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SUCTION PROFILE OF UNSATURATED RESIDUAL SOIL HILL SLOPES OF GUWAHATI

U. K. Das, Associate Professor, Department of Civil Engineering, Tezpur University, ukrdas@gmail.com
B. D. Saikia, Professor, Royal School of Engineering and Technology, bibha_saikia@yahoo.com

ABSTRACT: The stability analysis of the residual soil hills around Guwahati require a knowledge of the soil suction profile with respect to depth. In this work, seepage analyses of rainwater infiltration into these unsaturated slope soil for different rainfall intensities are carried out based on the unsaturated coefficient of permeability of the soils. The relation between soil suction and coefficient of water permeability for these soils are determined from the respective Soil Water Characteristic Curves (SWCC). The results of this analysis, which give the pore water pressure distribution in the slope soil with respect to depth under different rainfall intensities, are presented. The critical rainfall intensity for development of positive pore water pressure in the slope soil is also determined.

INTRODUCTION

The hill slopes in Guwahati, during the winter season, are found to be in unsaturated state. The two main factors contributing to this condition are dry climatic condition and deep ground water table. Field studies have indicated that the depth of ground water table from ground surface in the hills in Guwahati are in the range of 30-50 metre. This unsaturated condition of soil leads to the development of matric suction or negative pore water pressure in these hill soils. The positive effects of matric suction on the shear strength of these soils have already been established [1]. The stability of the hill slopes under study, therefore, increases due to the presence of matric suction. It is thought that, during rainy season, as the rain water infiltrates into the slope soil, the soil suction starts decreasing and thus, decreasing the shear strength and stability of the slopes. It is, therefore, essential to determine the effect of rain water infiltration on pore water pressures of the hill slope soil at various depths into the slope from its surface.

Table 1 Index properties and classification of the soils

Item	SOIL - I	SOIL - II
Colour	Reddish	Light Yellowish
Specific Gravity	2.44	2.64
In-situ Bulk Density	1.65 gm/cc	1.79 gm/cc
In-situ Dry Density	1.49 gm/cc	1.63 gm/cc
Liquid Limit	49%	39%
Plastic Limit	27%	Non-plastic
Co-eff. of Uniformity	2.52	5.16
Co-eff. of Curvature	1.36	1.43
Fines Content	72.7%	7.45%
Classification	Silty Clay	Poorly Graded Silty Sand

DESCRIPTION OF THE SLOPE SOIL

Field investigation of the hill slopes around Guwahati has revealed that they are made up two types of residual soils. A top layer of Reddish residual soil (SOIL-I) of thickness varying from few centimeters to about 30m is underlain by a Light Yellowish residual soil (SOIL-II). The index properties of the two soils determined in laboratory are tabulated in Table1. The Soil Water Characteristic Curves (SWCC), which relates matric suction to water content, were established by modifying the conventional Triaxial Testing Equipment to suit unsaturated soil testing. The modification involves changing the base of cell with one having a ceramic plate fixed on it following the procedure given by Fredlund and Rahardjo [2]. The SWCCs of the two residual soils are presented in Fig. 1 and Fig.2. Sample preparation for these tests are described in [1].

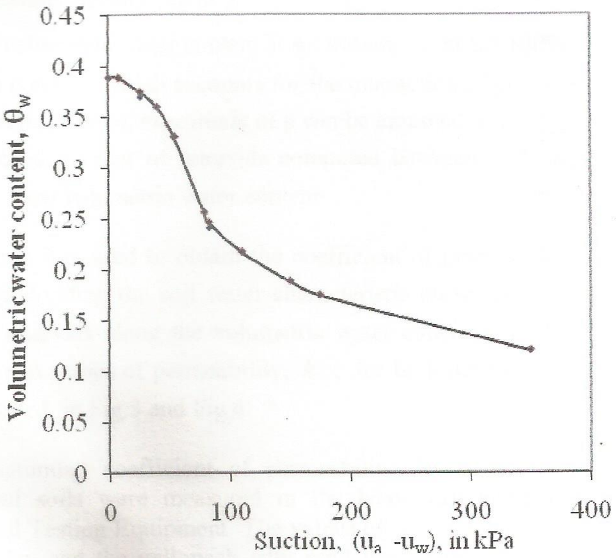

Fig. 1 Soil Water Characteristic Curve showing θ_w Vs Suction plot for SOIL-I

COEFFICIENT OF PERMEABILITY OF UNSATURATED SOIL

Unsaturated soil mass essentially contains both air and water and so, unlike saturated soils, its coefficient of permeability

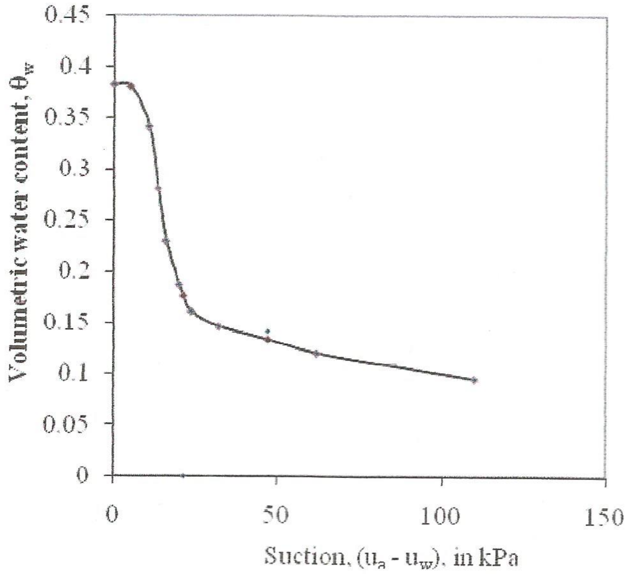

Fig. 2 Soil Water Characteristic Curve showing θ_w Vs Suction plot for SOIL-II

can not be uniquely defined. The presence of both water and air in unsaturated soil leads to two different coefficients of permeability:
Coefficient of permeability with respect to water phase, k_w, and Coefficient of permeability with respect to air phase, k_a. k_w and k_a are the measures of the space available for water and air respectively to flow through the soil. Since the percolation of rain water into soil is mainly related to the coefficient of permeability with respect to water phase, k_w, of the soil, emphasis is laid on the understanding and determination of k_w in this study.

The coefficient of permeability with respect to water phase, k_w, can be predicted from the soil water characteristic curves plotted between degree of saturation and matric suction by the following equations presented by Brooks and Corey [3].

$$k_w = k_s$$

for $(u_a - u_w) \le (u_a - u_w)_b$

and

$$k_w = k_s \times \left\{ \frac{(u_a - u_w)_b}{(u_a - u_w)} \right\}^{(2+3\lambda)}$$

for $(u_a - u_w) > (u_a - u_w)_b$

where,

$(u_a - u_w)$ = Soil Suction.

$(u_a - u_w)_b$ = Air Entry Value of the soil.

λ = Pore size distribution index

The water coefficient of permeability, k_w, can be related to the volumetric water content, θ_w [4].. Volumetric water content, θ_w, is defined as the ratio of the volume of water present in a soil sample to the total volume of the soil. A coefficient of permeability function, $k_w(\theta_w)$, has been proposed using configurations of the pore space of the soil filled with water [5].

Fredlund and Rahardjo [2] presented the following permeability function equation for calculation of water coefficient of permeability $k_w(\theta_w)$ for the suction values of the soil determined from the soil-water characteristic curve.

$$k_w(\theta_w)_i = \frac{k_s}{k_{sc}} A_d \sum_{j=i}^{m} \{(2j + 1 - 2i)(u_a - u_w)_j^{-2}\} \qquad (1)$$

where i = 1, 2, 3, ……, m

A_d = Adjusting constant = $\dfrac{T_s^2 \rho_w g}{2\mu_w} \dfrac{\theta_s^p}{N^2}$ (m. sec^{-1}.kPa^2).

$k_w(\theta_w)_i$ = calculated water coefficient of permeability (m/sec) for a specified volumetric water content, (θ_w), corresponding to the i^{th}. Interval.

k_s = measured saturated coefficient of permeability (m/sec).

k_{sc} = calculated saturated coefficient of permeability (m/sec).

$(u_a - u_w)_j$ = matric suction (kPa) corresponding to the midpoint of j^{th}. Interval.

T_s = surface tension of water (KN/m).

μ_w = absolute viscosity of water (N.sec/m^2).

ρ_w = water density (kg/m^3).

θ_S = volumetric water content at saturation, i.e. at Sr=100%.

p = a constant which accounts for the interaction of pores of various sizes; magnitude of p can be assumed as 2.0 [6].

N = total number of intervals computed between θ_S, and zero volumetric water content.

Equation 1 is used to obtain the coefficient of permeability, k_w, by dividing the soil water characteristic curve into "m" equal intervals along the volumetric water content axis The computed values of permeability, k_w, for both the two soils are plotted in Fig.3 and Fig.4.

The saturated coefficient of permeability, k_s, of the two residual soils were measured in the laboratory using the Triaxial Testing Equipment. The values of k_s for the reddish silty clay and the yellowish silty sand were observed to be 1.864 x 10^{-7} m/sec and 1.208x10^{-6} m/sec respectively.

SEEPAGE ANALYSIS

The flow of water in a saturated soil is commonly described by using Darcy's law. Darcy's law also applies for the flow of water through an unsaturated soil [5]. Water can be visualised as flowing only through the pore space filled with

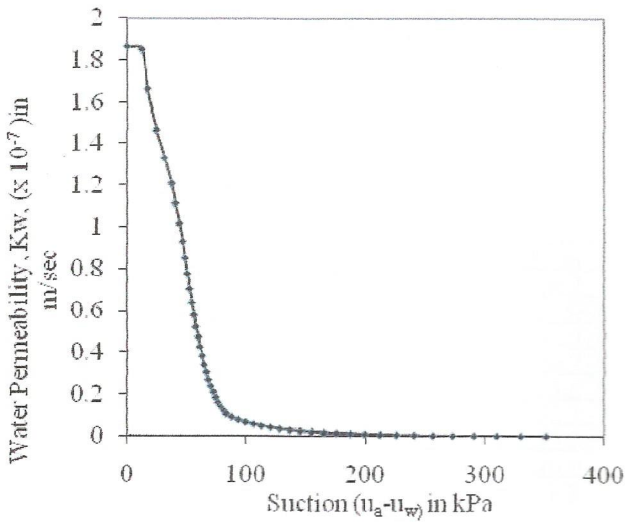

Fig. 3 Water co-efficient of permeability(k_w) Vs Suction plot for SOIL-I

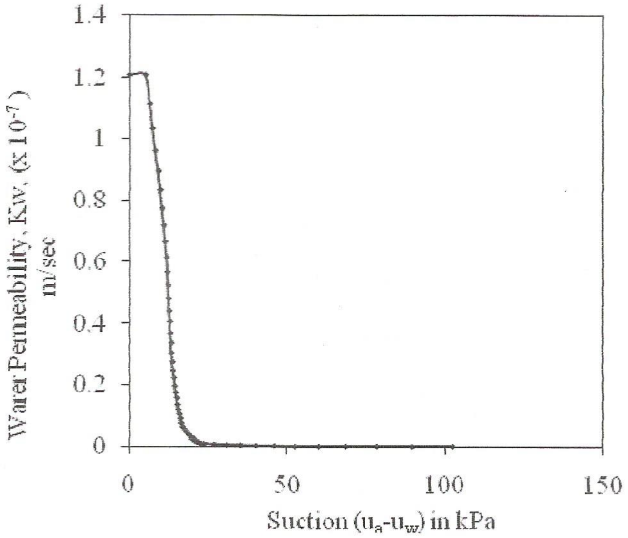

Fig. 4 Water co-efficient of permeability(k_w) Vs Suction plot for SOIL-II

water. Therefore, the air filled pores in an unsaturated soil can be considered as behaving similarly to the solid phase and the soil can be treated as saturated soil having a reduced water content [7].

For steady-state flow analysis in unsaturated soil, the coefficient of permeability usually varies from point to point within the soil mass. This is true even for homogeneous distribution of soil solids. The main reason for this spatial variation of permeability is the heterogeneous volume distribution of the pore water, which in turn, is due to the variation of the matric suction with space within the soil mass.

In this study, it is assumed that the rainwater infiltrates the ground surface and flows steadily downwards into the slope towards the water table. The flow in this study, therefore, is taken as a Steady-state One-dimensional flow in the downward direction. Fredlund and Rahardjo [2] presented the following formulation of one-dimensional steady-state flow into unsaturated soil:

$$k_{wy}\frac{d^2h_w}{dy^2}+\frac{dk_{wy}}{dy}\frac{dh_w}{dy}=0 \tag{2}$$

where, dk_{wy}/dy = change in water coefficient of permeability in y-direction due to change in matric suction.

The differential equation, Eq.2, for one-dimensional steady-state flow through an unsaturated soil requires a complex solution by the method of integration. As an alternative, Eq.2 can be solved numerically. In this study, finite difference method proposed by Fredlund and Rahardjo [2] is used for solving the steady-state flow equation for unsaturated soils.

The following assumptions are made to set the boundary conditions of the problem under study:

1) steady state infiltration into the soil slope in the downward direction due to rainfall has been established and the infiltration rate of rainwater is equal to the intensity of rainfall.

2) the ground water table remains at a constant elevation and the pore water pressure at ground water table is equal to zero.

Different Conditions Under Which Seepage Analyses Are Carried Out

The analyses are carried out for the following conditions based on actual field data:

i) The seepage analyses are carried out for different intensities of rainfall. A study of the rainfall data of Guwahati from the year 2003 to 2010 reveals the following key information:

a) Range of average daily rainfall over a period of one year = 3.5 to 5.2 mm/day

b) Range of average daily rainfall over the wet months = 5.7 to 7.8 mm/day

c) Range of average daily rainfall in the wettest month = 8.2 to 18.1 mm/day.

Based on the above information, the seepage analyses are carried out for the following average daily rainfall intensities: 6mm, 10mm, 14mm, 17mm ,18mm per day.

ii) The depth of water table is taken as 45m from slope top surface based on field study.

iii) The hill slopes in Guwahati has varying thickness of layer of SOIL-I over SOIL-II. The analysis is carried out for a 30m thicknesses of layer of SOIL-I over SOIL-II.

This analysis was carried out by developing a computer program in c++.

PRESENTATION OF THE RESULTS OF SEEPAGE ANALYSIS

The results of the seepage analyses carried out under the above different conditions and the computed pore water pressure at vertical interval of 1m are presented in Table 2.

Table 2 Pore water pressure distribution in kPa across slope section at 1.0m vertical interval, 0 Ht. indicates water table

Ht. from Water		Rainfall in mm per day				
		6mm	10mm	14mm	17mm	18mm
45m	SOIL - I	-53.6	-38.5	-19.8	0.8	18.2
44m		-53.6	-38.5	-19.8	0.2	17.0
43m		-53.6	-38.4	-19.8	-0.3	15.9
42m		-53.6	-38.4	-19.8	-0.9	14.7
41m		-53.6	-38.4	-19.8	-1.4	13.5
40m		-53.6	-38.4	-19.8	-2.0	12.3
39m		-53.6	-38.3	-19.8	-2.5	11.2
38m		-53.6	-38.3	-19.8	-3.1	10.0
37m		-53.5	-38.2	-19.8	-3.6	8.8
36m		-53.5	-38.2	-19.8	-4.2	7.6
35m		-53.5	-38.1	-19.8	-4.8	6.4
34m		-53.5	-38.0	-19.8	-5.3	5.3
33m		-53.5	-37.9	-19.8	-5.9	4.1
32m		-53.5	-37.8	-19.8	-6.4	2.9
31m		-53.5	-37.6	-19.8	-7.0	1.7
30m		-53.5	-37.4	-19.9	-7.5	0.6
29m		-53.5	-37.2	-19.9	-8.1	-0.6
28m		-53.5	-37.0	-19.9	-8.6	-1.8
27m		-53.5	-36.7	-19.9	-9.2	-3.0
26m		-53.5	-36.3	-19.9	-9.8	-4.1
25m		-53.4	-35.9	-20.0	-10.3	-5.3
24m		-53.3	-35.4	-20.0	-10.9	-6.5
23m		-53.1	-34.8	-20.1	-11.4	-7.7
22m		-52.7	-34.1	-20.1	-12.0	-8.9
21m		-52.0	-33.2	-20.2	-12.6	-10.0
20m		-50.8	-32.2	-20.3	-13.3	-11.2
19m		-48.8	-31.1	-20.4	-14.2	-12.4
18m		-45.9	-29.7	-20.5	-15.3	-13.8
17m		-42.5	-28.1	-20.6	-16.6	-15.5
16m		-38.8	-26.3	-20.8	-18.2	-17.6
15m	SOIL - II	-38.8	-26.3	-20.8	-18.2	-17.6
14m		-38.8	-26.3	-20.8	-18.2	-17.6
13m		-38.8	-26.3	-20.8	-18.2	-17.6
12m		-38.8	-26.3	-20.8	-18.2	-17.6
11m		-38.8	-26.3	-20.8	-18.2	-17.6
10m		-38.8	-26.3	-20.8	-18.2	-17.6
9m		-38.8	-26.3	-20.8	-18.2	-17.6
8m		-38.8	-26.3	-20.8	-18.2	-17.6
7m		-38.8	-26.3	-20.8	-18.2	-17.6
6m		-38.8	-26.3	-20.8	-18.2	-17.6
5m		-38.8	-26.3	-20.8	-18.2	-17.6
4m		-38.8	-26.3	-20.8	-18.2	-17.6
3m		-38.8	-26.3	-20.8	-18.2	-17.6
2m		-38.8	-26.3	-20.8	-18.2	-17.6
1m		-9.5	-9.1	-8.8	-8.5	-8.4
0		0.0	0.0	0.0	0.0	0.0

CONCLUSIONS

Rainfall decreases the slope soil suction to different extents depending on its intensity. When the intensity of the rainfall is low, the soil suction is maximum at slope surface and gradually decreases downward into the slope to zero value at water table. As the rainfall increases, the maximum value of the suction at surface decreases. At 14mm/day rainfall intensity the suction is nearly uniform throughout the entire depth. This is due to the increase of coefficient permeability with respect to water phase of the soil as result of rainwater seepage. As the rainfall intensity increases to 17mm/day intensity, positive pore water pressure starts developing at the top part of the slope indicating saturation condition and development of perched water table at 2m depth from top. Moreover the pore suction of the slope soil substantially drops. At 18mm per day rainfall intensity this perched water table pushes down to a depth of 15m into the slope. This condition the slope will loss the positive contribution of suction towards its stability and the perched water table will induce instability condition to the slope.17 mm per day rainfall may, therefore, be taken as the critical rainfall intensity for these slopes.

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