EVALUATION OF A PREDICTION MODEL FOR SHEAR STRENGTH OF UNSATURATED SOILS

U. K. Das, Associate Professor, Department of Civil Engg., Tezpur University, Tezpur, Assam, email: ukrdas@gmail.com
B. D. Saikia, Professor,Civil Engg. Dept.,Royal school of Engg.&Technology, Guwahati, email: bibha_saikia@yahoo.com

ABSTRACT: Experience of shear strength of unsaturated residual soils in India is very limited . A technique for prediction of unsaturated soil parameters applicable to residual soils of the hills around Guwahati, therefore, has practical application. Houston et al. have recently presented a hyperbolic model for estimation of the unsaturated soil parameter, φ^b, from Soil Water Characteristic Curves (SWCC) and saturated soil parameters. To test the validity of the Houston model for the residual soils of Guwahati hills, a series of unsaturated soil triaxial tests were performed on these soils. Based on these laboratory test data the feasibility of estimating φ^b from SWCC and c' & φ' values of the residual soils of Guwahati hills is demonstrated.

INTRODUCTION

The hill slopes in North-east India covered by residual soil layer frequently experience rainfall induced slope failures. Some of these residual soil slopes have deep ground water table and, as a result, are mostly unsaturated and posses high matric suction. The matric suction positively contributes to the shear strength of the soil and increases the stability of the slopes. During the rainy season, the matric suction of the soil is decreased by the percolating rain water which, in turn, effects the shear strength and stability of the slopes. It is, therefore, important to consider the effect of soil suction on shear strength during the stability analysis of these residual soil slopes.

Fredlund and Rahardjo [1] postulated the following shear strength equation for unsaturated soils.

$$\tau_f = c' + (\sigma_n - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b \qquad (1)$$

where, c' and φ' = effective shear strength parameters ,
$(u_a - u_w)$ = matric suction, $(\sigma_n - u_a)$ =net normal stress,
φ^b = angle for increase of shear strength with matric suction.

Laboratory testing of unsaturated soil is rather time consuming and requires specialized testing equipment. Consequently, evaluation of φ^b for determination of shear strength in Eq.1. has been challenging. A literature review shows that φ^b is not constant but varies as a function of soil suction. Fredlund et al. [2] summarized the importance of Soil Water Characteristic Curve (SWCC), which relates matric suction to water content or degree of saturation, in estimating the shear strength of unsaturated soil. The SWCC, together with results from saturated soil testing, can be used to predict the shear strength of unsaturated soils.

Houston et al. [3] has presented a hyperbolic model for estimating φ^b as a function of matric suction based on the SWCC. The model was validated based upon the results of a few unsaturated shear strength tests carried out on sand, silt and low plasticity clay soils.

The primary objective of this research study is to examine through detailed laboratory testing the applicability of this prediction model for φ^b on the unsaturated residual soils of the hills around Guwahati.

MODEL FOR PREDICTION OF φ^b PRESENTED BY HOUSTON ET AL.

Houston et al. [3] carried out unsaturated tests on different types of soils by modifying the triaxial apparatus as proposed by Fredlund et al. [1] and by applying Axis Translation Technique [4]. The results showed that shear strength increased with increase of suction and the increase of shear strength was nonlinear when the range of suction was large.

The authors back calculated φ^b from total cohesion intercept value, c. This was done by rearranging Eq.1. and ascribing the difference $(c - c')$ to the increase in shear strength due to suction as shown in Eq.2., yielding a Secant value of φ^b

$$\varphi^b = \arctan\left[\frac{(c - c')}{(u_a - u_w)}\right]. \qquad (2)$$

At matric suction values below Air Entry Value (AEV) of the soil, the φ^b was found to be close to φ'. For suction beyond AEV, the equation for the prediction of φ^b was derived as a hyperbolic equation as given by Eq.3.

The residual Saturation (S_{res}) and Pore Size Distribution Indux (λ) for the silty clay are found to be 31% and 1.08 respectively. For the silty sand, the values of S_{res} and λ are determined as 33% and 2.37 respectively.

The saturated co-efficient of permeability, k_s, for the reddish silty clay and the yellowish silty sand were observed to be 1.864×10^{-7} m/sec and 1.208×10^{-6} m/sec respectively.

EXPERIMENTAL RESULTS

The shear strength characteristics of the two types of residual soils under study were evaluated by using Constant Water Content Triaxial Tests (CW Tests) in the Modified Triaxial Equipment. The tests were conducted at constant rate of axial strain of 0.0386mm/min. Constant Water Content Tests for the two residual soils were conducted under constant net normal stresses, $(\sigma - u_a)$, of 50kPa, 100kPa and 150kPa. For each net normal stress, samples with increasing value of initial saturation were tested. From the test results it is observed that shear strength of each of the two residual soils increase as the matric suction is increased [6].

From the results of the triaxial tests on saturated samples, the effective angle of internal friction, φ', and effective cohesion, c' are determined. The φ' and c' values for the reddish silty clay were found to be 31^0 and 10kPa respectively. The φ' and c' values for the yellowish silty sand were found to be 38.5^0 and 0.00 respectively. For unsaturated samples the total cohesion (c) is given by the intercept of the Extended Mohr-Coulomb failure envelope [1] in the Shear Strength (τ) vs. Suction $(u_a - u_w)$ plane. The total cohesion (c) of unsaturated sample is the result of the combined effect of effective cohesion (c') and apparent cohesion due to the soil suction. The total cohesion (c) for a sample with suction $(u_a - u_w)$ was obtained by drawing a tangent to the single Mohr's circle with a slope equal to the saturated φ'.
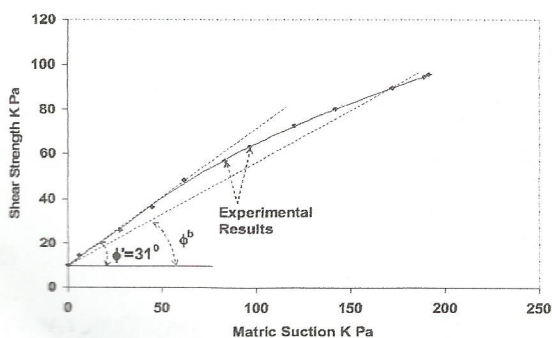

Fig.3 : Failure envelope on τ versus (u_a-u_w) plane for the Silty Clay residual soil (SOIL-I).

The τ vs. $(u_a - u_w)$ plots thus obtained from the results of the unsaturated triaxial tests of the silty clay and the silty sand are shown in Fig.3 and Fig.4 respectively.
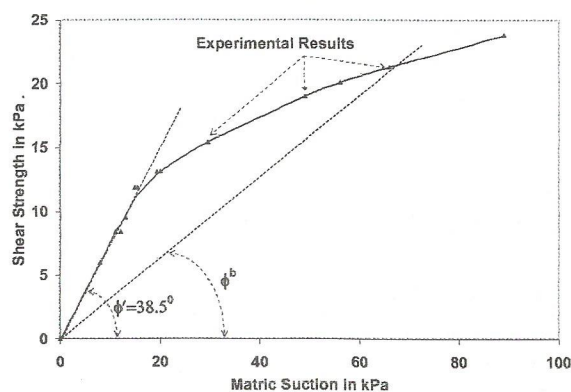

Fig.4 : Failure envelope on τ versus (u_a-u_w) plane for the Silty Sand residual soil (SOIL-II).

TESTING OF MODEL PRESENTED BY HOUSTON ET AL. FOR RESIDUAL SOILS OF HILLS AROUND GUWAHATI

From the experimental values of total cohesion, c, of SOIL-I and SOIL-II in Fig.3. and Fig.4., the Secant φ^b values for the corresponding suction values, $(u_a - u_w)$, are computed using Eq.2. and plotted in Fig.5 anf Fig.6 respectively.
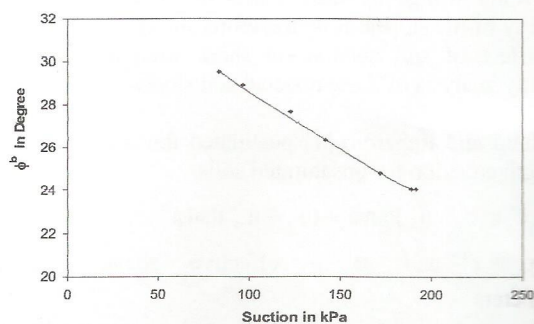

Fig.5 : φ^b vs. Suction for the Silty Clay residual soil
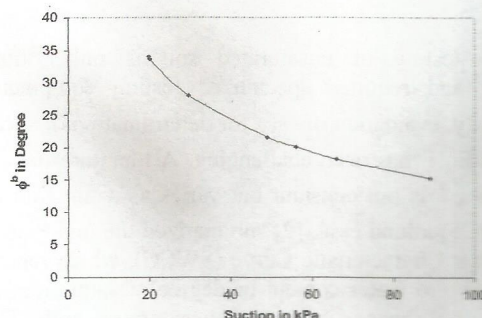

Fig.6 : φ^b vs. Suction for the Silty Sand residual soil

$$\varphi^b = \varphi' - \left[\frac{\psi^*}{a + b\psi^*} \right] \qquad (3)$$

where, $\psi^* = [(u_a - u_w) - AEV]$

a, b = fitting parameters.

The authors described the following Transformed Linear plot to determine the fitting parameters a & b by rearranging Eq.3.

$$a + b\psi^* = \frac{\psi^*}{\varphi' - \varphi^b} \qquad (4)$$

Transformed Eq.4. plots as a straight line, where, a = intercept and b = slope of the resulting line.

The average value of the Correlation Coefficient (R^2) of the best fit straight lines reported by Houston et al. [3] from the experimental data was 0.92.

SOILS USDED IN THIS STUDY

The soils used in this study were collected from the hills around Guwahati. Field investigation of the hill slopes around Guwahati has revealed that they are made of two types of residual soils. A top layer of Reddish residual soil (SOIL - I) is underlain by Light Yellowish residual soil (SOIL – II). The index properties of the two types of residual soils determined in the laboratory of Civil Engineering Department, Assam Engineering College, Guwahati, are as listed in Table 1.

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

SAMPLE PREPERATION, EQUIPMENTS USED AND TESTING PROCEDURE

For preparation of samples for triaxial tests, the soil collected from field was air dried, manually pulverized and screened through IS 2.36mm sieve. Water content of this soil was adjusted to about 12%. The soil was then carefully tamped in five layers in a mould to a density equal to the in-situ density of the soil.

The shear strength of the saturated samples were measured by using the conventional triaxial testing equipment [5]. The conventional triaxial testing equipment for saturated

soils was modified as described by Fredlund and Rahardjo [1] in the soil mechanics laboratory of Assam Engineering College to suit testing of unsaturated samples. In this modification to the triaxial testing equipment, the coarse porous stone used at the base of the sample was replaced by a ceramic plate of rated air entry value and the pedestal of the triaxial cell was specially fabricated with a recess at the top to accommodate the ceramic plate.

For the unsaturated tests, the prepared samples were tested under constant water content condition at constant rate of axial strain after isotropic consolidation. The suction in the soil sample was measured by using the Axis Translation Technique.

Fig. 1 and Fig.2 show the SWCC of the two types of residual soils under study, i.e. reddish silty clay and yellowish silty sand respectively. The SWCC in Fig.1 and Fig.2 were established in the laboratory by using the Modified Triaxial Testing Equipment.
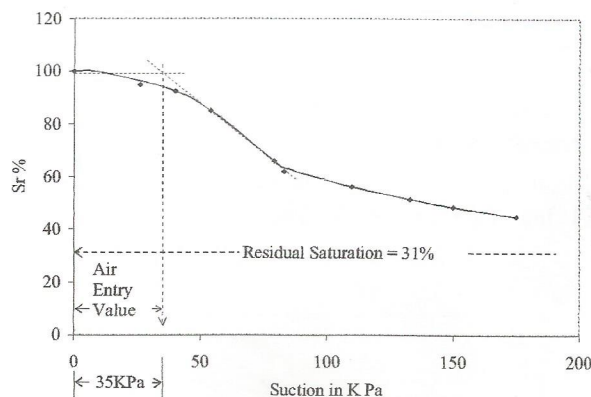

Fig.1 : Soil-water Characteristic Curve for the Reddish Silty Clay
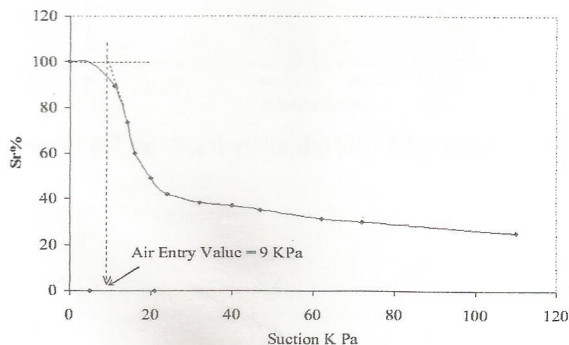

Fig.2 : Soil-water Characteristic Curve for the Yellowish Silty Sand

The value of suction after which the soil starts to desaturate is referred to as the Air Entry Value (AEV) of the soil. The AEV of the reddish silty clay soil and the yellowish silty sand under study are found to be 35kPa and 9kPa respectively.

The residual Saturation (S_{res}) and Pore Size Distribution Indux (λ) for the silty clay are found to be 31% and 1.08 respectively. For the silty sand, the values of S_{res} and λ are determined as 33% and 2.37 respectively.

The saturated co-efficient of permeability, k_s, for the reddish silty clay and the yellowish silty sand were observed to be 1.864×10^{-7} m/sec and 1.208×10^{-6} m/sec respectively.

EXPERIMENTAL RESULTS

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From the results of the triaxial tests on saturated samples, the effective angle of internal friction, φ', and effective cohesion, c' are determined. The φ' and c' values for the reddish silty clay were found to be 31^0 and 10kPa respectively. The φ' and c' values for the yellowish silty sand were found to be 38.5^0 and 0.00 respectively. For unsaturated samples the total cohesion (c) is given by the intercept of the Extended Mohr-Coulomb failure envelope [1] in the Shear Strength (τ) vs. Suction $(u_a - u_w)$ plane. The total cohesion (c) of unsaturated sample is the result of the combined effect of effective cohesion (c') and apparent cohesion due to the soil suction. The total cohesion (c) for a sample with suction $(u_a - u_w)$ was obtained by drawing a tangent to the single Mohr's circle with a slope equal to the saturated φ'.
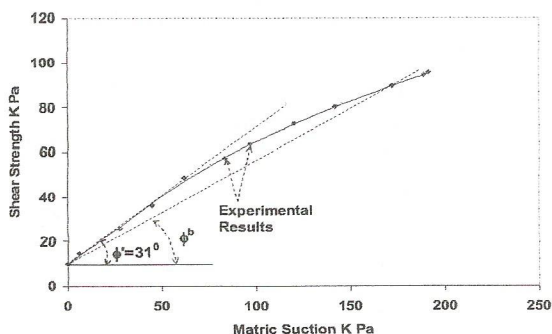
Fig.3 : Failure envelope on τ versus $(u_a\text{-}u_w)$ plane for the Silty Clay residual soil (SOIL-I).

The τ vs. $(u_a - u_w)$ plots thus obtained from the results of the unsaturated triaxial tests of the silty clay and the silty sand are shown in Fig.3 and Fig.4 respectively.
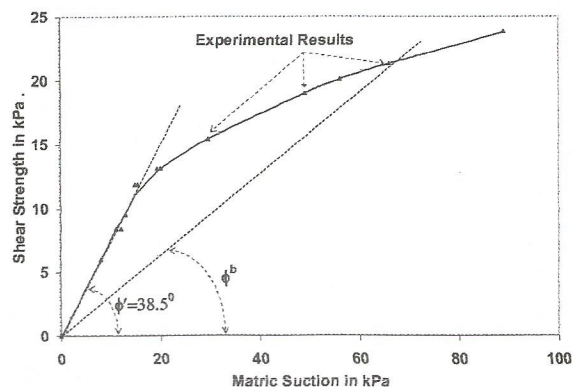
Fig.4 : Failure envelope on τ versus $(u_a\text{-}u_w)$ plane for the Silty Sand residual soil (SOIL-II).

TESTING OF MODEL PRESENTED BY HOUSTON ET AL. FOR RESIDUAL SOILS OF HILLS AROUND GUWAHATI

From the experimental values of total cohesion, c, of SOIL-I and SOIL-II in Fig.3. and Fig.4., the Secant φ^b values for the corresponding suction values, $(u_a - u_w)$, are computed using Eq.2. and plotted in Fig.5 anf Fig.6 respectively.
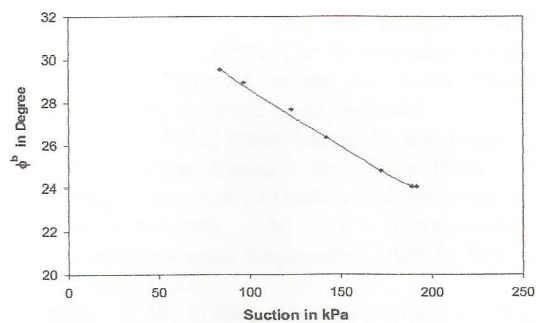
Fig.5 : φ^b vs. Suction for the Silty Clay residual soil
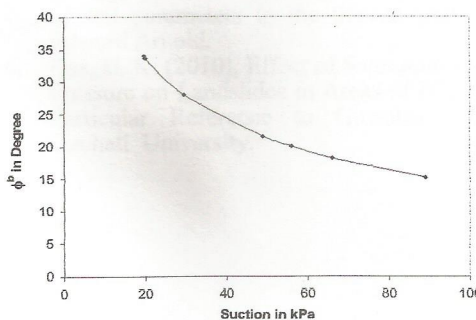
Fig.6 : φ^b vs. Suction for the Silty Sand residual soil

The transformed hyperbolic plots, i.e. $\psi^*/(\varphi'-\varphi^b)$ vs. ψ^* plots, for the SOIL-I and SOIL-II are plotted in Fig.7 and Fig.8 respectively. The fitting parameters a and b, as described in Eq.4, for each soil under study are determined from regression lines fitted to the experimental data in Fig.7 and Fig.8 are shown in table.2 along with the Correlation Coefficient (R^2) for SOIL-I and SOIL-II.
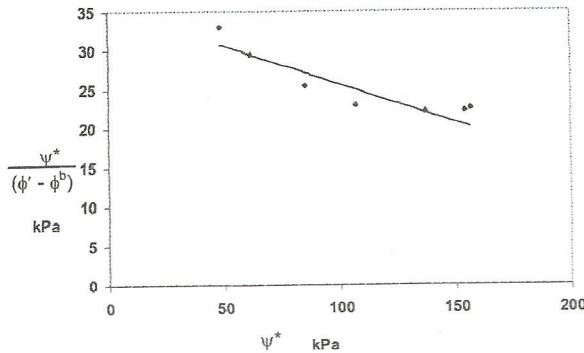

Fig.7 : $\psi^*/(\varphi'-\varphi^b)$ vs. ψ^* plots, for the Silty   Clay residual   soil (SOIL-I)
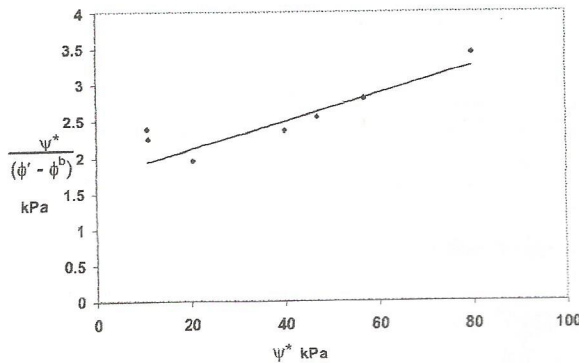

Fig.8 : $\psi^*/(\varphi'-\varphi^b)$ vs. ψ^* plots, for the Silty Sand residual soil (SOIL-II)

Table 2 Fitting parameters and coefficient of correlation for the Silty Clay (SOIL-I) and Silty Sand (SOIL-II) soils

Soil	Fitting Parameters		R^2
	a	b	
SOIL-I	135.56	-0.099	0.85
SOIL-II	1.73	0.0191	0.85

CONCLUSION

Implementation of unsaturated soils theory at the highest level involves direct unsaturated soil testing with soil suction determination, which is relatively complex and time consuming. Predictive techniques for implementation of unsaturated soils theory into practice has been, therefore, suggested wherein the SWCC is used along with saturated soil properties to establish unsaturated soil properties at any level of suction. One such predictive technique is recently presented by Houston et al. [3] for estimating φ^b parameter as a function of soil suction.

The prediction model of Houston et al. is tested for its applicability on the Silty Clay and Silty Sand Residual soils that mostly cover the hills around Guwahati. The experimental data obtained from unsaturated testing of the two types of residual soils, when fitted to the proposed model, give Regression Coefficient (R^2) equal to 0.85 for both the two soils. The correlation proposed by Houston et al. can, therefore, be concluded to have a fairly good fit with the experimental results for the two types of residual soils under study. These unsaturated soil shear strength correlations can be used for limit equilibrium analysis of the unsaturated residual soil slopes on the hills around Guwahati

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