CAPILLARY BARRIER EFFECT ON THE RESPONSE OF RESIDUAL SLOPE TO RAINFALL INFILTRATION

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Dedicated to my beloved parents
(Joseph Chai Jee Min and Connie Ho Geok Hiang), brother
(Alexander Chai Pak Siew), and friends.
Thanks for all your love and supports.

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ABSTRACT

Rainfall-induced slope failure is a common problem in areas covered by residual soil in tropical countries. The soil exists in unsaturated condition as ground water table is located well below the ground surface. Rainfall infiltration results in a reduction of matric suction of soil which in turn reduces the soil shear strength, and subsequently triggers the slope failure. Natural formation of the residual soil has lead to the variation of hydraulic conductivity in which soil closer to the ground surface usually has lower permeability as compared to the deeper layer. This condition causes the development of capillary barrier effect at the interface. The water accumulates at the interface and flow for some distance down-slope before it manages to infiltrate into the deeper layer. The distance that the water has to travel before breakthrough is referred as the water diversion length. Numerical simulation using SEEP/W was performed in this study to determine the water diversion length for two cases representing natural slopes i.e. Silty SAND over SAND and Silty SAND over Highly Weathered Granite. Parametric study was performed to study the effect of several variables including hydraulic conductivity of soil, thickness of layers, slope dip angle and the rate of infiltration. Results show that the diversion length is linearly correlated with the difference in the permeability of two soil layers and slope dip angle. The effect of rainfall infiltration depends on the saturated permeability of the upper layer (MRL). The optimum thickness of MRL obtained in this study is 1.5m. Results of numerical analysis are compared with analytical method by Ross model, however good agreement between the two methods was not reached because the difference in saturated hydraulic conductivity of the soils used is not very big. Moreover, under an infiltration rate, the maximum suction existing in the CBL (ψ_{c_CBL}) should be as low as possible while the maximum suction attained in the MRL (ψ_{c_MRL}) should be as high as possible, which was not the case especially for Silty SAND over Highly Weathered Granite.

ABSTRAK

Di negara tropika, kestabilan cerun dengan tanah sisa sering tergugat akibat hujan. Tanah ini sering wujud dalam keadaan tak tepu akibat kedudukan aras air tanah yang jauh draipada permukaan tanah. Penyusupan air hujan akan mengurangan sedutan matrik dalam tanah lalu akan mengurangkan kekuatan ricih dan seterusnya mengakibatkan keruntuhan cerun. Kewujudan semulajadi tanah sisa pada cerun manghasilkan ciri seperti perbezaan kekonducksian hidraulik dengan kekonducksian hidraulik yang rendah pada paras dekat dengan permukaan tanah dibanding dengan lapisan yang lebih dalam. Keadaan ini menghasilkan perkembangan kesan sawat rerambut di antara muka. Air akan kumpul di antara muka and mengalir untuk jarak tertentu sebelum ia dapat menyusup ke lapisan yang lebih dalam. Jarak untuk air mengalir sebelum burus terjadi ialah jarak lencongan. Simulasi dengan menggunakan SEEP/W diperkenalkan untuk menentukan jarak lencongan bagi dua kes menwakili cerun semulajadi i.e. pasir berlodak atas pasir dan pasir berlodak atas granit terluluhawa. Kajian berparameter dijalakan untuk mengaji kesan daripada beberapa kadar berubah termasuk kekonduksi hidraulik tanah, ketebalan lapisan, sudut miring cerun dan kadar penyusupan. Keputusan yang diperolehi menunjukan yang jarak lencongan berkolerasi secara linear dengan perbezaan dalam kekonduksian hidraulik dua lapisan tanah dan sudut miring cerun. Kesan penyusupan air hujan bergantung pada kekonduksian hidraulic tepu lapisan atas (MRL). Ketebalan optimum MRL yang diperlukan ialah 1.5m. Selain itu, keputusan yang diperolehi daripada keadah berangka dibandingkan dengan analisis oleh model Ross, walaubagaimanapun, keserasian keputusan tidak dapat diperolehi antara kedua-dua analisis kerana perbezaan antara kekonduksi hydraulik tepu lapaisan tanah yang digunakan tidak sangat besar. Di samping itu, sedutan matrik maxima dalam lapisan CBL (ψ_{c_CBL}) perlu serendah yang mungkin dan setinggi yang mungkin dalam MRL, namun ini bukan kesnya terutamanya bagi pasir berlodak atas granit terluluhawa.

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CBL	-	Capillary break layer
MRL	-	Moisture Retention layer
h_e	-	Elevation head
h_p	-	Pressure head
H	-	Total Head
z	-	Vertical coordinates distance from a prescribed datum
z_c	-	Height which pressure head profile breaks away from the 45°line
u_w	-	Pore water pressure
u_a	-	Pore-air pressure
g	-	Gravitational acceleration
ρ_w	-	Density of water
k_ψ	-	Hydraulic conductivity in terms of matric suction,
k_{sat}	-	Saturated hydraulic conductivity
$k_r(\psi)$	-	The relative permeability function
ψ_m	-	Matric suction
ψ_c	-	Maximum suction value
L	-	Diversion length
Q	-	Diversion capacity
q	-	Infiltration rate
q	-	Specific discharge
t	-	Time
Q_b	-	The applied boundary flux
K	-	Hydraulic conductivity

k_x	-	Hydraulic conductivity in the x-direction
k_y	-	Hydraulic conductivity in the y-direction
θ	-	Volumetric water content
i	-	Gradient of fluid head or potentials

CHAPTER 1

INTRODUCTION

1.1 Background

Tropical residual soils have some unique characteristics related to their composition and the environment under which they developed. The most distinctive is the microstructure, which changes in a gradational manner with depth. The soil closer to the ground surface consists of finer grained as compared to the soil at greater depth due to the effect of weathering process.

Most classical concepts related to soil properties and soil behaviour was developed for temperate zone soils hence; it is difficult to accurately model the procedures and conditions to which residual soils in tropical region has been subjected. Engineers appear to be slow in recognizing that residual soils hold negative in situ pore-water pressures or suction, and that much of the unusual behaviour exhibited during laboratory testing is related to the change in the matric suction within the soil (Fredlund and Rahardjo 1985, 1993).

Residual soil in tropical country and subtropical regions frequently exist in unsaturated condition because the position of groundwater table is far below the ground surface. These soils experience high matric suction during dry periods, which contributes to the shear strength. During prolonged wet periods, sufficient infiltration of rainwater will change the water content and the pore-water pressure in the soil. The increase in water content will reduce the matric suction (negative pore-water pressure) which in turn will reduce the additional shear strength of the soil provided by the matric suction. As a result, surface sloughing will occur on slope following prolonged period of precipitation. This type of failure has received little attention from an analytical standpoint in the past. One of the main difficulties is associated with the assessment of pore-water pressures in the zone above the groundwater table or unsaturated zone. The assessment of slope surface failure in residual soil was made possible by the introduction of unsaturated soil mechanics.

Permeability is a dominant factor in the suction distribution and the stability of slopes (Pradel and Raad, 1993; Gofar *et al*,, 2007). As mentioned in the preceding paragraph, the residual soil is formed by weathering forces, resulting in the variation of particle size, hence the variation in hydraulic conductivity with depth. In other words, the permeability of the soil changes with depth. Study by Iverson and Major (1987) showed that the variation of coefficient of permeability in residual soil mantels is more than three orders of magnitude however; Agus *et al*. (2005), based on his study in Singapore, that the variation of coefficient of permeability is only within two orders of magnitude. Nevertheless, the presence of finer over coarser layer could create capillary barrier effect due to the change in hydraulic conductivity; hence reduces the rainfall infiltration to a deeper layer.

The effect of capillary barrier on controlling the rainfall infiltration has been studied by several researchers (e.g. Parent and Cabral, 2005 a and b) for the purpose of the design of landfill cover or slope cover. The ability of a slope to divert infiltrating water depends upon the contrast in the unsaturated hydraulic properties of fine and coarse layers, layer thickness, the angle of the slope, and the infiltration rate. Analytical method to calculate the diversion length has been developed by Ross (1990). However, not much research focused on the effect of variation of hydraulic conductivity resulting from the residual soil formation on the development of slip surface for rainfall induced slope failure.

1.2 Problem Statement

The variation of hydraulic conductivity of residual soil with depth influences the suction distribution in residual soil. The presence of finer over coarser layer slow down the rainfall infiltration to a deeper layer hence; water will be collected near the interface (boundary between the upper finer layer and the lower coarse layer) due to capillary forces. This will promote the development of slip surface at or above the interface. The length of slip surface, or the water diversion length depends on several factors e.g. the infiltration rate, variation of hydraulic conductivity, the thickness of finer layer and slope inclination.

1.3 Aims and Objectives

This study is aimed at identifying the influence of various variables on the water diversion length of inclined slope with capillary barrier effect based on results from numerical simulation performed using a finite element unsaturated seepage software called SEEP/W. The following objectives set forth in order to reach the aim of the study:

1. To study the mechanism of rainfall infiltrations through unsaturated residual soil.
2. To simulate the effect of different hydraulic conductivity, layer thickness, dip angle and infiltration rate on capillary barrier effect on water diversion length due to capillary barrier effect.
3. To compare the water diversion length obtained numerically by Seep/W with analytical calculation using Ross (1990) model.

1.4 Scope of Study

The study is limited to seepage analysis of water infiltration into an inclined residual soil slopes with capillary barrier effects in steady-state condition in order to evaluate the effects of several factors toward the seepage behaviour and ultimately, the change in diversion lengths. The followings are the four parameters considered in the analysis: (1) Hydraulic conductivity, (2) Layer thickness, (3) Infiltration rate, and (4) Dip angle of slope.

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