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F. B. Kasim, D. G. Fredlund, and J. K-M. Gan

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Fauziah B. Kasim, Delwyn G. Fredlund, and Julian K-M. Gan
(Department of Civil Engineering, University of Saskatchewan,
Saskatoon, Canada S7N 5A9)

Abstract

Geotechnical engineers have long been aware of the adverse effect of rainfall on the stability of slopes. Reduction of the matric suction of the unsaturated soil is a significant factor contributing to slope instability. The understanding of the effect of rainfall on the matric suction conditions in slopes can be facilitated through a better understanding of the influence of the coefficient of permeability function (with respect to the ground surface flux) on the matric suction conditions in a soil. The effect of evaporation is not addressed in this study.

This paper presents the numerical modelling of steady state rainfall conditions on slopes of various inclinations. The slopes range from horizontal to steep slopes in excess of 60 degrees to the horizontal. Series of parametric analyses that consider varying coefficient of permeability functions and steady state rainfall conditions for the soil have been done for the study. Each coefficient of permeability function is characterized by a saturated coefficient of permeability, k_s, an approximate air-entry value represented by the variable, a, and a desaturation rate parameter represented by the variable, n.

The study shows that the rainfall flux, q_f, to the saturated coefficient of permeability, k_s ratio (i.e., q_f/k_s) and the air-entry value of the soil are the dominant factors affecting the long term matric suction conditions in a slope. The results show that the long term matric suction will not disappear unless the steady state rainfall flux, q_f, approaches the saturated coefficient of permeability, k_s. The numerical modelling results show that the air-entry value of a soil (which determines the a value) has a greater influence than the desaturation rate parameter, n, on the long term matric suction conditions for both the horizontal and the sloping soil profiles.

Introduction and Background of the Study

The stability of a slope is affected by the matric suction conditions in the slope. When the failure of a slope is brought on by rainfall, the mechanism of failure involves water infiltration causing a reduction in the matric suction of the unsaturated soils.

A number of investigators have measured matric suctions in the upper 1 to 2 m of slopes using instruments such as tensiometers. In general, the long term matric suction values are highest at shallow depths, somewhere between the water table and ground surface. Results from Malaysia [1] show a marked variation in matric suctions between the wet and dry seasons, particularly at shallow depths. Results from South Africa [2] compare matric suctions measured in an old section of a tailing dams where no irrigation for vegetation was occurring, with those from a recently built slope where emergent vegetation was being extensively irrigated. Studies [3] have shown that during periods of rainfall, the fluctuations in the matric suction values were greatest near the ground surface. Measurements of the variation in matric suctions in slopes in Hong Kong [3] found that the matric suctions decreased almost to zero at shallow depth during wet seasons, but remained positive at depths of a few meters.

Objective of the Study

A research program was conducted to study the effects of the steady state rainfall on the long term matric suction conditions in a slope. The focus is on the relationship between steady state rainfall, the coefficient of permeability function and the soil-water characteristic curve, on the long term (i.e., steady state) matric suction conditions in the soil mass.

Seepage and Infiltration in a Saturated-Unsaturated Soil

The rate at which water infiltrates a soil is controlled by the coefficient of permeability function and the water storage function for the soil. The coefficient of permeability decreases with the degree of saturation of the soil. The time to reach saturation is primarily a function of the water storage capability of the soil. The maximum flow rate at which water can enter a soil is limited by the rainfall flux and the saturated coefficient of permeability of the soil, k_s. When the ground surface flux is higher than the saturated coefficient of permeability, k_s, the infiltration rate will be a maximum value equals to k_s and the excess rainfall flux becomes runoff.

Darcy [4] postulated that the flow rate of water through a soil mass was proportional to the hydraulic head gradient. The flow equation for the y-direction is as follows:

$$v_w = k_w\left(\frac{dh_w}{dy}\right) \tag{1}$$

where:

v_w = flow rate of water

k_w = coefficient of permeability with respect to water phase

$\frac{dh_w}{dy}$ = hydraulic head gradient in the y-direction

Darcy's Law also applies for the flow of water through an unsaturated soil. In an unsaturated soil, the coefficient of permeability is not a constant. Rather, the coefficient of permeability is a function of the degree of saturation or the suction (or pore-water pressure) in the soil.

From Darcy's law (Eq. 1), a two-dimensional transient flow equation for the flow of water through an unsaturated soil can be formulated as follows [5]:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)=\rho_w g m_2^w\frac{\partial h}{\partial t} \tag{2}$$

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 $(u_a\text{-}u_w)$ versus volumetric water content, θ_w, curve when $d(\sigma\text{-}u_a)$ 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 [6]. 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, time effects disappear and the storage term drops out in the formulation. Under steady state conditions, Eq. 2 simplifies to:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)=0 \tag{3}$$

Numerical Seepage Modelling

A horizontal soil surface and various infinite slopes with a fixed groundwater table located at a vertical depth of 20 m were used in the numerical, seepage modelling program (Fig. 1). The finite element seepage analysis software, SEEP/W

[7] was used for this study. The parameters required for obtaining the coefficient of permeability function from the soil-water characteristic curve are shown in Fig. 2, where the variables are defined as follows:

- *a* = suction value at the inflection point on the soil-water characteristic curve. This suction value bears a relationship to the air-entry value of the soil. The air-entry value of a soil is the suction beyond which the soil starts to desaturate (Fig. 2)
- *n* = 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. It is a measure of anti-symmetry for the soil-water characteristic curve (Fig. 2)

A total of forty five coefficient of permeability functions were used in the simulations for the horizontal soil surface. The coefficient of permeability functions were obtained using combinations of k_s, *a* and *n* values. For each saturated coefficient of permeability, k_s, the coefficient of permeability functions vary for different combinations of *a* and *n* values. The saturated coefficients of permeability were 1E-04 m/s, 1E-05 m/s and 1E-06 m/s. The *a* values were 10 , 20 , 40, 60, and 100 kPa. The *n* values were 1.5, 2.5 and 3.5. The *m* parameter was maintained at a value of 0.5 throughout the simulations. Annual rainfall flux values varying between 0.001 k_s and 1 k_s were used with each permeability function in the simulations for the horizontal soil surface profiles.

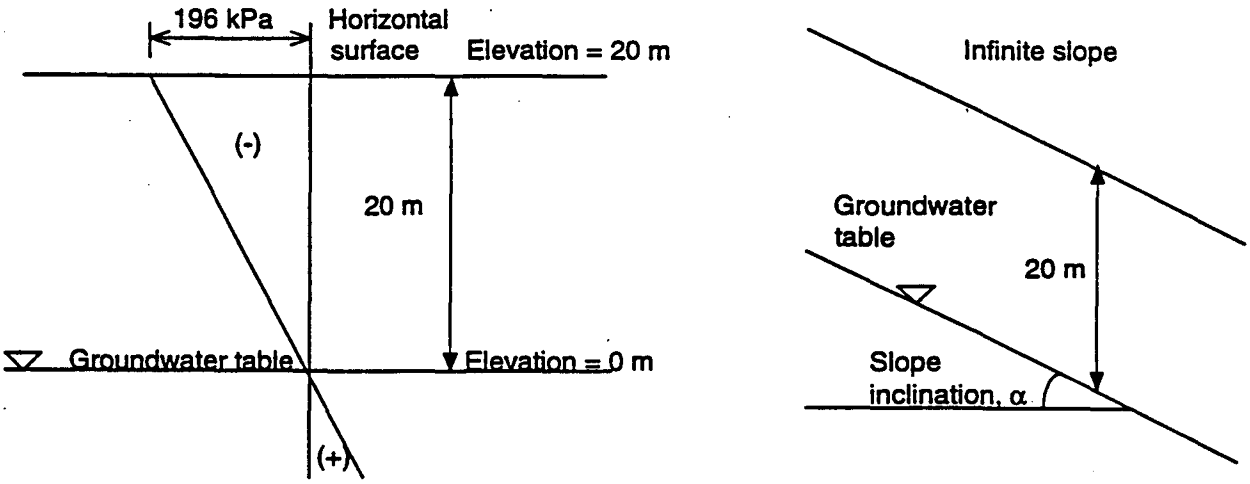


Fig. 1 Hydrostatic pore-water pressure profiles for a horizontal ground and an infinite slope with a groundwater table at a vertical depth of 20 m.

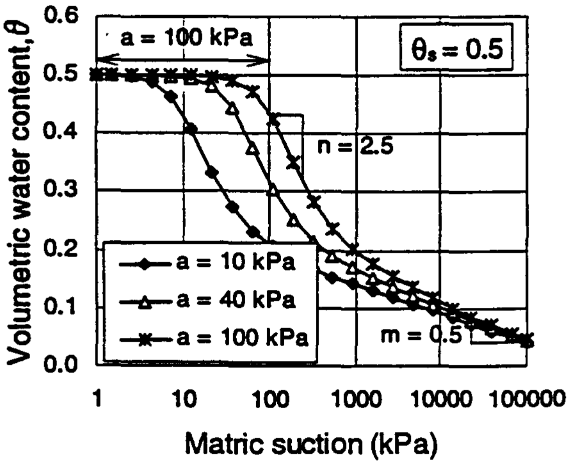


Fig. 2 Soil-water characteristic curves for soils having a saturated volumetric water content, $\theta_s = 0.5$ and $n = 2.5$, corresponding to *a* values of 10, 40 and 100 kPa.

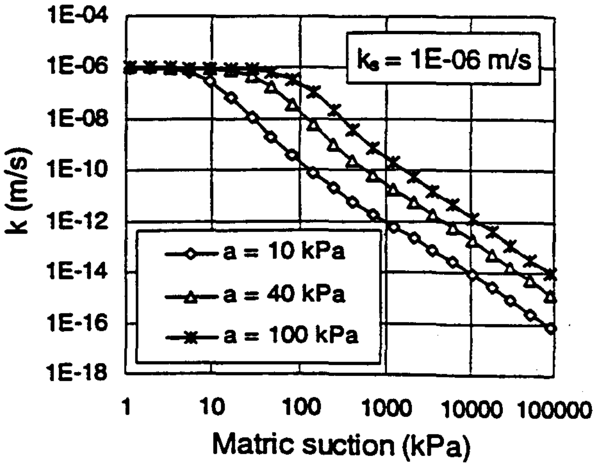


Fig. 3 Coefficient of permeability functions corresponding to the soil-water characteristic curves data in Fig. 2 for soils with k_s = 1E-06 m/s.

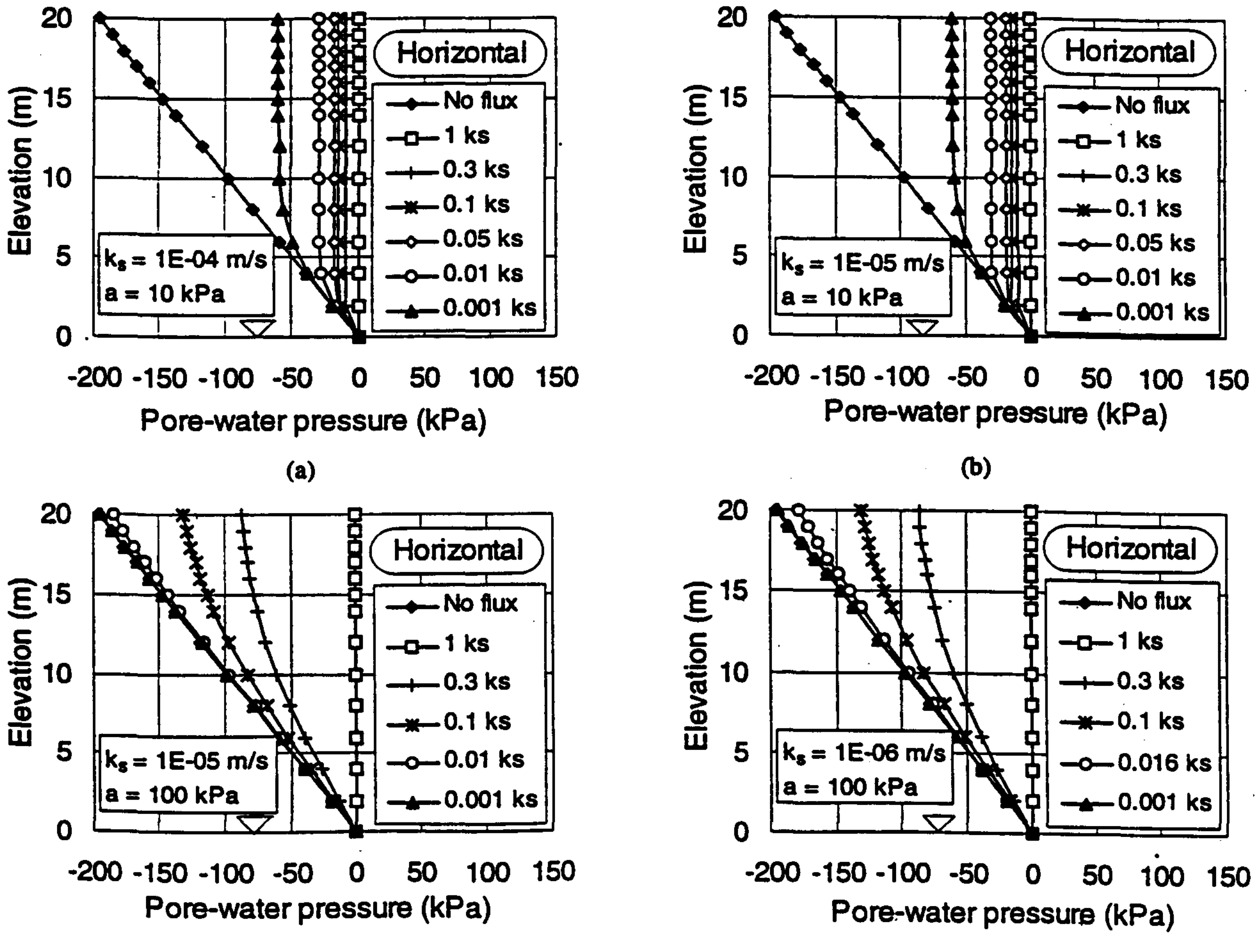
The numerical seepage analyses for the infinite slopes were done for slopes of 1V:2H (α = 25.7 deg), 1V:1H (α = 45 deg) and 2V:1H (α = 63.4 deg). A total of fifteen coefficient of permeability functions were used for each infinite slope. The a values were 10, 20, 40, 60, and 100 kPa. The n values were 1.5, 2.5 and 3.5. The saturated coefficient of permeability was 1E-05 m/s and the m value was 0.5. Annual rainfall flux values varying between 0.0001 k_s and 1 k_s were used with each permeability function in the simulations for the infinite slopes.

Presentation and Interpretation of the Numerical Modelling Results

For the horizontal ground surface, the pore-water pressure profiles corresponding to various steady state rainfall fluxes are presented in Figs. 4a, 4b, 4c and 4d. The soils in Fig. 4a and Fig. 4b have a saturated coefficient of permeability of 1E-04 m/s and 1E-05 m/s, respectively, with a common a value of 10 kPa. The soils in Fig. 4c and 4d have a saturated coefficient of permeability of 1E-05 m/s and 1E-06 m/s, respectively, with a common a value of 100 kPa. All the soils in Figs. 4a, 4b, 4c and 4d have the same n and m values of 2.5 and 0.5, respectively.

The results in Figs. 4a to 4d show that the pore-water pressure profiles are a function of the ratio of steady state rainfall, q_f, to the saturated coefficient of permeability, k_s. For the same q_f/k_s ratio, soils with identical a, n, and m values have identical steady state matric suction profiles. For example, the steady state matric suction profiles in Fig. 4a are identical to those in Fig. 4b and the steady state matric suction profiles in Fig. 4c are identical to those in Fig. 4d. The steady state matric suctions decreases with the q_f/k_s ratio. The matric suctions throughout the entire depth eventually reduce to zero when the q_f/k_s ratio approaches 1.0 (i.e., when the rainfall flux is equal in magnitude to the saturated coefficient of permeability of the soil).

The results in Figs. 4a to 4d also show that the steady state matric suction values for the same q_f/k_s ratio increase with the a values of the soils. In addition, the matric suction profiles are found to be essentially constant with depth for soils with low a values (Figs. 4a and 4b).



(a)

(b)

(c)

(d)

Fig. 4 Pore-water pressure profiles for the horizontal ground with the same n values of 2.5 for various a and steady state rainfall flux values.

For the infinite slopes, the pore-water pressure profiles are presented in Figs. 5 and 6. The slope in Fig. 5 has an inclination of 1V:2H and was subjected to the rainfall flux, q_f, of 0.1 k_s. The slope in Fig. 6 has an inclination of 1V:1H and was subjected to a rainfall flux, q_f, of 0.01 k_s. The results in Figs. 5 and 6 show that the matric suction values increase with *a* values, similar to the results for the horizontal ground surface presented in Figs. 4a to 4d.

The reduction of the surface matric suction as a function of the q_f/k_s ratio are presented in Fig. 7 for the horizontal ground and Fig. 8 for the slope with 2V:1H inclination. The results in Figs. 7 and 8 show that the matric suctions at the surface decrease with both *a* and *n* values. Similar trend was observed for matric suctions at depth. The reduction in the surface matric suction with *a* value is greater than the reduction in the matric suction with *n* value. The effect of the *n* value appears to be more significant when the *a* value increases (Fig. 7). A comparison of Fig. 7 and Fig. 8 shows that the reduction of the surface matric suction decreases with slope inclination for equal q_f/k_s ratio, *m*, *a* and *n* values.

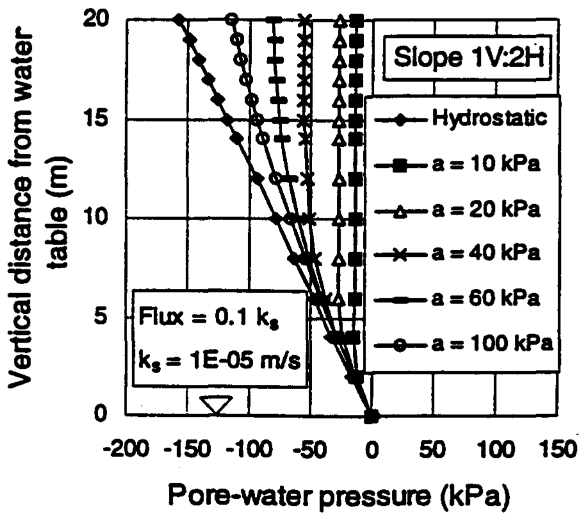


Fig. 5 Pore-water pressure profiles for the 1V:2H slope subjected to a rainfall flux of 0.1 k_s (i.e., k_s = 1E-05 m/s) for various *a* values.

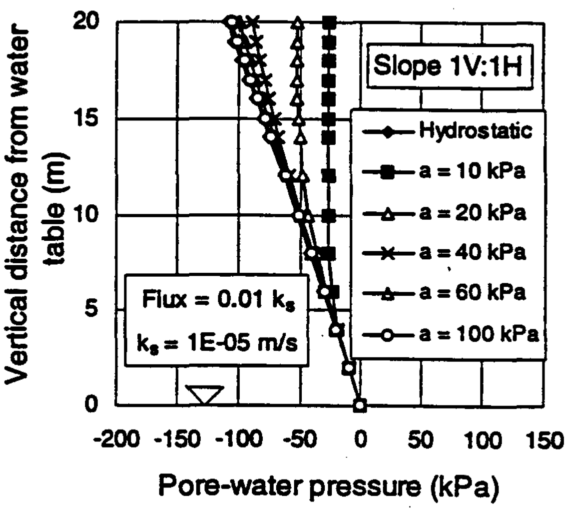


Fig. 6 Pore-water pressure profiles for the 1V:1H slope subjected to a rainfall flux of 0.01 k_s (i.e., k_s = 1E-05 m/s) for various *a* values.

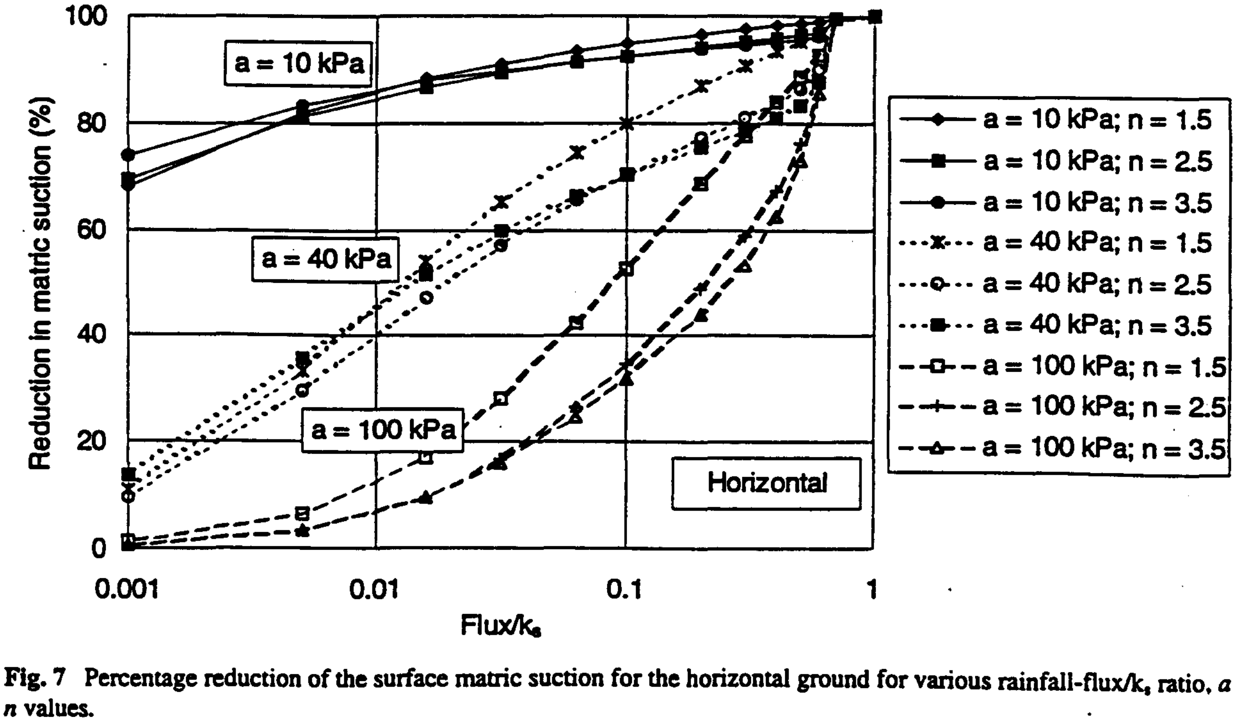


Fig. 7 Percentage reduction of the surface matric suction for the horizontal ground for various rainfall-flux/k_s ratio, *a* and *n* values.

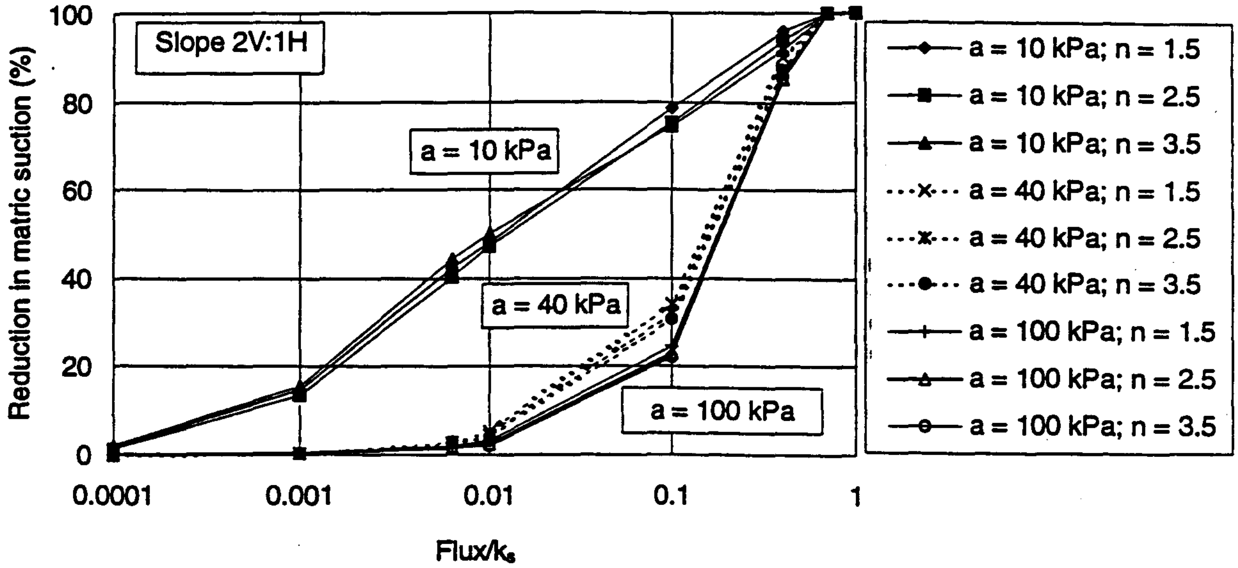


Fig. 8 Percentage reduction of the surface matric suction for the 2V:1H slope for various rainfall-flux/k$_s$ ratio, *a* and *n* values.

Conclusions

The conclusions from the numerical analysis are:

A. The long term matric suction in a soil is a function of the ratio of the steady state rainfall flux to the saturated coefficient of permeability of the soil, k$_s$. The long term matric suctions in a soil profile decrease with q/k_s ratio. The matric suctions reduce to zero throughout the entire depth when the steady state rainfall flux approaches the value of the saturated coefficient of permeability of the soil.

B. For a finite depth of an unsaturated soil subjected to a steady state rainfall flux, the matric suction profile is essentially constant with depth for soils with low *a* values.

C. 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 the long term matric suction conditions in a soil.

References

[1] Abdullah, A. M. L. B., Negative pore pressure characteristics in partially saturated residual soils. *Proceedings of Eleventh Southeast Asian Geotechnical Conference*, Singapore, (1993), 611-616.

[2] Rowe D., *Infiltration induced instability of tailings dam slopes*, MSc. (Engineering) Dissertation, University of Witwatersrand, South Africa (1994).

[3] Sweeney D. J. and Robertson, P. K., A fundamental approach to slope stability problems in Hong Kong, *The Hong Kong Engineer*, 7 (10) (1979), 35-44.

[4] Darcy H., *Historie Des Foundationes*, Publique de Dijon, Dalmont, Paris (1856), 590-594.

[5] Lam L. W., Fredlund, D. G. and Barbour, S. L., Transient seepage model for saturated-unsaturated soil systems: A geotechnical engineering approach. *Canadian Geotechnical Journal*, 24 (4) (1988), 565-580.

[6] Fredlund, D. G. and Rahardjo H., *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, New York (1993), 517.

[7] Geo-Slope International, *SEEP/W Manual - Version 3*, Calgary, Alberta, Canada (1993).