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The effect of steady state rainfall on long term matric suction conditions in soil

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ABSTRACT: The stability of a natural slope is a function of the matric suction conditions in the slope, in addition to the net normal stresses and cohesive resistance of the soil. The understanding of the effect of rainfall on the matric suction conditions in natural slopes can be facilitated through a better understanding of the physical meaning of the coefficient of permeability function relative to the ground surface moisture flux conditions. The objective of this paper is to illustrate the relationship between steady state rainfall, the

The rate at which water infiltrates into a soil is controlled by the coefficient of permeability function for the soil. The maximum flow rate that can enter a soil is limited by the coefficient of saturated permeability of the soil. The coefficient of permeability decreases with the degree of saturation of the soil. The time to reach saturation is a function of the water storage capability of the soil. Under steady state conditions, the time dependence of the equilibrium matric suction profile disappears and the storage term drops out in the seepage formulation.

The study will show that steady state rainfall does not necessarily eliminate matric suction in the soil. The study will also show that the air-entry value of a soil has a significant influence on the long term matric suction conditions in the soil.

1 INTRODUCTION

The accurate prediction of slope failures has been a concern around the world. This concern is evidenced by the catastrophic failure of slopes such as reported by Heath and Saroso (1988) in Indonesia, Addo-Abedi (1988) in Ghana, and Barata (1969) in Brazil. The geotechnical engineer has long been aware of the relationship between rainfall conditions and instability of slopes (Lumb, 1962 and Blight, 1977). The relationship between rainfall and the instability of slopes involves numerous factors such as rainfall intensity, rainfall duration, antecedent soil moisture, soil properties, geometric conditions and climatic variations.

When the failure of a slope is brought on by rainfall, the mechanism of failure is that of water infiltration causing a reduction to the matric suction in the unsaturated soils. A decrease in the matric suction of the soil results in a decrease in the shear strength of the soil.

2 OBJECTIVE AND SCOPE OF STUDY

The objective of this paper is to study the relationship between steady state rainfall, the coefficient of permeability function, and the soil-water characteristic curve on the equilibrium matric suction conditions in a soil. While an actual slope is subjected to transient rainfall conditions, this study will only address steady state condition on a horizontal surface. However, this simplified model will illustrate the significance of the relationship between the ground surface flux and the soil properties in the long term matric suction conditions in the soil.

The study is mainly to address erroneous ideas concerning the effect of ongoing (steady state) rainfall on the matric suction in a soil. In other words, the study is designed to show that steady state rainfall does not necessarily eliminate matric suction from a soil. Further studies are underway with respect to a sloping ground surface, however, the primary processes involved can be illustrated using a horizontal ground surface.

3 SEEPAGE AND INFILTRATION IN A SATURATED/UNSATURATED SOIL

Darcy (1856) postulated that the flow rate of water through a soil mass was proportional to the hydraulic head gradient:

$$v_w = - k_w (\partial h_w/\partial y) \qquad (1)$$

where:
v_w = flow rate of water
k_w = coefficient of permeability with respect to water phase
$\partial h_w/\partial y$ = hydraulic head gradient in the y direction

Equation 1 can also be written for the x- and z-directions.

Darcy's Law also applies for the flow of water through a saturated soil as well as an unsaturated soil. However, the coefficient of permeability in an unsaturated soil is not a constant. The amount of water which infiltrates a soil is controlled by the coefficient of permeability function for the soil. The coefficient of permeability decreases with a decrease in the degree of saturation of a soil.

In keeping with the original formulation in Darcy's law, a two-dimensional transient flow equation for the flow of water through an unsaturated soil can be formulated as follows (Lam et. al, 1988):

$$\partial/\partial x(k_x \partial h/\partial x) + \partial/\partial y(k_y \partial h/\partial y) = \rho_w g m_2^w (\partial h/\partial t) \qquad (2)$$

where:
k_x, k_y = the coefficients of permeability with respect to x and y directions as function of pore-water pressure
h = total head
ρ_w = density of water
g = acceleration due to gravity
m_2^w = slope of the (u_a-u_w) versus volumetric water content, θ_w, curve when $d(\sigma-u_a)$ is zero
θ_w = volumetric water content
u_a = pore-air pressure
u_w = pore-water pressure
σ = normal stress

Equation 2 utilizes the constitutive relationships for stress and deformation in the water phase (Fredlund and Rahardjo, 1993). Transient pore-water pressures occur when the volume of water stored in a soil changes, in response to changes in the pore-water pressures. In other words, the time to reach saturation is a function of water storage (i.e., the right hand side term of Eq. 2) in the soil. Under steady state conditions, the time effects disappear and the storage term drops out in the formulation, thus simplifying the analysis. Under steady state conditions, Eq. 2 simplifies to:

$$\partial/\partial x(k_x \partial h/\partial x) + \partial/\partial y(k_y \partial h/\partial y) = 0 \qquad (3)$$

4 NUMERICAL MODELING STUDY OF STEADY STATE RAINFALL

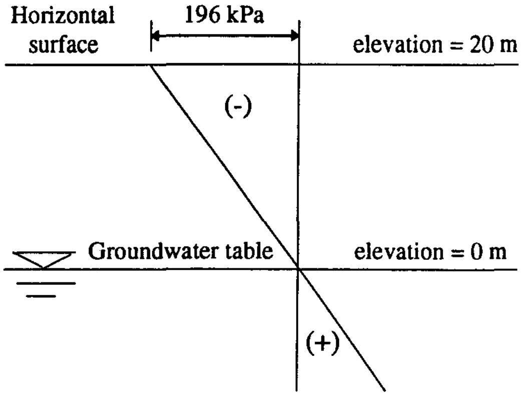

Figure 1. The hydrostatic pore-water pressure profile as a reference state for the numerical seepage analyses.

A horizontal soil surface profile with a groundwater table at a depth of 20 m (Fig. 1) was used in the numerical analysis. The analyses study the relationship between steady state rainfall, the coefficient of permeability function, and the soil-water characteristic curve on the long term matric suction condition in a soil.

The parameters required for obtaining the coefficient of permeability function from the soil-water characteristic curve are shown in Figure 2. The combination of input parameters used in the parametric study are shown in Figure 3, where:

a = matric suction value at the inflection point. This matric suction value is closely related to the air-entry value of the soil (Fig. 2). An air-entry value of a soil is a suction beyond which the soil starts to desaturate

n = soil desaturation rate parameter, a parameter designating the slope at the inflection point of the soil-water characteristic curve (Fig. 2)

m = a parameter which is associated with the residual water content (Fig. 2)

The finite element seepage analysis software, SEEP/W (Geo-Slope, 1993) was used for this study. A total of forty five coefficient of permeability functions (Fig. 3) were used in the simulations. For each coefficient of saturated permeability, the coefficient of permeability functions vary for different combinations of a and n values. The m value was maintained at a value of 0.5 throughout. Annual rainfall flux values varying between 0.001 k_s and 1 k_s were used with each permeability function in the simulations (where k_s is the coefficient of saturated permeability of a soil).

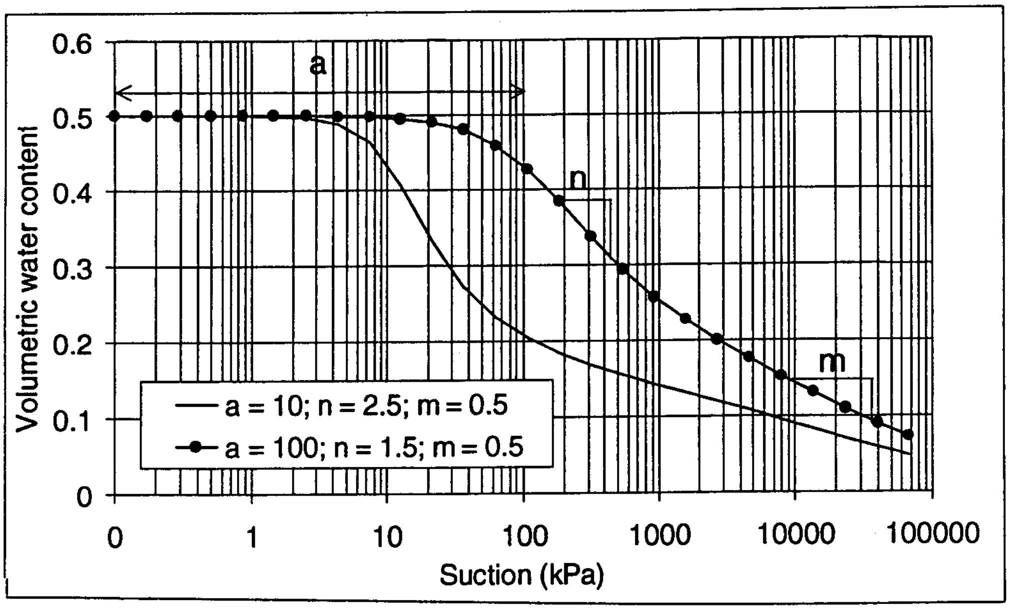

Figure 2. Examples of soil-water characteristic curves

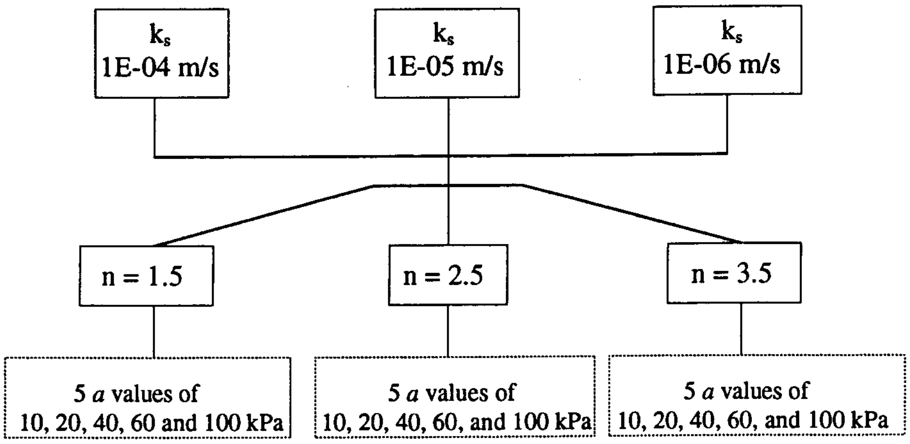

Figure 3. Input parameters used in the parametric numerical seepage analyses.

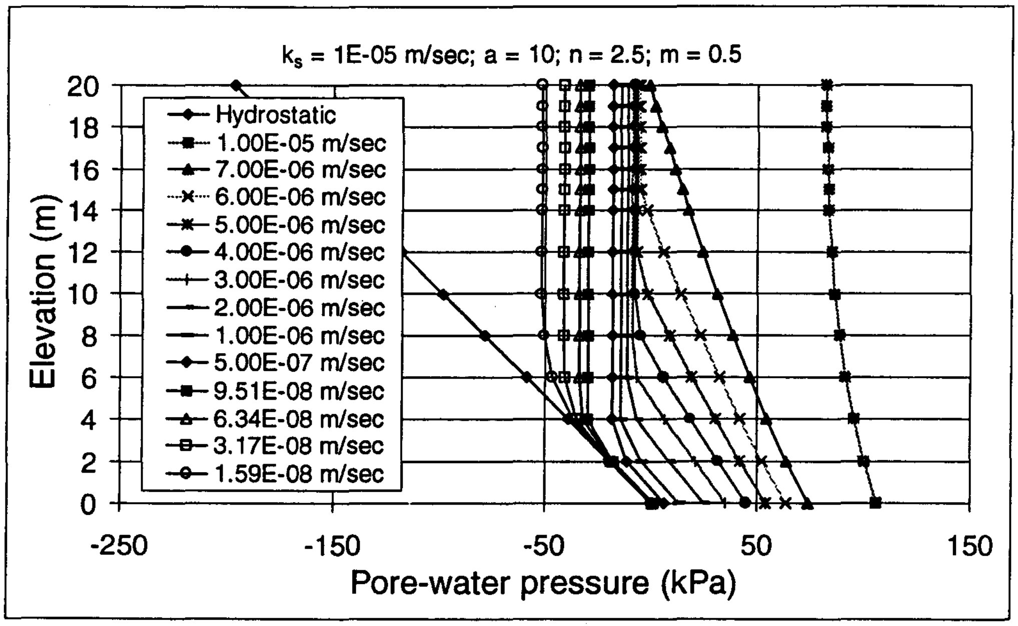

Figure 4. The pore-water pressure profile results for a soil with a coefficient of saturated permeability of 1E-05 m/sec, a = 10 kPa, n = 2.5, and m = 0.5 for various steady state rainfalls.

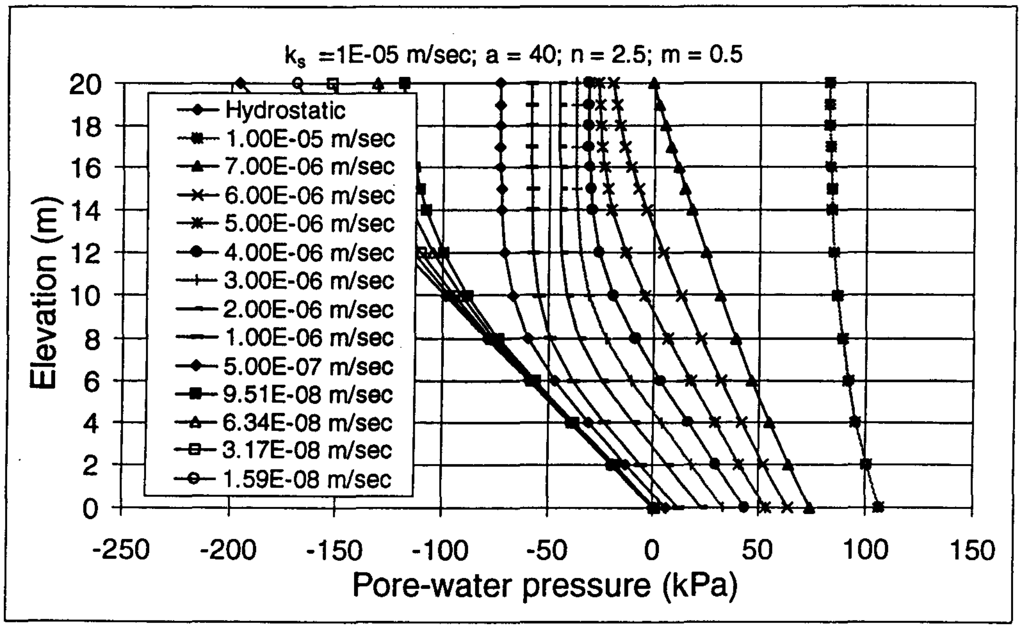

Figure 5. The pore-water pressure profile results for a soil with a coefficient of saturated permeability of 1E-05 m/sec, a = 40 kPa, n = 2.5, and m = 0.5 for various steady state rainfalls.

5 NUMERICAL MODELING RESULTS

The numerical modeling results are presented in the form of pore-water pressure profiles versus the elevation of the soil.

The results in Figs. 4 and 5 were obtained for soils having the same coefficients of saturated permeability of 1E-05 m/sec and n and m values of 2.5 and 0.5, respectively. The pore-water pressure profiles in Figs. 4 and 5 correspond to a values of 10 kPa and 40 kPa, respectively. Similarly, the results in Figs. 6 and 7 were obtained for soils with the same coefficients of saturated permeability of 1E-06 m/sec and n and m values of 2.5 and 0.5, respectively. The pore-water pressure profiles in Figs. 6 and 7 correspond to a values of 10 kPa and 100 kPa, respectively.

Figures 4 and 6 show that for soils with coefficient of permeability functions derived from soil-water characteristic curves having the same a value of 10 kPa, along with coefficients of saturated permeability of 1E-05 m/sec and 1E-06 m/sec, respectively, have pore-water pressure profiles which are uniform in the upper half of the 20 m depth of the unsaturated soil. For a steady state rainfall of 0.001 k_s, the matric suction values at the horizontal surfaces are about 51.9 kPa and 60.1 kPa for the above mentioned soils with coefficients of saturated permeability, k_s, of 1E-05 m/sec and 1E-06 m/sec, respectively. Figures 4 to 7 illustrate that as the steady state rainfall approaches the coefficient of saturated permeability of the soil, the matric suction at the horizontal soil surface approaches zero.

When the steady state rainfall flux is 1.59E-08 m/sec for a soil with a coefficient of saturated permeability, k_s, of 1E-05 m/sec (and n = 2.5; m = 0.5), the matric suction at the horizontal soil surface increases from 51.9 kPa to 169 kPa (Figs. 4 and 5) when the a value increases from 10 kPa to 40 kPa. A similar change occurs for the soil with a coefficient of saturated permeability, k_s, of 1E-06 m/sec (and n = 2.5; m = 0.5). The matric suction at the horizontal soil surface increases from 60.1 kPa to 195 kPa (Figs. 6 and 7) when the a value of the soil increases from 10 kPa to 100 kPa. The soil was subjected to a steady state rainfall flux of 1E-09 m/sec.

6 ANALYSIS OF NUMERICAL MODELING RESULTS

The numerical modeling results show the relationship

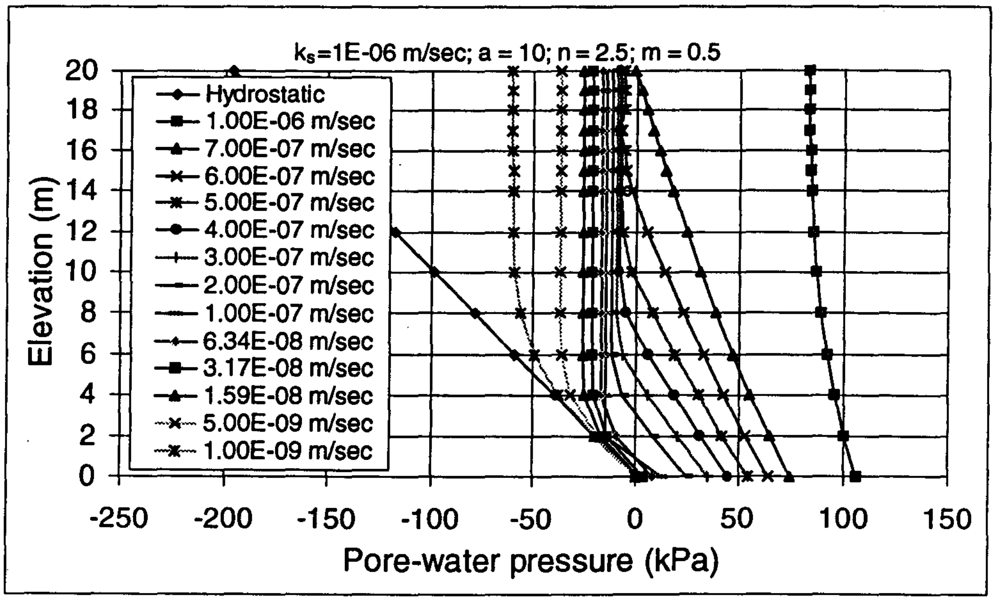

Figure 6. The pore-water pressure profile results for a soil with a coefficient of saturated permeability of 1E-06 m/sec, a = 10 kPa, n = 2.5, and m = 0.5 for various steady state rainfalls.

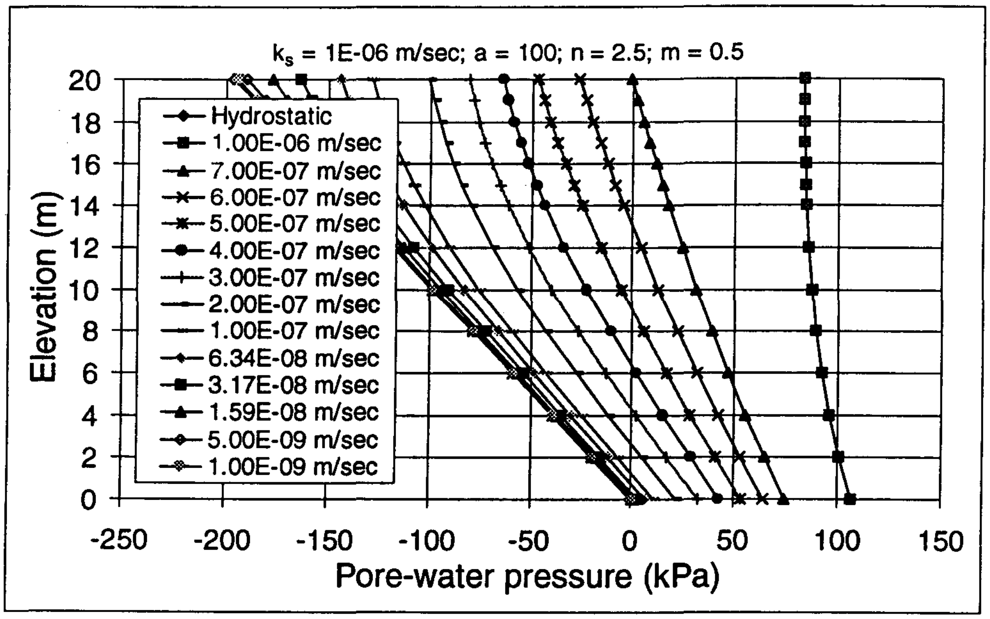

Figure 7. The pore-water pressure profile results for a soil with a coefficient of saturated permeability of 1E-06 m/sec, a = 100 kPa, n = 2.5, and m = 0.5 for various steady state rainfalls.

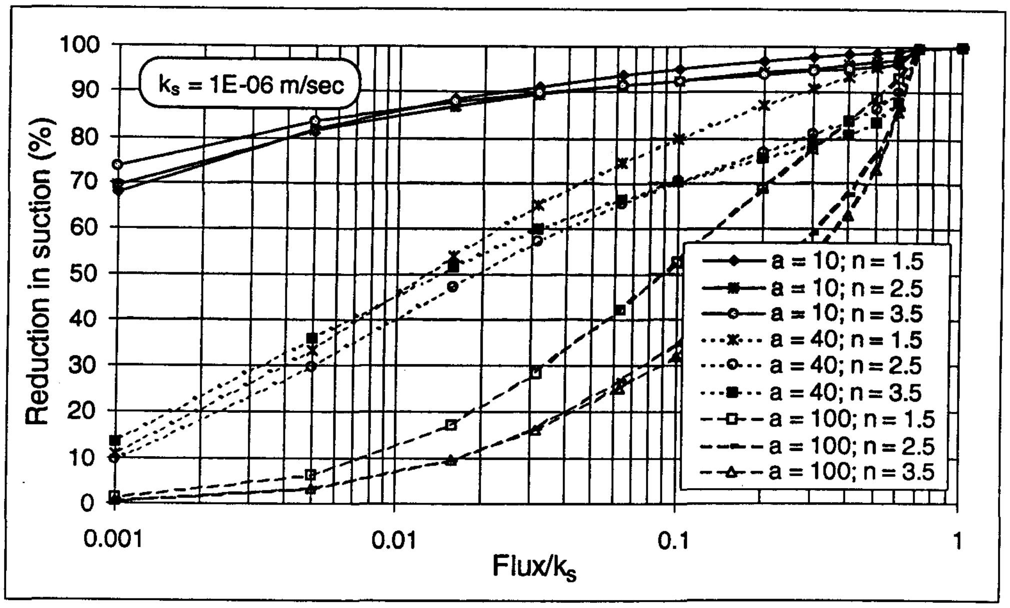

Figure 8. The relationship between the matric suction reduction at the horizontal soil surface (relative to the hydrostatic value) and the rainfall-flux/k_s ratio for various air-entry values and soil desaturation rate parameter.

between steady state rainfall and the coefficient of permeability function (and indirectly the soil-water characteristic curve) on the long term matric suction in a soil. Figure 8 shows the reduction in matric suction versus the ratio of steady state rainfall flux to the coefficient of saturated permeability of the soil. The rise in the water table versus the ratio of steady state rainfall flux to the coefficient of saturated permeability of the soil is presented in Figure 9.

Figure 8 indicates that as the *a* value of the soil increases, the percentage of reduction in suction at the horizontal soil surface decreases, for any steady state rainfall flux values. For example, at a flux of 0.001 k_s, the reduction in matric suction at the soil surface decreases from an average of 70% to 1.0% when the *a* value increases from 10 kPa to 100 kPa. Another observation from the numerical modeling analysis is that the steady state rainfall flux does not necessarily eliminate the long term matric suction of a soil unless the rainfall flux approaches within one order of magnitude of the coefficient of saturated permeability of the soil (i.e., k_s = 1E-06 m/sec in Fig. 8).

The numerical modeling results from this study show that the soil desaturation rate parameter, *n*, does not have a significant influence on the long term matric suction conditions in a soil. It is noted for soils having the same *a* value but different desaturation rate parameter, *n*, that the matric suction reduction versus the rainfall-flux/k_s ratio curves overlap for *a* value of 10 kPa and becomes increasing divergent as *a* value increases (Fig. 8). The parametric study results also indicate that the rise in the water table is not significantly affected by the variations in the *a* or *n* values (Fig. 9).

7 SIGNIFICANCE OF OBSERVATIONS

The significance of the observations from the numerical analysis are:

1. Matric suction in a soil will not disappear unless the steady state rainfall flux approaches the coefficient of saturated permeability of the soil. For example, if the steady state rainfall flux is one order of magnitude less than of the coefficient of saturated permeability of the soil and the soil has a coefficient of saturated permeability, k_s, of 1E-06 m/sec and *a*, *n*, and *m* values of 100 kPa, 2.5, and 0.5, respectively, the matric suction decreases about 35% and 30% at the soil surface and at the 5m depth, respectively.
2. The air-entry value of a soil (which determines the *a* value of the soil) has a greater influence than the soil desaturation rate parameter, *n*, on

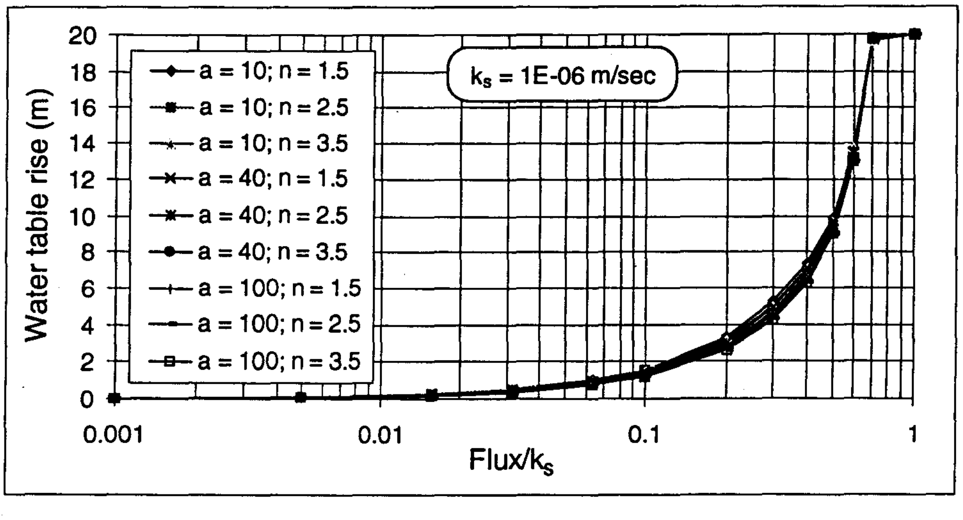

Figure 9. The rise in the water table versus the rainfall-flux/k_s ratio for soils of various coefficient of permeability functions.

the long term matric suction conditions in the soil. The soil desaturation rate parameter, *n*, influences the long term matric suction only in soils with high air-entry values.

3. The study indicates that the rise in the water table in a soil is not significantly affected by the variations in the air-entry value or the soil desaturation rate parameter.
4. Although the study is done for a horizontal soil surface, the primary processes involve in the modeling holds true for a sloping ground surface.

There is much to be learned from the steady state analyses and these studies should be undertaken prior to attempting to simulate transient conditions in a soil.

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