 1 through 3.

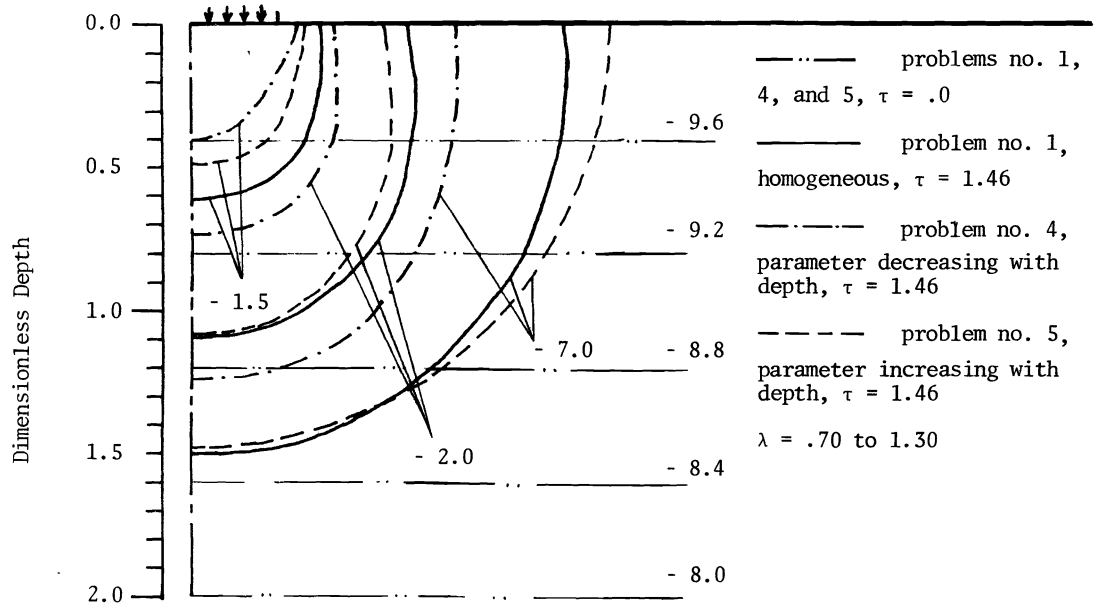


Figure 3. Effect of variation of pore size distribution exponent, λ , on distribution of dimensionless capillary pressure P_c prior to infiltration and at dimensionless time $\tau = 1.46$ from maintaining the surface circle of application at 80% saturation for problems 1, 4, and 5.

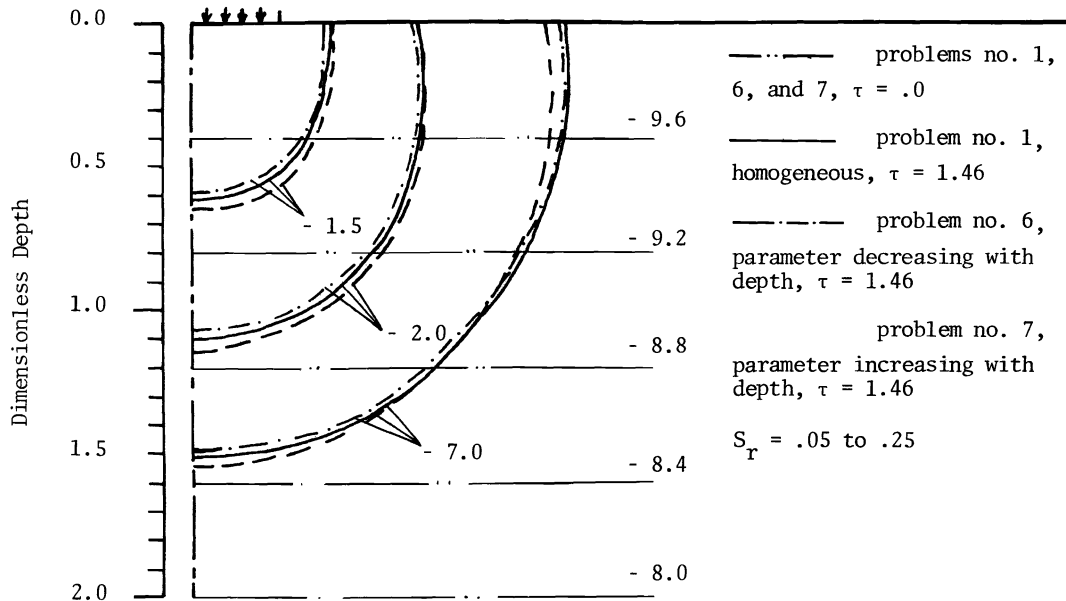


Figure 4. Effect of variation of residual saturation, S_r , on distribution of dimensionless capillary pressure P_c prior to infiltration and at dimensionless time $\tau = 1.46$ from maintaining the surface circle of application at 90% saturation for problems 1, 6, and 7.

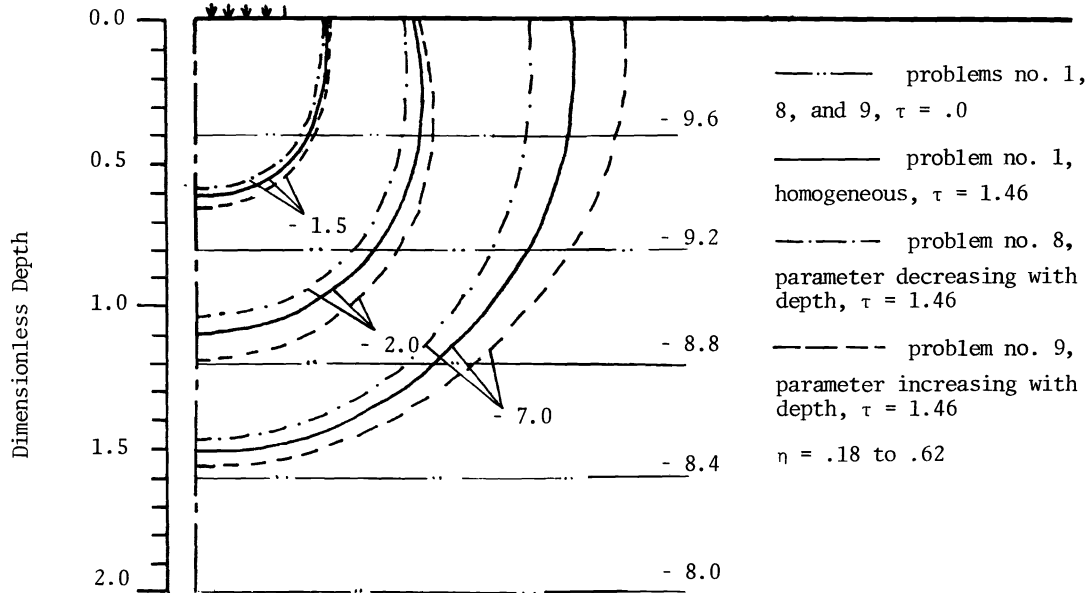


Figure 5. Effect of variation of porosity, η , on distribution of dimensionless capillary pressure P_c prior to infiltration and at dimensionless time $\tau = 1.46$ from maintaining the surface circle of application at 90% saturation for problems 1, 8, and 9.

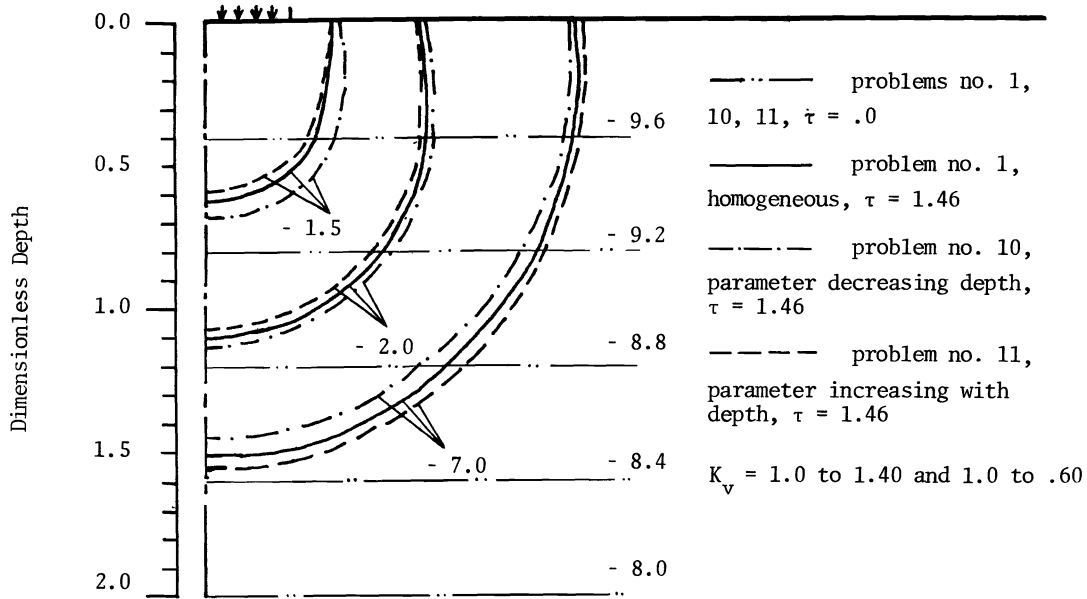


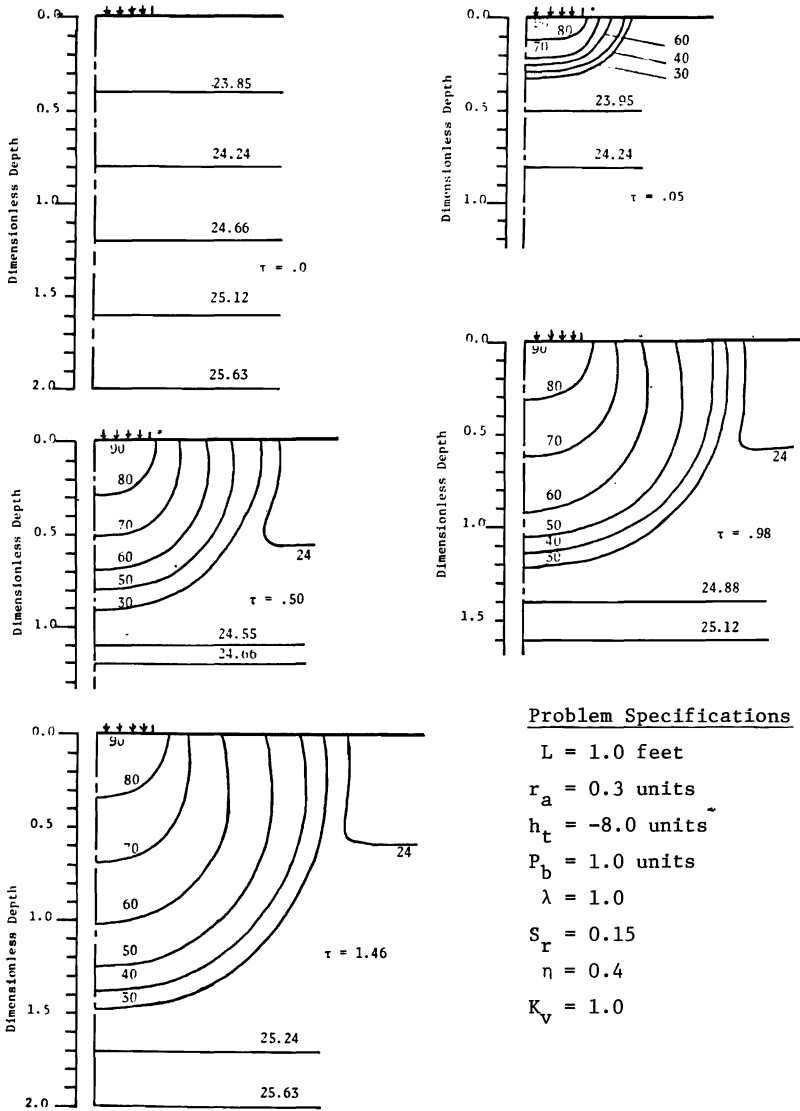
Figure 6. Effect of variation of saturated hydraulic conductivity, K_v , on distribution of dimensionless capillary pressure P_c prior to infiltration and at dimensionless time $\tau = 1.46$ from maintaining the surface circle of application at 90% saturation for problems 1, 10, and 11.

linearly increases with depth and dash-dot-dash line indicates that the magnitude of the variable parameter linearly decreases with depth. Finally, the homogeneous soil condition where the soil parameters are constant, is shown by solid lines. The saturation condition before there is water movement is shown for each problem at the right side of Figures 8 through 14.

The increase in relative saturation from the beginning of water application is another item of interest. Distribution of saturation at several time steps from results of the solution to problem 1 (homogeneous soil), upon a plane passing through the axis of symmetry are plotted in Figure 7. The individual graphs show the vertical penetration and lateral movement of the wetting front at different dimensionless times.

The resultant flow patterns from the solutions to the problems in Table 1 have been plotted for several dimensionless times, τ , in Figures 8 through 14. These figures show how heterogeneity effects saturation with depth and how changes continue during the infiltration process. Each different heterogeneity causes a different initialization of saturation except the porosity, n , and saturated hydraulic conductivity, K_0 . For these two parameters the initial saturation is identical to the homogeneous case. In Figure 8, the value of bubbling pressure used in solution of problem 1, the homogeneous case, is the average of the bubbling pressure heads of problems 2 and 3 ($\frac{.70 + 1.30}{2}$) = 1.0.

Introducing this heterogeneity not only causes the initial saturation under no moisture movement ($\tau = 0.0$) to be different in each problem, but also influences the position of subsequent iso-saturation lines. Figure 8 shows that the iso-saturation line of 30 percent at dimensionless time $\tau = 1.46$ has occurred at a depth of approximately 1.5 units for homogeneous soil (problem 1). For the same 30 percent iso-saturation line from problem 3, in which the bubbling pressure increases linearly with depth of soil, it is at a depth of 1.7 units. The lateral water movement for homogeneous and heterogeneous soil (Problems 1 and 3) is about 0.80 and 0.65 units, respectively, from the edge of the circular water application area. Where the bubbling pressure decreases linearly with depth (problem no. 2), at the same dimensionless time as $\tau = 1.46$ the vertical and lateral movement of the 30 percent iso-saturation line is 1.35 and 1.05, respectively (Figure 8). Thus Figure 8 shows that the rate of penetration of the wetting front is more rapid and lateral (or radial) movement of the wetting front is slower for soils with larger values of bubbling pressure near the surface, provided the other conditions and soil parameters are held constant. Small bubbling pressures generally correspond to coarse textured soils. Water applied to the surface of coarse soils will normally enter more rapidly than it does into fine soils. The pores are larger in coarse soils and the movement of the free water is under less restriction than in the fine soils with smaller pores. In the problem 2, where the soil texture becomes coarser with depth, i.e., P_b decreases, the wetting front has a tendency to spread laterally in the soil profile and the ratio of



Problem Specifications

- L = 1.0 feet
- r_a = 0.3 units
- h_t = -8.0 units
- P_b = 1.0 units
- λ = 1.0
- S_r = 0.15
- η = 0.4
- K_v = 1.0

Figure 7. Distribution of Saturation at Several Dimensionless Times Resulting from Maintaining the Surface Circle of Application at 90 Percent Saturation for Homogeneous Soil (Problem No. 1).

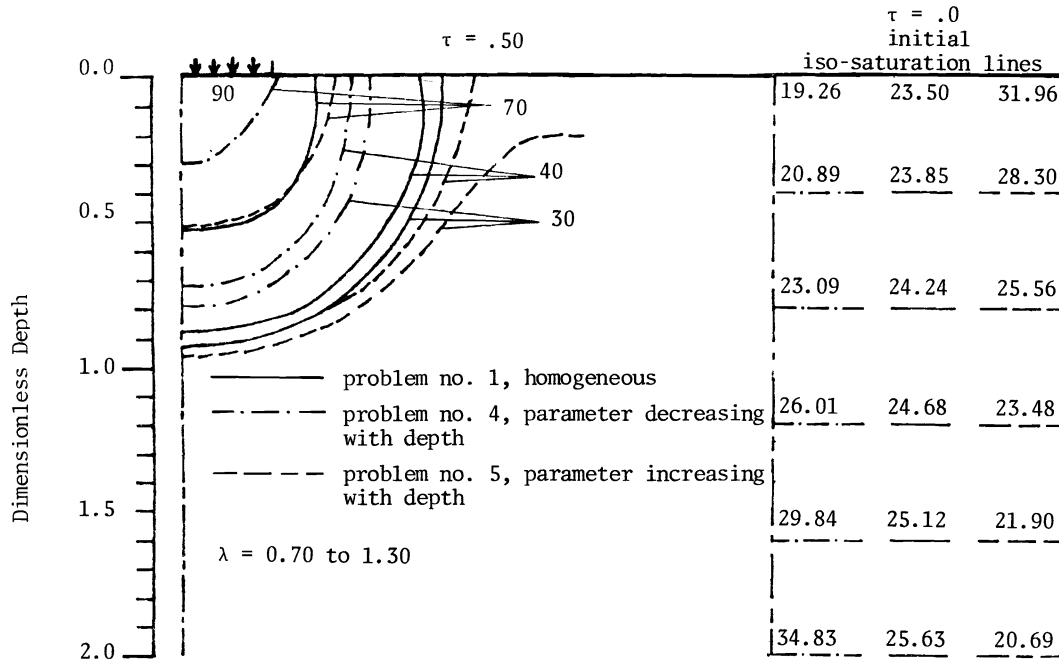


Figure 9. Effect of variation of pore size distribution exponent, λ , on position of iso-saturation lines prior to infiltration and at dimensionless time $\tau = .50$ from the results of solution of problems 1, 4, and 5.

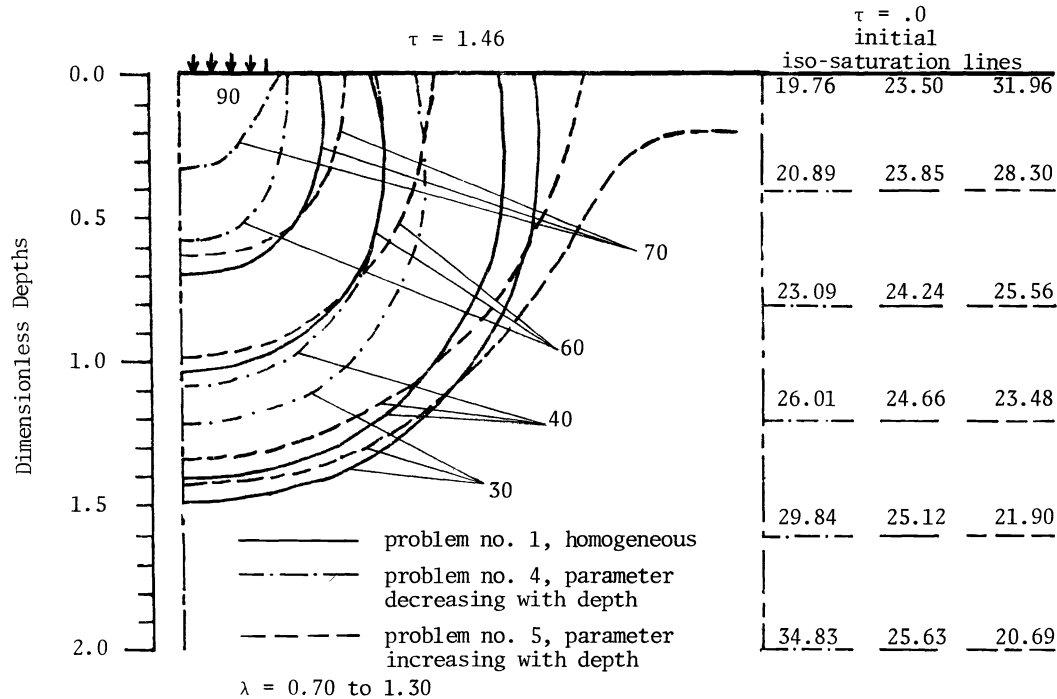


Figure 10. Effect of variation pore size distribution exponent, λ , on position of iso-saturation lines prior to infiltration and at dimensionless times $\tau = 1.46$ from the results of solution of problem 1, 4, and 5.

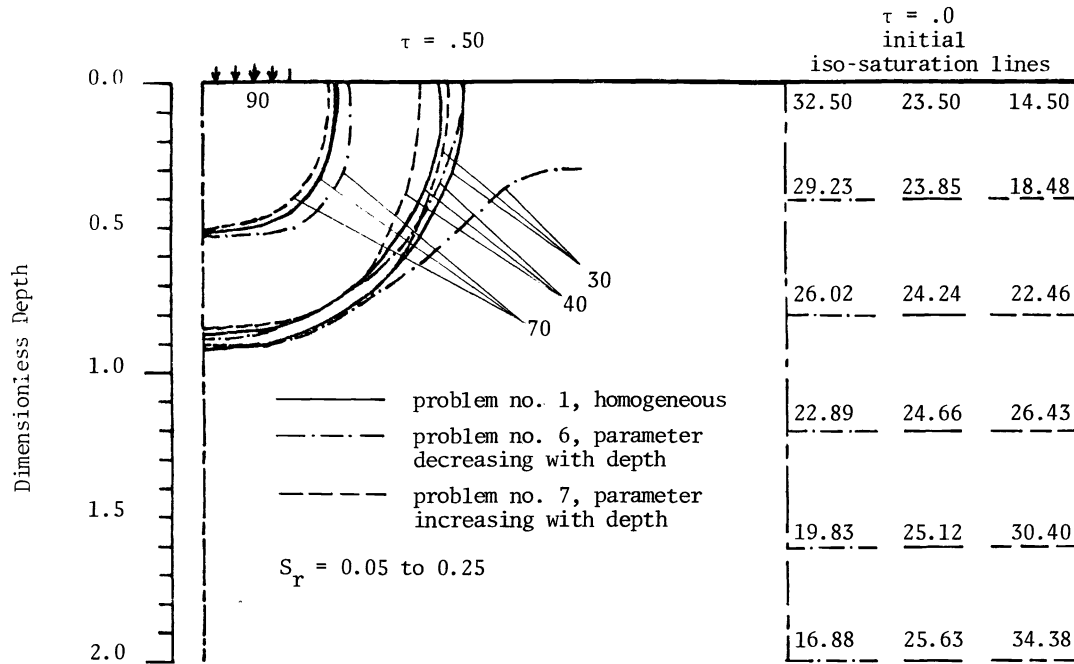


Figure 11. Effect of variation of residual saturation, S_r , on position of iso-saturation lines prior to infiltration and at dimensionless time $\tau = .50$ from the results of solution of problems 1, 6, and 7.

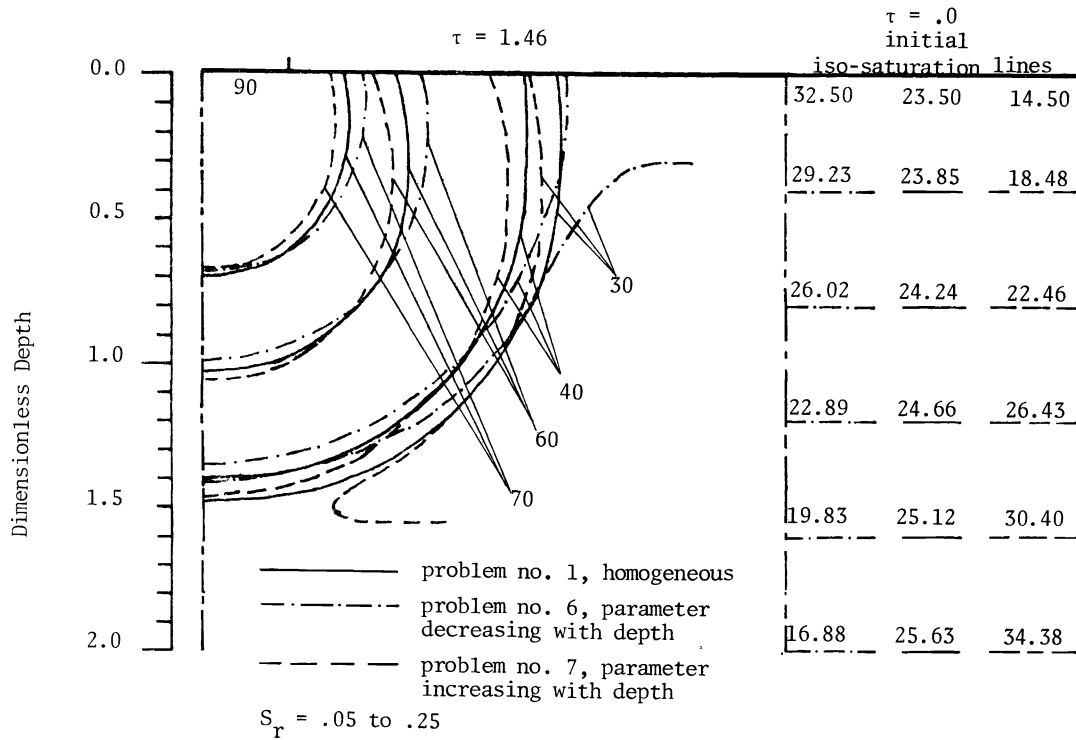


Figure 12. Effect of variation of residual saturation, S_r , on position of iso-saturation lines prior to infiltration and at dimensionless time $\tau = 1.46$ from the results of solution of problems 1, 6, and 7.

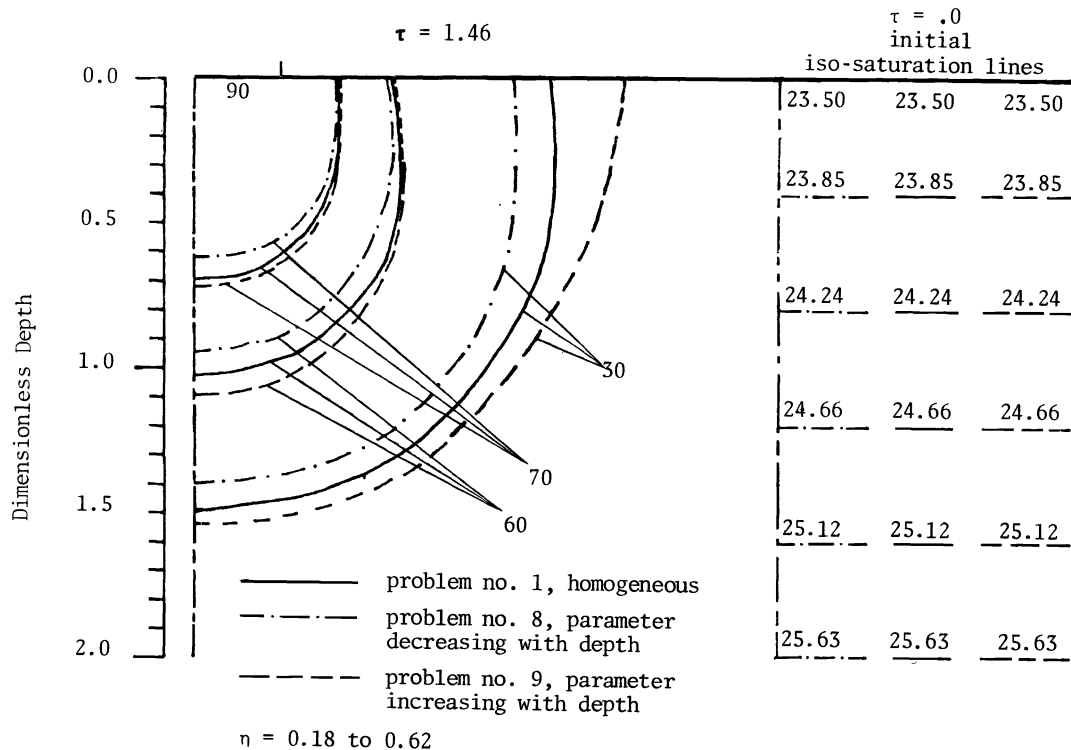


Figure 13. Effect of variation of porosity, η , on position of iso-saturation lines prior to infiltration and at dimension less time $\tau = 1.46$ from the results of solution of problems 1, 8, and 9.

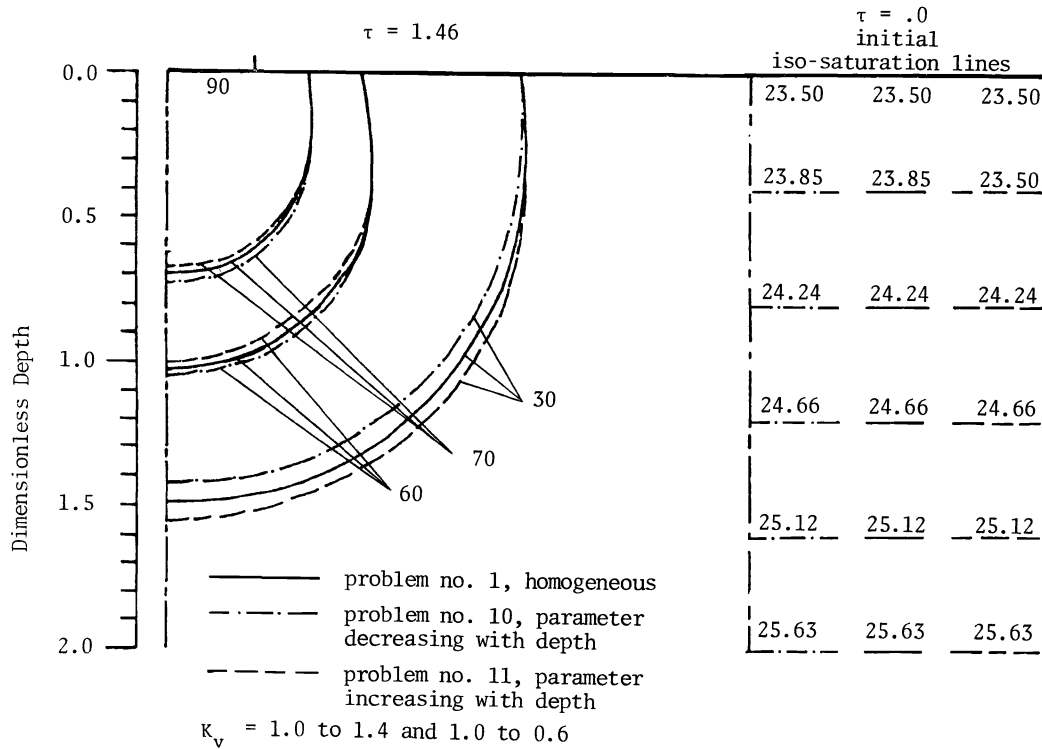


Figure 14. Effect of variation saturated hydraulic conductivity, K_0 , on position of iso-saturation lines prior to infiltration and at dimensionless time $\tau = 1.46$ from the results of solution of problems 1, 10, and 11.

horizontal movement and vertical penetration is $\frac{H}{V} = .83$. Whereas the $\frac{H}{V}$ ratio for the problems 1 and 3 is .61 and .44, respectively.

The effects of variation of the pore size distribution exponent, λ , on the flow patterns for solutions of problems 1, 4, and 5 are shown in Figures 9, and 10. The different distribution of saturation at the beginning of water application in Figures 9 and 10 shows how λ affects the water movement patterns. Usually sandy soils which have a narrow range of pore sizes have larger values for pore size distribution exponent than soils with finer texture. That is, a larger range of pore sizes in a soil causes λ to be smaller. Figure 9 shows that at dimensionless time $\tau = 0.50$, the iso-saturation line of 40 percent for homogeneous soil (problem no. 1) lies between the heterogeneous cases (problems 4 and 5) where the wetting front has not penetrated to the middle of the soil profile. The vertical penetration for the problems 1, 4, and 5 are .87, .72, and .94 and lateral movement are .42, .21, and .50, respectively. At later times, where the wetting front has passed the middle of the soil profile, the condition changes. For example, in Figure 10 at dimensionless time $\tau = 1.46$, the 40 percent iso-saturation line for homogeneous soil (problem no. 1) has moved faster in the vertical direction and is ahead of the other 40 percent than lines from problems 4 and 5. Iso-saturation lines for problem 4 are always inside the isosaturation lines of the homogeneous soil (problem 1). The iso-saturation lines of the problem 5 in which the values of λ increase with depth, are crossed by the iso-saturation lines of homogeneous soil after the wetting front has passed the middle of the soil profile. In problem 5 the value of pore size distribution exponent, λ , linearly increases with depth ($\lambda = .70$ at soil surface) and at the middle of soil profile its magnitude is $\lambda = 1.0$. The pore size distribution exponent affects the relative hydraulic conductivity as given by the Brooks-Corey's equation (2). An examination of the Equation (2) shows that smaller values of the, λ , will result in higher relative conductivity. Consequently, smaller values of, λ , are related to a high hydraulic conductivity of the soil, and soil with larger values of, λ , may act as a hard pan.

Figures 11 and 12 indicate the influence of the variation of residual saturation, S_r , on the water distribution before infiltration and on the position of the iso-saturation lines during infiltration. The range of variation of the initial saturation (at $\tau = 0.0$) for problems 6 and 7 is larger than for all problems shown in Table 1. The magnitude of residual saturation directly affects the value of computed saturation from the Brooks-Corey equation (1) and as Figures 11 and 12 show, the vertical penetration of water has not been greatly affected. More effect can be seen in lateral water movement. For example, for time $\tau = 0.50$ (Figure 11) and $\tau = 1.46$ (Figure 12) the iso-saturation lines of 40 percent show that the difference between vertical penetration for the three problems 1, 6, and 7 is small and that this difference increases with time. Also, Figures 11 and 12 show that the rate of vertical penetration of the wetting front is decreased when the values of residual saturation are decreased. At dimensionless time $\tau = 0.50$ as

Figure 11 shows, the iso-saturation line of 40 percent for problem 1 lies between the iso-saturation lines of the problems 6, 7. Later on, at $\tau = 1.46$, the iso-saturation line of 40 percent of problems 6, 7 is shifted. In the lateral direction the water movement pattern is consistent at all times. Since the initial value of saturation is high (32.50 percent for the problem 6 on the soil surface) and decreases with depth, the wetting front moves more rapidly. Also the increasing residual saturation causes the wetting front to move more rapidly in the lower layers.

Variation of soil porosity does not effect the initial distribution of saturation because the computed saturation is independent of the porosity. Consequently, the initial saturation conditions of the homogeneous and heterogeneous cases are the same. An examination of Figure 13 shows that for the three problems 1, 8, and 9 whose solutions are plotted, the 30 percent iso-saturation line for homogeneous soil lies between the heterogeneous solutions. This is caused by the linear variation of the porosity, η with depth. In the case where the porosity decreases with depth the volume of wetted soil is smaller than for the both homogeneous and the heterogeneous case in which porosity increases linearly with depth. Soils with high porosity at the upper layers have larger water storage capacity and therefore the rate of advance of wetting front is smaller. A longer time is required to fill the pore spaces.

The positions of the iso-saturation lines from solution of problems 1, 10, and 11 are shown in Figure 14. The heterogeneity is caused by linear variation of saturated hydraulic conductivity with depth. Since the values of the computed saturation are independent of the magnitude of the saturated hydraulic conductivity, K , the saturation at the beginning of the solution (at $\tau = 0.0$) for the problems 10 and 11 is the same as for homogeneous soil (problem 1). The saturated hydraulic conductivity is defined as the product of a constant, K_a , with units of velocity and a dimensionless function of the depth, K_v , [$K(z) = K_a K_v(z)$]; in which the constant K_a is taken to be equal to the saturated hydraulic conductivity on the soil surface. Therefore on the soil surface the value of K_v is always equal to one for all problems and linearly decreases or increases with depth, and the magnitudes of all soil parameters (λ , p_b , S_r , η , and K_v) are the same in problems 1, 10, and 11. For this reason the rate of lateral movement near the soil surface is the same for all cases. It can be concluded that the heterogeneity caused by the variation of the saturated hydraulic conductivity does not have a significant effect on the resulting flow patterns in the upper layers. As in the distribution of iso-saturation lines in Figure 13 for variable porosity, the 30 percent iso-saturation line for homogeneous soil lies between the lines for the heterogeneous soils (problems 10, and 11). Also Figure 14 indicates that as saturated hydraulic conductivity increases with depth, the wetting front moved faster than when its magnitude decreased with depth. But the differences between the vertical penetration of the iso-saturation lines for heterogeneous cases and homogeneous case are not great. These differences may be greater for a greater range of variation of saturated hydraulic conductivity. Otherwise, the properties of the soil near the surface is

governing the resulted water flow patterns. Since near the soil surface these properties are almost the same, it is expected to get a unique iso-saturation line for three problems 1, 10 and 11.

However, it is erroneous to draw final conclusions concerning the effects of various degrees of heterogeneity on the water flow pattern from the extremely limited number of solutions given in this paper, particularly in view of the number of parameters involved in specifying the problem. With data from solutions obtained in a more systematic manner, water movement trends can be defined more adequately. Other series of solutions in which more than one parameter is varied at a time are needed to investigate the possible interaction between the soil parameters.

CONCLUSIONS

The actual water flow patter in the field and location of the wetting front for any irrigation event can be found as a function of the 5 soil properties used in the study. A precise estimate of the shape of wetted volume and flow patterns will be useful in determining of emitter spacing, irrigation interval and discharge rate, for a specific soil. To use the results of this study the soil parameters at different depths must be determined. The measurements should be defined by a continuous curve as a function of depth. This analysis will give more guidance and help in gaining greater insight into the factors affecting trickle irrigation design.

REFERENCES

- Brooks, R. H. and Corey, A. T. 1966. Properties of Porous Media Affecting Fluid Flow. Journal of the Irrigation and Drainage Division, ASCE, 92(IR2):61-88.
- Jeppson, R. W. and Nelson, R. W. 1970. Inverse Formulation and Finite Difference Solution to Partially Saturated Seepage from Canals. Soil Science Society of America, Proceedings. 34(1):9-14.
- Jeppson, R. W. and Schreiber, D. L. 1972. Solution of a Two-dimensional Steady-State Watershed Flow System, Part I. Description of Mathematical Model. Transactions of the ASAE. 15(3):457-463.
- Philip, J. R. 1968. Steady Infiltration from Buried Point Sources and Spherical cavities. Water Resources Research 4:1039-1047.
- Philip, J. R. 1969. Theory of Infiltration. Advanced. Hydro Science 5:215-296.
- Philip, J. R. 1971. General Theorem on Steady Infiltration from Surface Sources, with Application to point and Line Sources. Soil Science Society of America proceedings. 35:867-871.

- Raats, P. A. C. 1971. Steady Infiltration from Point Sources, Cavities, and Basins. Soil Science Society of America, Proceedings 35:689-694.
- Raats, P. A. C. 1972. Steady Infiltration from Sources at Arbitrary Depth, Soil Science Society of America, Proceedings, 36:399-401.
- Reisenauer, A. E. 1963. Methods of Solving Problems of Multidimensional, Partially Saturated Steady Flow in Soils. Journal Geophysical Research 68:5725-5733.
- Watson, K. K. and Whisler, F. D. 1972. Numerical Analysis of Drainage of a Heterogeneous Porous Medium. Soil Science Society of America, Proceedings 36:251-256.
- Wooding, R. A. 1968. Steady Infiltration from a Circular Pond. Water Resources Research 4:1259-1273.

