A SIMPLE TECHNIQUE FOR DETERMINING THE SHEAR STRENGTH OF FINE-GRAINED UNSATURATED SOILS USING THE CONVENTIONAL DIRECT SHEAR APPARATUS

S. K. Vanapalli
Lakehead University, Thunder Bay, Ontario, Canada, P7B 5E1
J. J. Lane
EBA Engineering Consultants Ltd, Edmonton, Alberta, Canada, T5L 2M7

ABSTRACT
In recent years, several investigators have developed semi-empirical procedures for predicting the shear strength of unsaturated soils using computing techniques. The input parameters for predicting the unsaturated shear strength include effective shear strength parameters and the soil-water characteristic curve data. The soil-water characteristic curve data is represented as a mathematical equation in the shear strength function. The prediction procedures developed and proposed in the literature are however based using limited experimental data. In this paper, a simple experimental technique is proposed for determining the unsaturated shear strength of fine-grained soils using the direct shear testing apparatus, which is conventionally used for determining the shear strength of saturated soils. The simple experimental procedure proposed in this paper can be used in conjunction with the semi-empirical procedures to predict the shear strength of fine-grained unsaturated soils with greater reliability.

RESUMÉ
Pendant les dernières années, plusieurs chercheurs ont développé des methods numériques semi empiriques et des procédures pour prédire la résistance au cisaillement des sols non saturés. Les données requises pour ces predictions incluent les paramètres effectifs de résistance au cisaillement et les courbes caractéristiques sol/eau. Ces courbes sont représentées par une equation mathématique dans la fonction de résistance au cisailllement. Les methods prédictives proposées dans la littérature sont basées sur un nombre limité de données expérimentales. Dans cet article, on propose une technique expérimentale simple pour déterminer la résistance au cisaillement de sols fins et non saturés à l'aide d'un appareil qui est courramment utilisé pour déterminer la résistance au cisaillement de sols saturés. Cette nouvelle procédure peut être utilisée avec des méthodes semi empiriques pour prédire de façon fiable la résistance au cisaillement de sols fins.

1. INTRODUCTION

The shear strength of an unsaturated soil can be determined using modified direct shear or triaxial shear equipment (Escario 1980, Ho et al. 1982, Gan et al. 1988, Escario and Juca, 1989, Wheeler and Sivakumar 1992, Vanapalli et al. 1996). However, experimental studies related to determination of the shear strength of unsaturated soils are time consuming and require extensive laboratory facilities, which are costly. Due to this reason, application of shear strength studies in engineering practice has been limited. In recent years, several semi-empirical shear strength functions were proposed to predict the shear strength of unsaturated soils. The proposed procedures use the saturated shear strength parameters (i.e., c' and ϕ') along with the soil-water characteristic curve data (Vanapalli et al. 1996, Fredlund et al. 1996, Oberg & Salfors 1997, Khallili and Khabbaz 1998, and Bao et al. 1998). The soil-water characteristic curve is defined as the relationship between soil suction, ψ, and the degree of saturation, S, or volumetric water content, θ, or the gravimetric water content, w. The soil-water characteristic curves are conventionally measured using the Tempe cell or the pressure plate apparatus (Fredlund and Rahardjo, 1993). The prediction procedures use the soil-water characteristic curve as a tool as there is a strong relationship between water content and the shear strength of a soil. The proposed shear strength functions include the information of variation of water content with respect to suction (i.e., soil-water characteristic curve data) relationship as a mathematical equation (Fredlund and Xing, 1994). There are also knowledge based software packages such as SoilVision, which can be used to estimate the soil-water characteristic curve from the grain size analysis data (Fredlund 1998). Computing techniques are used as tools in prediction of the variation of shear strength with respect to soil suction. These computing techniques are encouraging to practicing engineers to put the theories related to shear strength of unsaturated soils into engineering practice.

The presently available semi-empirical approaches in the literature for predicting the shear strength of unsaturated soils are proposed based on limited number of experimental studies mainly in the low suction range (i.e., 0 to 500 kPa). As conventional experimental procedures for determining the shear strength of unsaturated soils are time consuming and costly, it would be of value to develop a simple experimental technique both to determine and also use as a tool quickly to check the reliability of prediction procedures. A simple experimental technique is proposed in this research paper to determine the shear strength of unsaturated, fine-grained soils using direct shear testing apparatus that is conventionally used for determining the shear strength of saturated soils.

The experimental program consisted of determining the shear strength of statically compacted clay till specimens. The clay till used for the study was obtained from Indian Head, Saskatchewan. The measured experimental test results using conventional direct shear apparatus are compared with published experimental results measured using the modified direct shear tests on the same soil (Vanapalli et. al. 1996).

2. SHEAR STRENGTH OF UNSATURATED SOILS

The concept to use stress state variables for interpreting the engineering behavior of unsaturated soils was introduced by Fredlund and Morgenstern (1977). The two-stress state variables used are: net normal stress, $(\sigma - u_a)$ and the matric suction, $(u_a - u_w)$. Extending the stress state variable approach, Fredlund et al. (1978) proposed shear strength equation for unsaturated soils as follows:

$$\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad [1]$$

where:

- τ_f = the shear strength of an unsaturated soil
- c' = the effective cohesion of the soil
- ϕ' = the effective angle of shearing resistance for a saturated soil
- σ = the total stress
- u_a = the pore air pressure
- u_w = the pore water pressure
- ϕ' = the angle of internal friction
- ϕ^b = the angle of internal friction with respect to matric suction.
- $(u_a - u_w)$ = matric suction
- $(\sigma - u_a)$ = net normal stress

Vanapalli et al. (1996) proposed a general, nonlinear function for predicting the shear strength of an unsaturated soil extending the stress state variable approach using the entire soil-water characteristic curve (i.e., 0 to 1,000,000 kPa) and the saturated shear strength parameters (i.e., c' and ϕ') as shown below:

$$\tau = [c' + (\sigma_n - u_a)\tan\phi'] + [(u_a - u_w)\{(\Theta^\kappa)(\tan\phi')\}] \qquad [2]$$

where:

- κ = fitting parameter used for obtaining a best-fit between the measured and predicted values
- Θ = normalized water content, θ_w/θ_s (θ_w = volumetric water content and θ_s is the saturated volumetric water content).
- τ_{us} = the shear strength contribution due to suction, $[(u_a - u_w)\{(\Theta^\kappa)(\tan\phi')\}]$

To use Equation 2, the soil-water characteristic curve data is required. The soil-water characteristic curve data can be either conventionally measured in the laboratory or estimated from knowledge based software programs such as the SoilVision from grain size distribution information (Fredlund 1998). The soil-water characteristic curve data can be best-fit into a mathematical equation in terms of *a*, *n* and *m* parameters proposed by Fredlund and Xing (1994). The mathematical equation for fitting the soil-water characteristic curve is shown below:

$$\theta_w(\psi) = \theta_s\left[1 - \frac{\ln\left(1 + \frac{\psi}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\ln\left\{\exp(1) + \left(\frac{\psi}{a}\right)^n\right\}}\right]^m \qquad [3]$$

where:

- ψ = soil suction
- θ_w = volumetric water content
- θ_s = saturated volumetric water content
- a = suction related to the air-entry value of the soil
- n = soil parameter related to the slope at the inflection point
- m = soil parameter related to the residual water content
- h_r = suction related to the volumetric residual water content, θ_r

A fitting parameter, κ is necessary in Equation 2 to predict shear strength values. Vanapalli and Fredlund (2000) proposed a relationship between the fitting parameter, κ, and plasticity index, I_p (Figure 1). From this relationship, the fitting parameter κ can be estimated and used in Equation 2 to predict the shear strength of an unsaturated soil. The above relationship is developed using the experimental results undertaken on several soils using statically compacted specimens. The validity of this relationship for other soils such as the slurry consolidated, dynamically compacted, or natural soils are not known.

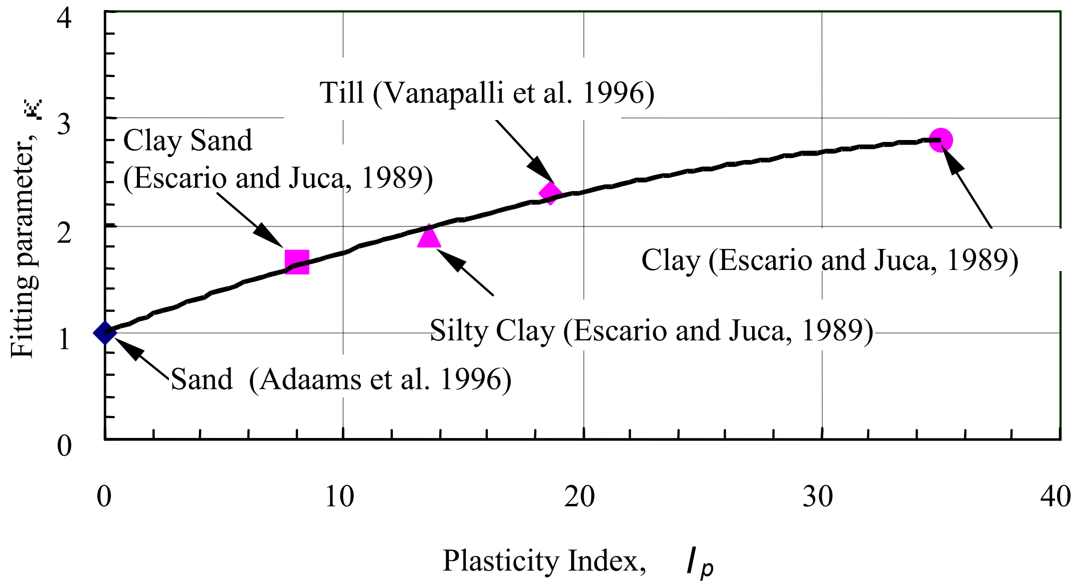

Figure 1. The relationship between the fitting parameter, κ, and the plasticity index, I_p (from Vanapalli and Fredlund, 2000).

3. EXPERIMENTAL PROGRAM

The primary objective of this paper is to propose a simple experimental technique to check the reliability of the procedures available for predicting the shear strength of fine-grained unsaturated soils. This objective is addressed through the use of conventional direct shear equipment (i.e., equipment used for measuring the shear strength of saturated soil) for determining the shear strength of a fine-grained, unsaturated soil.

A simple experimental program was undertaken to study this objective. The experimental program consisted of determining the shear strength of statically compacted clay till specimens under a constant net normal stress, $(\sigma - u_a)$, of 25 kPa. The soil specimens were compacted at optimum water content condition (i.e., 16.3%) with a dry density of 1.80 Mg/m^3. The measured experimental test results using conventional direct shear apparatus are compared with published experimental results measured using the modified direct shear tests on the same soil (Vanapalli et. al. 1996). As a secondary objective, the measured shear strength contribution due to suction using direct shear test results was compared with predicted shear strength values using Equation 2. The fitting parameter, κ value was determined from these results.

3.1 The Soil

A sandy-clay till obtained from Indian Head, Saskatchewan, was used in this testing program. The liquid limit and plastic limit are 35.5% and 16.8% respectively. Sand, silt and clay fractions are 28%, 42%, and 30% respectively. The AASHTO standard compacted maximum density is 1.80 Mg/m^3 at optimum water content of 16.3%.

3.2 Testing Program

Figure 2 shows the statically compacted specimens prepared in 100 mm diameter constant volume moulds to a thickness of 27 mm to achieve the desired dry density and initial water content conditions. The specimens were wrapped in saturated filter papers, placed atop porous stones submerged in a bath of distilled water to saturate the specimens (shown in Figure 3). Trial studies have shown that the specimens attain saturated conditions within a period of 24 hours. The saturated specimens were removed from the bath and subjected to different increments of air-drying to produce variations in the degree of saturation from specimen to specimen and soil suction (i.e. the soil suction in the specimens increase with an increase of drying time). The air dried soil specimens were wrapped in plastic and placed in an airtight plastic bag and left in a humidity and temperature controlled environment for a minimum of 24 hours to attain equilibrium conditions with respect to water content and suction throughout the specimen.

A 51 mm x 51 mm square soil specimen was extracted forcing a square cutter into the prepared round soil specimen (shown in Figure 4). The soil specimens were subjected to consolidation in a conventional direct shear apparatus under an applied net normal stress, $(\sigma - u_a)$ of 25 kPa for a period of 24 hours. The specimens were then sheared at a strain rate of 1.25 mm/min. The direct shear tests were conducted in accordance with ASTM standard

D3080-98 (ASTM, 1999). It can be assumed that the specimens were sheared under undrained conditions due to the relatively rapid strain rate used for shearing and the low coefficient of permeability of the soil specimens. The test results were analyzed based on the assumption that there was no significant change in suction of the soil specimen during the shearing stage.

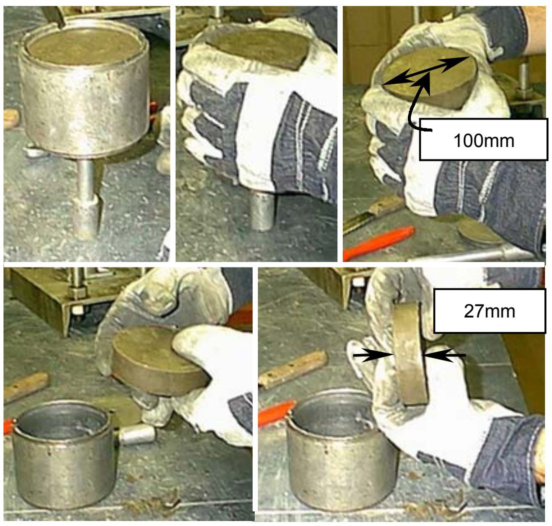

Figure 2. Compacted soil specimen extraction from constant volume mould.

Figure 3. Saturating specimens wrapped in filter paper.

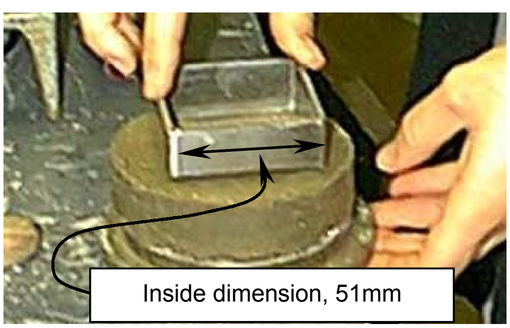

Figure 4. Soil specimen and cutter.

This is a reasonable assumption for compacted fine-grained soils due to the reason that shearing of the specimen was completed over a short period (i.e., 5 to 10 minutes). Vanapalli et al. (2000) used similar assumptions for analyses of shear strength test results on a silty soil.

The direct shear tests were conducted on unsaturated soil specimens with different initial degrees of saturations as detailed earlier. The matric suctions of the soil specimens for different values of degrees of saturation in the soil specimens were estimated from the soil-water characteristic curve data. A detailed description of the testing procedure is available in Lane et al. (2001).

3.3 Soil-water Characteristic Curve

The information of the geometry and distribution of water in the liquid phase and stress within the pore water is derived from the soil-water characteristic curve. The area of water in contact with the soil particles is related to the shear strength of unsaturated soil conditions. Vanapalli et al. (1996) provide more details with respect to the use of the soil-water characteristic curve in the prediction of the shear strength of unsaturated soils.

Soil-water characteristic curves are measured conventionally over a limited suction range, usually 0 to 1500 kPa. However, to model unsaturated soil behaviour, from fully saturated soil conditions to total dry soil conditions, the soil-water characteristic curve has to be measured for the entire suction range (i.e., from 0 to 1,000,000 kPa).

Several factors such as the initial moulding water content, stress history of the soil, soil structure (aggregation), type of soil, void ratio, texture and mineralogy influence the soil-water characteristic curve (Vanapalli et. al. 1999). The factors that influence the soil-water characteristic curve behavior also influence the shear strength of unsaturated soils. Soils that have different initial water contents and densities should be considered as “different” soils from an engineering soil behaviour perspective. The engineering behaviour of fine-grained soils will differ from one specimen to another because of the differences in soil structure that arise due to different “initial” water contents.

The laboratory preparation of the specimens is important to represent the field conditions if proper assessment of shear strength parameters is to be achieved. For fine-grained soils, the initial moulding water content and the stress history has the greatest effect on the soil water characteristic curve and the shear strength behavior.

Vanapalli et al. (1996) determined the soil-water characteristic curve with an applied stress of 25 kPa for Indian Head soil (shown in Figure 5).

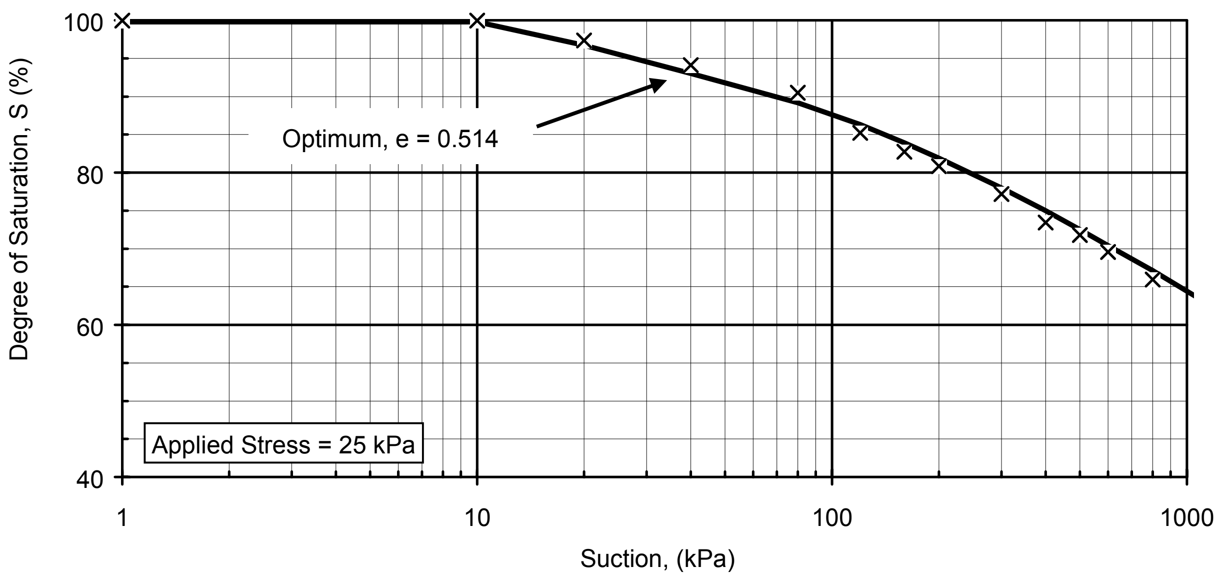

Figure 5. Soil-water characteristic curves used for estimating suction for specimen compacted at optimum water content conditions (modified after Vanapalli et al. 1996)

4. COMPARISON AND DISCUSSION OF EXPERIMENTAL RESULTS

The shear strength of the soil specimens were determined in conventional direct shear test apparatus using soil specimens that were saturated and air-dried under controlled environmental conditions. These specimens were consolidated and sheared under undrained conditions. The soil suction in air-dried specimens was back calculated from water content data using the soil-water characteristic curve shown in Figure 5. The analysis of the shear strength results was based on the assumption that there was no change in suction during the shearing process. This is a reasonable assumption for fine-grained soils as the soil specimens were sheared under undrained conditions in a considerably short period (i.e., 5 to 10 min.).

4.1 Comparison of Experimental Results Using Conventional and Modified Direct Shear Apparatus

The shear strength contribution due to matric suction, τ_{us}, is plotted as ordinate in Figures 6 thru 9, which is equal to $(u_a - u_w) \tan\phi^b$ from experimental results (see Eqn. 1) or $[(u_a - u_w)\{(\Theta)(\tan\phi')\}]$ from the semi-empirical prediction procedure (see Eqn. 2)

The variation of shear strength with respect to matric suction was found to be nonlinear for the suction range tested (Figure 6).

The trends of experimental results using the proposed simple technique presented in this research project were consistent with the trends of experimental results on the same soil using modified direct shear testing equipment (Figure 7).

Comparisons between the measured shear strength and published experimental shear strength values determined using the modified direct shear test on the same soil showed promising comparison between both testing methods (Figure 8). More studies are under progress at the Lakehead University to investigate the shear strength behaviour of the same soil under different net normal stresses with different initial compaction water content conditions. The results presented in the paper form only a part of the research program.

4.2 Comparison of Experimental Results to Empirical Procedure for Predicting the Shear Strength of Unsaturated Soils

Comparisons between the measured shear strength values using the conventional direct shear apparatus and predicted shear strength values using Equation 2 (Figure 9). The fitting parameter, κ, equal to 2.5 was used produce the best-fit curve. This value is close to the value used by Vanapalli et al. (1996) (i.e., κ = 2.3) for providing comparisons between the measured and predicted values of shear strength. The results of the present study show a reasonably good comparison was observed between the predicted and measured shear strength results (Figure 9).

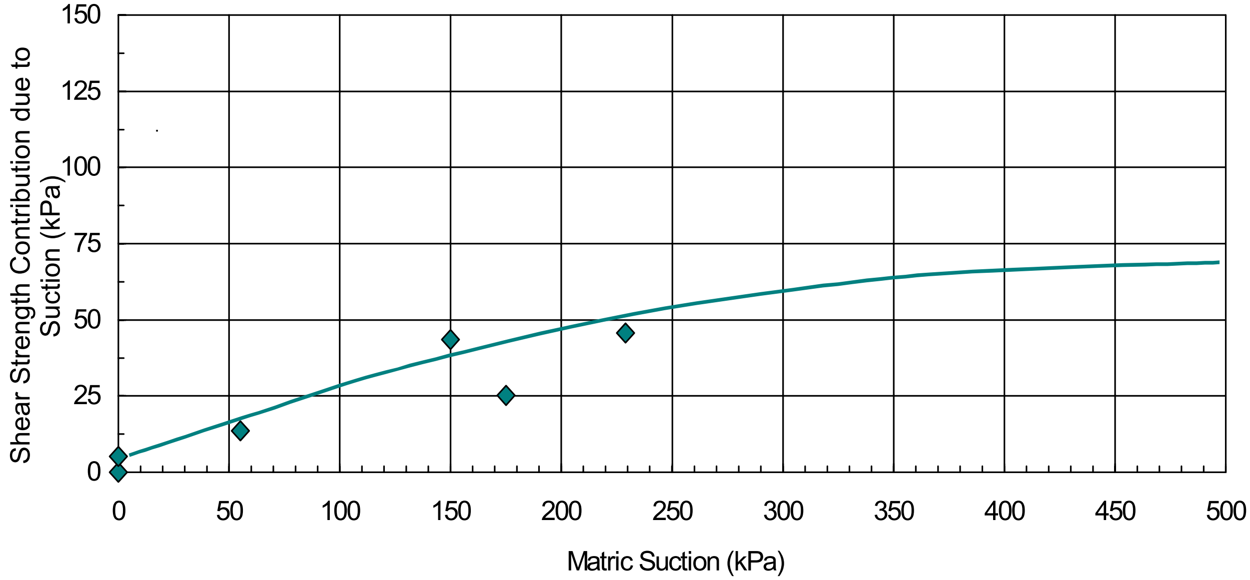

Figure 6. Experimental results of Shear Strength versus matric suction at three different initial water content conditions.

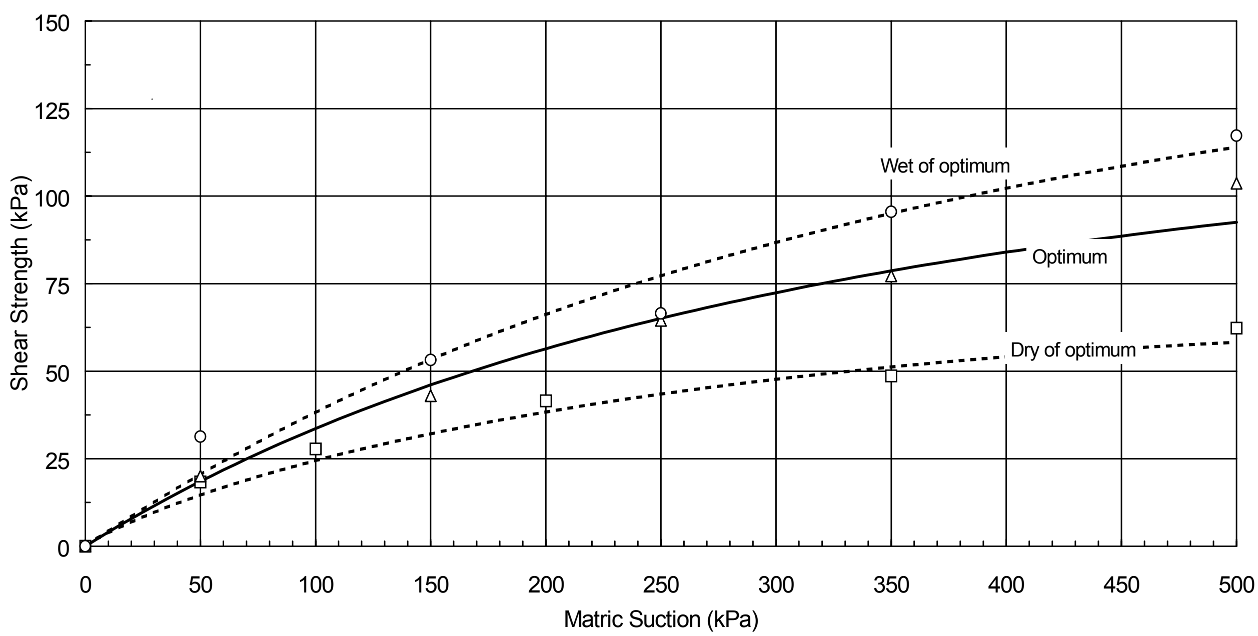

Figure 7. Variation of shear strength with respect to matric suction at three different initial water content conditions (modified after Vanapalli et al. 1996).

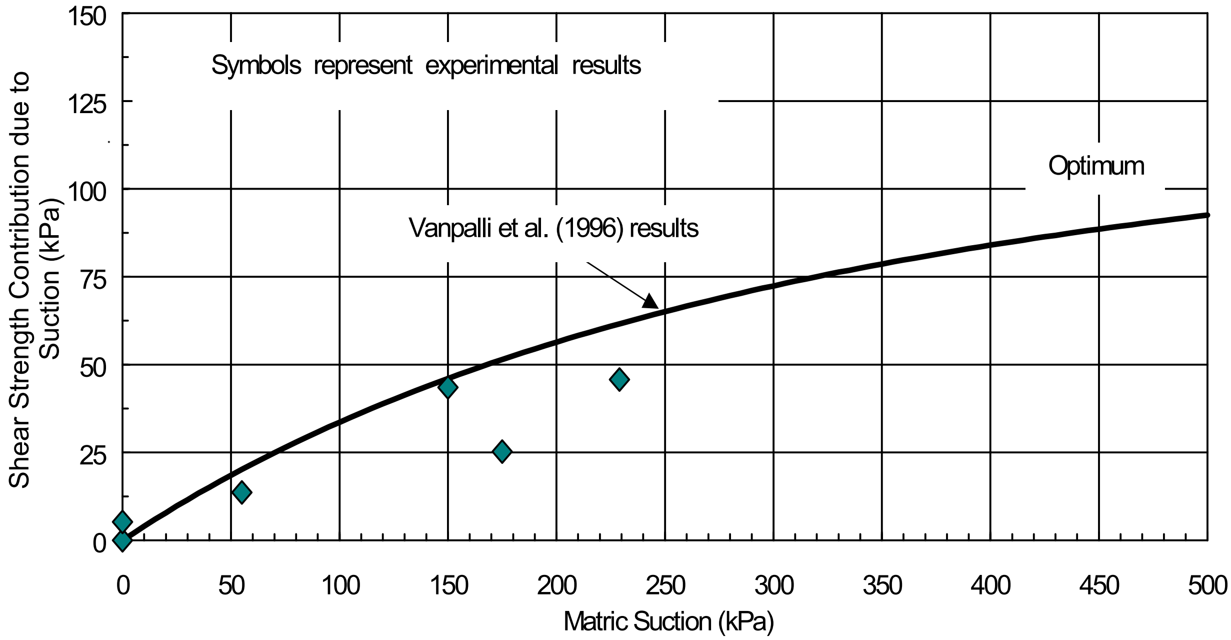

Figure 8. Comparison of measured shear strength values using the simple technique with modified direct shear test results of Vanapalli et al. (1996)

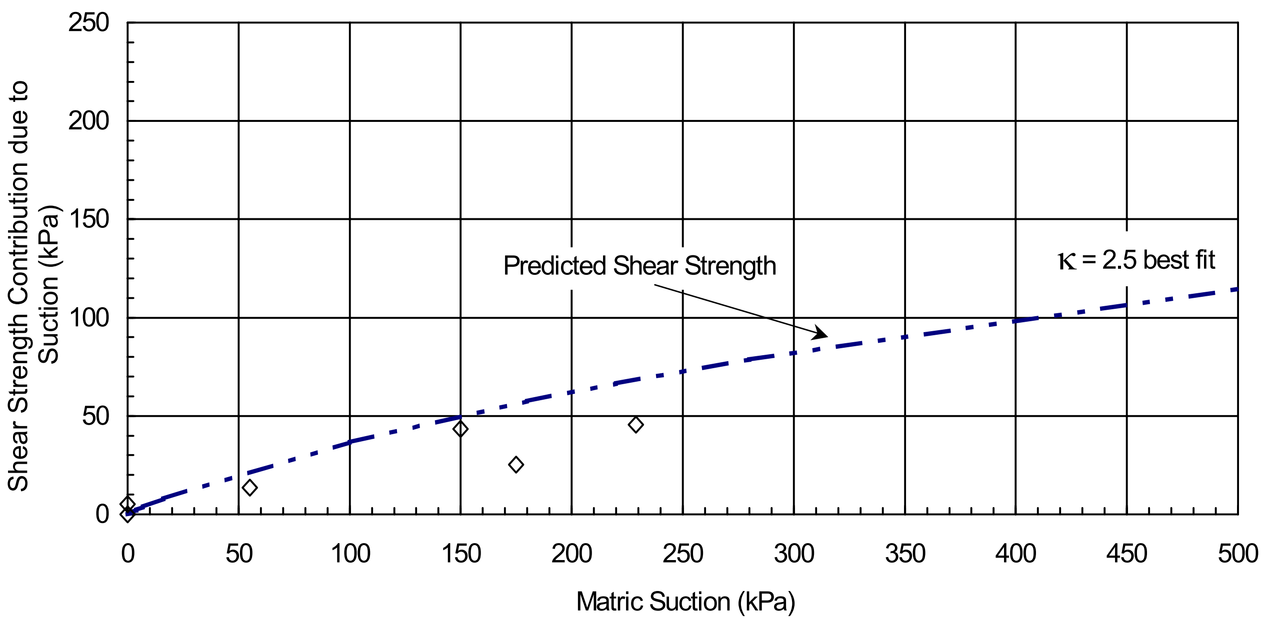

Figure 9. Comparison between the measured and predicted variation of shear strength versus matric suction

5. SUMMARY AND CONCLUSIONS

The primary objective of this paper was to propose a simple technique to determine the shear strength of fine-grained unsaturated soils. In the present study, the direct shear equipment that is conventionally used for determining the shear strength of saturated soils is used for determining the unsaturated shear strength. Experimental studies were undertaken on Indian Head till obtained from Saskatchewan, Canada under a net normal stress, $(\sigma - u_a)$ of 25 kPa using soil specimens compacted at optimum water content conditions for a matric suction, $(u_a - u_w)$, range of 0 to 500 kPa. The measured results of the present research study were compared with the experimental results of modified direct shear tests that were undertaken on the same soil under identical conditions by Vanapalli et. al. (1996). There is a reasonably good comparison between both methods.

The second objective of this research project involved the comparison of the experimental results with the semi-empirical procedure for predicting the shear strength of an unsaturated soil using the soil-water characteristic curve and the saturated shear strength parameters proposed by Vanapalli et al. (1996).

The studies of this research project were found to be useful determining the shear strength of fine-grained unsaturated soils using the conventional direct shear equipment and the soil-water characteristic curve. The duration of time required for testing is considerably less than the testing time required in comparison to conventional testing procedures. In addition, the proposed testing procedure can be undertaken in conventional soil's laboratories. The simple experimental procedure can be used in conjunction with the semi-empirical procedures to reliably estimate the shear strength of fine-grained unsaturated soils.

The simple approach presented throughout this project should encourage geotechnical and geo-environmental engineers to put the unsaturated shear strength theories to practice, as well as stimulate further investigations for proposing simple techniques for interpreting the shear strength of unsaturated soils. More studies must be undertaken on different fine-grained soils under controlled environment conditions to firmly establish the findings of the present research study.

6. ACKNOWLEDGMENTS

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