EFFECT OF RAINFALL INTENSITY AND DURATION ON SOIL SUCTION FOR TWO HONG KONG SOILS

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Synopsis

A reduction in the matric suction of an unsaturated soil during rainfall has long been recognized as an important factor contributing to slope instability. The objective of this paper is to study the effects of rainfall intensity and rainfall duration on the matric suctions for decomposed granite and decomposed volcanic soils in Hong Kong.

Based on a statistical study of the experimental soil-water characteristic curves for decomposed granite and decomposed volcanic soils, a range of air-entry values of the two soils is considered. Pore-water pressure profiles under long-term rainfall conditions illustrate that the primary factor that affects the matric suction near ground surface is the intensity of rainfall flux expressed as a percentage of the saturated coefficient of permeability of the soil. Under transient conditions the pore-water pressure depends on the duration of the rainfall. The advance of the wetting front at a specific cross-section in a decomposed volcanic soil slope is in average much faster. Matric suction in a decomposed granite soil slope may need a substantial time to dissipate.

Keywords

unsaturated soils, matric suction, rainfall intensity, rainfall duration, soil-water characteristic curve

1. Introduction

A reduction in the matric suction of an unsaturated soil during rainfall has long been recognized as an important factor contributing to slope instability. Researchers have studied the physical processes of infiltration of rainfall through a staturated-unsaturated soil system. Lumb (1962) introduced the concept of "wetting front" in the investigation of slope failures in Hong Kong. Sun et al. (1998) proposed a generalized wetting band equation based on Lumb's (1962) approach and compared the results of one-dimensional finite element analyses with the wetting band prediction.

In situ suction measurements illustrate that matric suctions do not disappear following a rainstorm in some situations while matric suctions are eliminated in a relatively short time after a rainfall in other situations. Sweeney (1982) presented suction measurements from a 30 m height weathered rhyolite slope in Hong Kong. It shows the pore-water pressures remained negative even during the rainy season. The second example is for a slope consisting of colluvium material in Hong Kong (Anderson 1983). The matric suctions measured were about 20 kPa prior to a rainstorm and decreased to approximately zero after a heavy rainstorm. Kasim (1997) and Kasim et al. (1998a, 1998b) illustrated the steady state rainfall does not necessarily eliminate matric suction in the soil unless the steady state rainfall flux approaches the saturated coefficient of permeability of the soil near the ground surface.

In this study, the pore-water pressure distributions in a decomposed granite soil slope and a decomposed volcanic soil slope are investigated by numerical analyses. The effects of rainfall intensity and rainfall duration on the matric suctions in the soil slopes are illustrated.

2. Theory of water flow in saturated and unsaturated soils

Two-dimensional water flow through saturated and unsaturated soils is governed by the following equation:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)=m_2^w\rho_w g\frac{\partial h}{\partial t} \qquad (1)$$

where k_x, k_y = coefficients of permeability in the x-direction and y-direction, m_2^w = water storage coefficient which is the slope of the soil-water characteristic curve (SWCC, the curve of volumetric water content θ_w versus soil suction ψ), h = hydraulic head, ρ_w = density of water, g = gravitational acceleration and t = time.

The above equation indicates the rate and amount of water that can infiltrate into an unsaturated soil depend on the permeability and the water storage of the soil. Under steady state conditions, the water storage term drops out in the formulation. Therefore, only the coefficient of permeability function influences the pore-water pressure distribution in the soil.

3. Numerical modeling study in a soil slope

A 20 m high slope inclined at 30 degrees shown in Fig. 1 was used in the numerical modeling study. A constant pressure head equal to zero was applied at the groundwater table. Rainfall was modeled as a flux boundary, q, applied along the slope surface. Both steady state and transient seepage analyses were conducted using the finite element seepage analysis software Seep/W for saturated-unsaturated soil system.

Laboratory studies on the SWCCs of decomposed granite (DG) soils and decomposed volcanic (DV) soils have been conducted by Gan and Fredlund (1997), Fung (2001) and Pang (1999). Based on their studies, a statistical analysis was performed for the parameters of the Fredlund and Xing (1994) SWCC model, which is expressed as:

$$\theta_w=\theta_s\Big/\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m \qquad (2)$$

where θ_s = saturated volumetric water content, a = matric suction value at the inflection point, which is related to the air-entry value of the soil, n = the slope of the soil-water characteristic curve at the inflection point and m = a fitting parameter related to residual water content.

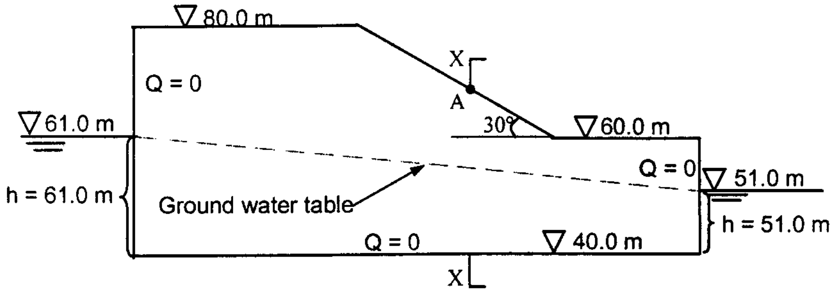

Figure 1. A soil slope profile for numerical modeling

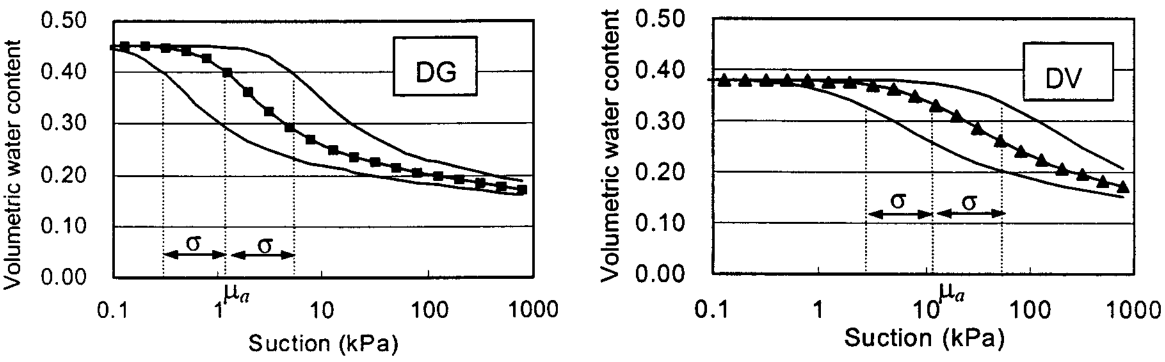

Figure 2. Soil-water characteristic curves of DG and DV

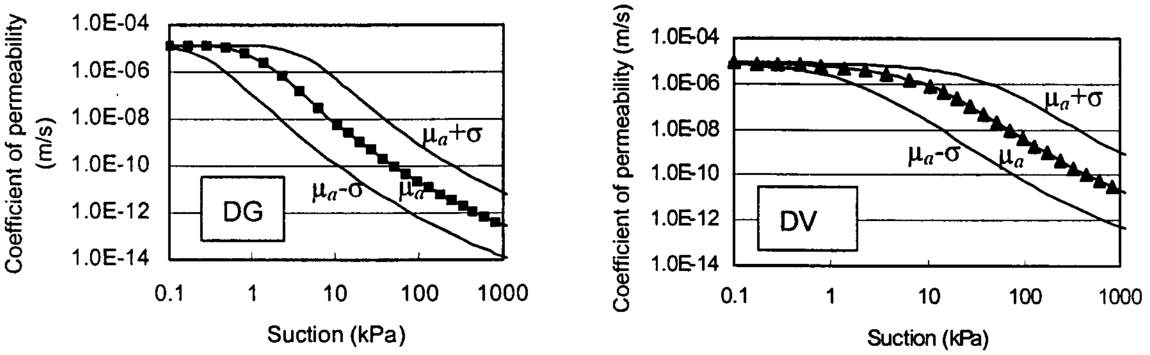

Figure 3. Coefficient of permeability functions for DG and DV

The mean values of θ_s, a, n and m for DG are 0.453, 1.08, 2.186 and 0.349, respectively. The mean values of θ_s, a, n and m for DV are 0.381, 10.62, 1.325 and 0.431, respectively. The saturated coefficients of permeability k_{sat} for DG and DV are respectively 1.42×10^{-5} m/s and 9.11×10^{-6} m/s. The parameter a follows a log-normal distribution. The coefficients of variation (COV) for ln(a) are 1.43 and 1.59 for DG and DV soils, respectively.

Kasim et al. (1998a, 1998b) found that the a value of a soil has a greater influence than the soil desaturation parameter, n, on the long term matric suction conditions in a soil. In this paper, only the variation of the parameter a is considered. The other four parameters, θ_s, n, m and k_{sat}, are chosen to be their respective mean values based on the statistical studies. Three SWCCs with the parameter a of mean value (μ_a), mean minus one standard deviation (μ_a-σ) and mean plus one standard deviation (μ_a+σ) for each soil are used in the numerical modeling. Figure 2 shows the mean curves and the one standard deviation bands of the soil-water characteristic curves for the two soils. The corresponding coefficient of permeability functions for DG and DV are shown in Fig. 3.

Numerical modeling results of steady state rainfall

Long-term rainfall fluxes q varying from 0.01 k_{sat} to 1.0 k_{sat} were applied on the slope of DG and DV soils. Fig. 4 illustrates the pore-water pressure profiles at the cross-section X-X in the DV soil slope with the mean value of a. There is a zone of constant pore-water pressure close to the ground surface. The pore-water pressure in the zone remains negative when the rainfall flux is less than k_{sat} of the soil. As the rainfall flux approaches k_{sat} of the soil, the matric suction approaches zero.

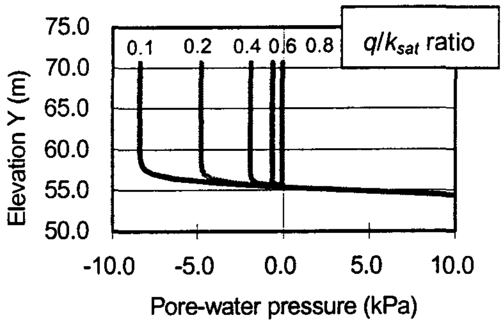

Figure 4. Pore-water pressure profiles at cross-section X-X of the slope with DV mean curve subjected to various rainfall fluxes under steady state condition

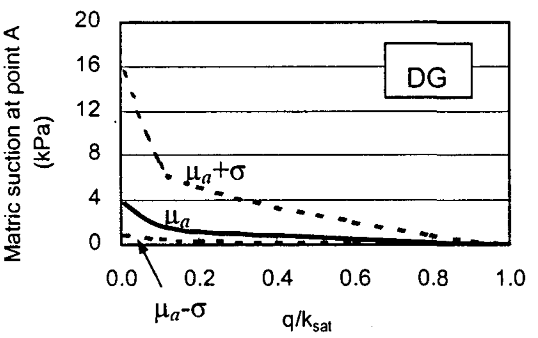

Figure 5. The matric suctions at the point A versus the ratio of q/k_{sat} for DG soils

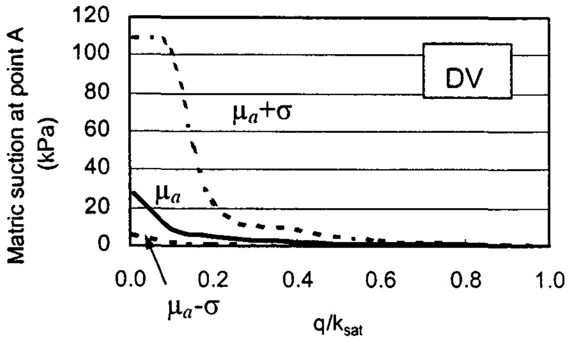

Figure 6. The matric suctions at the point A versus the ratio of q/k_{sat} for DV soils

Figs. 5 and 6 show the matric suction values at the point A of the section X-X in the slope versus q/k_{sat} for DG and DV, respectively. The results illustrate that the decrease of matric suction at the surface of the slope is not linearly related with q/k_{sat}. When q is only 1% of k_{sat}, the matric suction at the ground surface of the slope can be as great as 16 kPa for the DG soil and 110 kPa for the DV soil. When q/k_{sat} is greater than 0.3, the matric suction values at the surface of the slope decrease to a few kPa. As the mean value of a for the DG soil is only about 10% of that of the DV soil, the matric suctions at the point A in the DG soil are much less than those in DV soil. The variation of a for the DG soil is smaller than that of the DV soil, therefore the range of matric suctions in the DG soil is smaller than that in the DV soil.

Numerical modeling results of transient rainfall

The initial pore-water pressure profile in the slope for transient seepage analyses is assumed to be hydrostatic and the rainfall fluxes applied in the slope are assumed to be equal to k_{sat}.

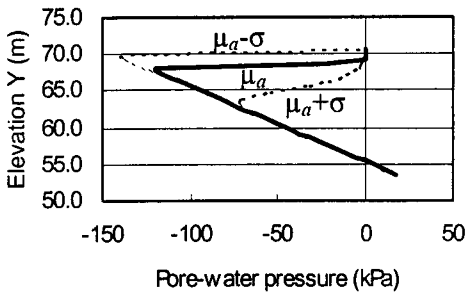

Figure 7. Pore-water pressure profiles at section X-X in the slope with DV soil under transient condition after 12 hours rainfall.

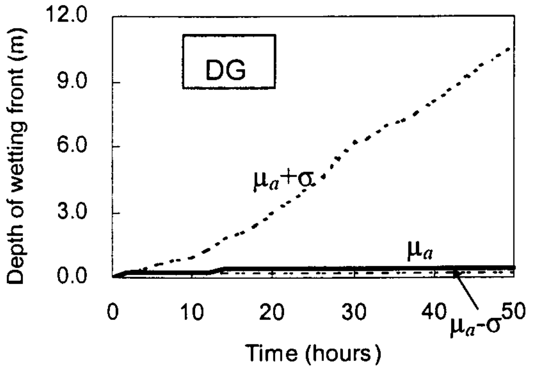

Figure 8. Advance of wetting front at section X-X in the slope with DG soils

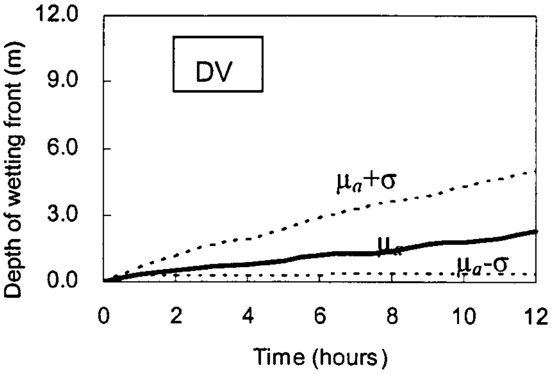

Figure 9. Advance of wetting front at section X-X in the slope with DV soils

Fig. 7 shows the pore-water pressure profiles at the section X-X in the DV soil slope after 12 hours rainfall. The depths of the wetting fronts vary from less than 1 meter to about 5 meters.

Figs. 8 and 9 show the advance of wetting fronts with the duration of rainfall. The advance of the wetting front in the DV soil is in average much faster. For the DV soil with the mean a value, the depth of wetting front is greater than 2 m after 12 hours rainfall. As the mean value of a of the DG soil is extremely small (1.08), the water storage capacity of the soil is very large. Therefore, the advance of the wetting front is extremely slow. After 50 hours rainfall, the depth of wetting front is only about 0.4 m for the DG soil with the mean a value. This indicates that matric suction in the DG soil slope needs a substantial time to dissipate. Although the water storage capacity of the DG soil with the value of $a = (\mu_a - \sigma)$ is greater than that of the DG soil with mean a value, the advance of the wetting front in the DG soil with the value of $a = (\mu_a - \sigma)$ is not significantly slower than the mean value one as shown in Fig. 8.

4. Conclusions

Numerical modeling studies of water infiltration and seepage were conducted on the slopes with two typical Hong Kong soils. The mean and one standard deviation bands of the air-entry values of the two soils are considered in both steady state and transient seepage analyses. The main conclusions are summarized as follows:

1. The matric suction maintained in a soil slope under long-term rainfall conditions is a function of the ratio of the rainfall flux q and k_{sat}. For a rainfall flux less than one percent of

the saturated coefficient of permeability of the soil, the matric suction sustained in the slope can be as much as 16 kPa for the DG soil and 110 kPa for the DV soil. When the ratio of q/k_{sat} is greater than 0.3, the matric suction values at the surface of the slope decrease to a few kPa.

2. Under transient conditions, the advance of the wetting front depends on the duration of rainfall. In average, the advance of the wetting front in DV soils is faster than in DG soils. The depth of wetting front in the DG soil with the mean a value is only about 0.4 m after 50 hours rainfall. For the DV soil with the mean a value, the depth of wetting front is greater than 2 m after 12 hours rainfall.

Acknowledgements

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References

[1] Anderson, M. G., *Prediction of soil suction for slopes in Hong Kong, Geotechnical Control Office Publication No. 1184*, Special Projects Division, Engineering Development Department, Hong Kong, 1983.

[2] Fredlund, D. G. and Xing, A., "Equations for the soil-water characteristic curve". *Canadian Geotechnical Journal*, 1994, **31**, pp521-532.

[3] Fung, W. T., *Experimental Study and Centrifuge Modeling on Loose Fill Slope*, M. Phil. thesis, The Hong Kong University of Science and Technology, Hong Kong, 2001.

[4] Gan, J. K-M. and Fredlund, D. G., *Study of the Application of Soil-water Characteristic Curves and Permeability Functions to Slope Stability, Part 1, Permeability and Soil-water Characteristic Curve Tests, and the Computation of Permeability Functions*, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, 1997.

[5] Kasim, F. B., *Effects of Steady State rainfall on Long Term Matric Suction Conditions in Slopes*, Internal Engineering Research Report, Unsaturated Soils Group, University of Saskatchewan, Saskatoon, Sask., Canada, 1997.

[6] Kasim, F. B., Fredlund, D. G., and Gan, J. K-M., "The effects of steady state rainfall on the matric suction conditions in a slope", *Proceedings of Second Internation Conference on Unsaturated Soils*, UNSAT2, Beijing, China, August, 1998a, **1**, pp78-83.

[7] Kasim, F. B., Fredlund, D. G., and Gan, J. K-M., "The effect of steady state rainfall on the matric suction conditions in soil", *Slope Engineering in Hong Kong*. K. S. Li, J. N. Kay and K. K. S. Ho (eds), Balkema, Rotterdam, 1998b, pp75-85.

[8] Lumb, P., "Effect of rain storms on slope stability", *Proceedings of the Symposium on Hong Kong Soils*, Hong Kong, 1962, pp73-87.

[9] Pang, Y. W., *Investigation on Soil-water Characteristics and Their Applications on Stability of Unsaturated Soil Slopes*, M. Phil. thesis, The Hong Kong University of Science and Technology, Hong Kong, 1999.

[10] Sun, H. W., Wong, H. N., and Ho, K. K. S., "Analysis of infiltration in unsaturated ground", *Slope Engineering in Hong Kong*. K. S. Li, J. N. Kay and K. K. S. Ho (eds), Balkema, Rotterdam, 1998, pp101-109.

[11] Sweeney, D. J., "Some *in situ* soil suction measurements in Hong Kong's residual soil slopes", *Proceedings of the 7th Southeast Asian Regional Conference*, 1982, **1**, pp91-106.