50th Canadian Geotechnical Conference
Golden Jubilee, Ottawa
October 20 – 22 1997

COMPARISON OF SATURATED-UNSATURATED SHEAR STRENGTH AND HYDRAULIC CONDUCTIVITY BEHAVIOR OF A COMPACTED SANDY-CLAY TILL

S. K. Vanapalli; D. G. Fredlund, and D. E. Pufahl

Proceeding, Volume 2, pp. 625 - 632

COMPARISON OF SATURATED-UNSATURATED SHEAR STRENGTH AND HYDRAULIC CONDUCTIVITY BEHAVIOR OF A COMPACTED SANDY-CLAY TILL

Vanapalli, S.K., Fredlund, D.G., and Pufahl, D.E.
Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada

ABSTRACT

Compacted fine-grained soils are commonly used in the construction of soil structures. Several factors such as void ratio, soil structure (aggregation), "initial" moulding water content, and stress state influence the properties of these saturated and unsaturated soils. Test results of statically compacted specimens of a fine-grained soil at three different "initial" water contents are presented. The data include saturated shear strength parameters, saturated coefficient of permeability, and soil-water characteristic curves. The coefficient of permeability and shear strength of the soil in its unsaturated state are predicted using the saturated soil properties and the soil-water characteristic curve. The parameters influencing the behavior of the saturated-unsaturated soil with respect to the coefficient of permeability and shear strength are presented and discussed in this paper.

RÉSUMÉ

Les sols granuleux compactés sont communément utilisés dans la construction de structures en sol. Plusieurs facteurs tels que le rapport vide, la structure du sol (agrégation), le contenu "initial" en eau du moulage et l'état de tension influencent les propriétés de ces sols saturés et insaturés. Les résultats de tests de spécimens statiquement compactés d'un sol granuleux à trois différents contenus "initiaux" en eau sont présentés. Les données incluent les paramètres force saturée de cisaillement, coefficient de perméabilité saturée et courbes caractéristiques eau-sol. Le coefficient de perméabilité et la force de cisaillement du sol dans son état insaturé sont prédient en utilisant les propriétés du sol saturé et la courbe caractéristique eau-sol. Les paramètres influençant la conduite du sol saturé-insaturé tout en considérant le coefficient de perméabilité et la force de cisaillement sont présentés et discutés dans cet article.

INTRODUCTION

Compacted fine-grained soils are commonly used in the construction of various soil structures. For example, geo-environmental structures such as soil covers and soil liners are constructed using such soils. There is a need to realistically predict/model the performance of these soil structures under saturated-unsaturated conditions. The coefficient of permeability and shear strength are two of the most important engineering properties of concern to engineers in the design of these structures. While experimental studies of coefficient of permeability and shear strength are time consuming and costly, for most practical applications an approximate assessment of these properties is sufficient.

The soil-water characteristic curve which is the relationship between water content (or degree of saturation) and soil suction has been found to be an effective tool for developing relationships, along with saturated soil properties, to predict/model the coefficient of permeability and shear strength of unsaturated soils (Fredlund et al. 1994, Fredlund et al. 1996). Several factors such as void ratio, soil structure (aggregation), initial moulding water content and stress state influence both the saturated and unsaturated properties of the compacted fine-grained soils. Specimens of a compacted fine-grained soil, in spite of having the same texture and mineralogy, can exhibit different soil properties when prepared at differing "initial" moulding water contents (Fredlund 1989, Vanapalli et al. 1996a).

A typical fine-grained soil (a sandy-clay till) from Indian Head, Saskatchewan was used in this research project. The "initial" water contents selected for this study represent the dry of optimum, optimum and wet of optimum conditions with corresponding densities determined from the standard AASHTO test. Shear strength parameters and the coefficient of permeability at saturation were determined for the three "initial" water contents. Multistage direct shear tests were conducted on the unsaturated specimens at these three "initial" water contents at a net normal stress of 25 kPa. Soil-water characteristic curves were also developed on specimens representing the same "initial" conditions. The coefficient of permeability of the unsaturated soil is predicted using the coefficient of permeability of the saturated soil and the soil-water characteristic curve. These results are presented and discussed in this paper. The parameters influencing the saturated-unsaturated soil behavior with respect to the coefficient of permeability and shear strength are also discussed in this paper.

SOIL PROPERTIES AND THE TESTING PROGRAM

The sandy-clay till used in this study contains percentages of sand, silt and clay of 28, 42, and 30 respectively. The liquid limit, ω_L, and plastic limit, ω_P, are 36 are 17% respectively. The specific gravity, G_s, of the soil is 2.73. The maximum compacted dry density, ρ_d, is 1.80 Mg/m^3 which corresponds to an optimum water content of 16.3%. Statically compacted specimens using three different "initial" water contents were selected using the soil compaction curve. The water contents and dry densities, ρ_d, are as follows: dry of optimum conditions (initial water content, 13%, and dry density, equals 1.73 Mg/m^3), optimum conditions (initial water content, 16.3% and dry density, ρ_d equals 1.80 Mg/m^3) and wet of optimum conditions (initial water content, 19.2%, and dry density, equals 1.77 Mg/m^3).

Specimens, 100 mm diameter and 21 mm height, were prepared at the prescribed densities and "initial" water contents using static compaction in a constant volume mold. The specimens used for the direct shear tests, the consolidation tests, and the specimens for developing the soil-water characteristic curves were obtained from the original specimens.

Effective shear strength parameters were determined using several procedures (single stage, multistage, and residual shear testing). The shear strengths of the unsaturated specimens were determined by using modified direct shear equipment for multistage testing (Gan and Fredlund 1988). The coefficients of permeability for saturated conditions were derived from the conventional consolidation tests. Soil-water characteristic curves were developed on prestressed specimens using a pressure plate apparatus for the suction range of 0 to 1,500 kPa. The specimens were loaded and unloaded in a conventional consolidation apparatus in a saturated condition to achieve a prestress value equivalent to the net normal stress used for determining the shear strength of unsaturated specimens. To attain the suction versus water content relationship beyond 1,500 kPa (i.e., 4,500 to 300,000 kPa), an osmotic desiccator was used. The testing procedures used for the study are available in Vanapalli (1994).

TEST RESULTS AND ANALYSIS

Saturated Shear Strength Results

Shear strength envelopes obtained from the three different types of tests (single stage, multistage, and residual shear testing) are shown in Fig. 1. The saturated shear strength parameters were essentially the same for all three different "initial" water content conditions. A series of residual strength tests and a series of multistage tests were also conducted on saturated specimens at optimum conditions (initial water content 16.3% and dry density 1.80 Mg/m^3). The shear strength parameters along with the strain rates are summarized in Table 1.

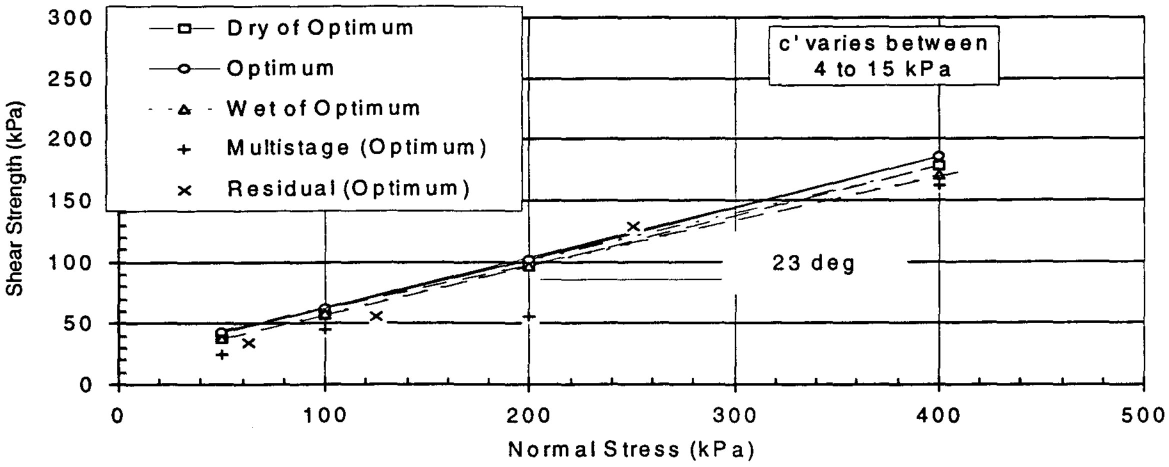

FIGURE 1. Results of saturated shear strength tests

The results in Table 1 show that there is no little variation in the angle of shearing resistance, ϕ', when using the three different types of tests. The variation in cohesion from 15 kPa in single stage testing to 4 kPa in multistage testing may be due to the variation in strain rate, different direct shear equipment used, type of testing procedures, and the possible variation in soil properties. Gan (1986) tested the same till used for this study and showed that at peak shear strength mobilized, the cohesion component was negligible. Thus the effective angle of shear resistance ϕ' equal to 23 degrees and an effective cohesion, c', tending to zero would be most reasonable for this soil for all the three "initial" water content conditions and densities tested.

TABLE 1
Strength Parameters of Saturated Till from Different Types of Direct Shear Tests

Type of Direct Shear Test	c' (kPa)	ϕ' (deg)	Strain Rate (mm/day)
Single Stage	15	22.5	18
Residual	8	23	18
Multistage	4	23	2.7

Coefficient of Permeability Results for Saturated Specimens

The coefficient of permeability values for saturated soil specimens are derived from conventional consolidation test results (Fig. 2). These values are 1.2 x 10^{-9} m/s, 5 x 10^{-10} m/s and 2.2 x 10^{-10} m/s respectively for specimens compacted at dry, optimum and wet of optimum conditions at a normal stress of 25 kPa. The coefficient of permeability of saturated specimens compacted at dry of optimum conditions is approximately one order of magnitude higher than specimens compacted at wet of optimum conditions.

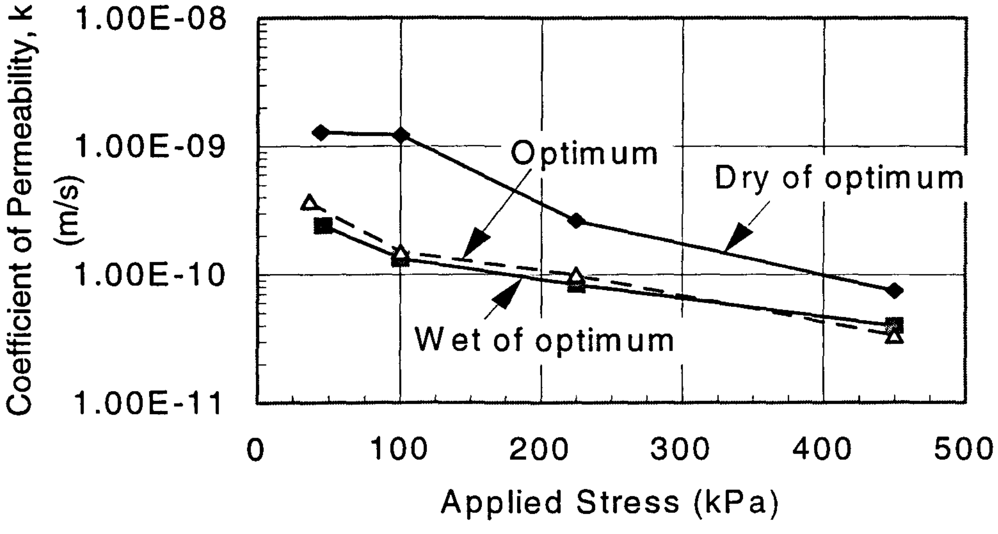

FIGURE 2. Coefficient of permeability test results from one-dimensional, consolidation tests (saturated specimens)

Soil-Water Characteristic Curve

Fine-grained soils will, in general, have two levels of soil structure: a macro structure and a micro structure. These structures which are present in both natural and compacted soils are a function of the type of soil, initial water content, compaction procedures and the applied stresses. The micro structure is the arrangement of the elementary particle associations within the soil aggregates, whereas the macro structure is the arrangement of soil aggregates (Mitchell, 1976). The influence of soil structure is reflected in the measured soil-water characteristic curves (Fig. 3).

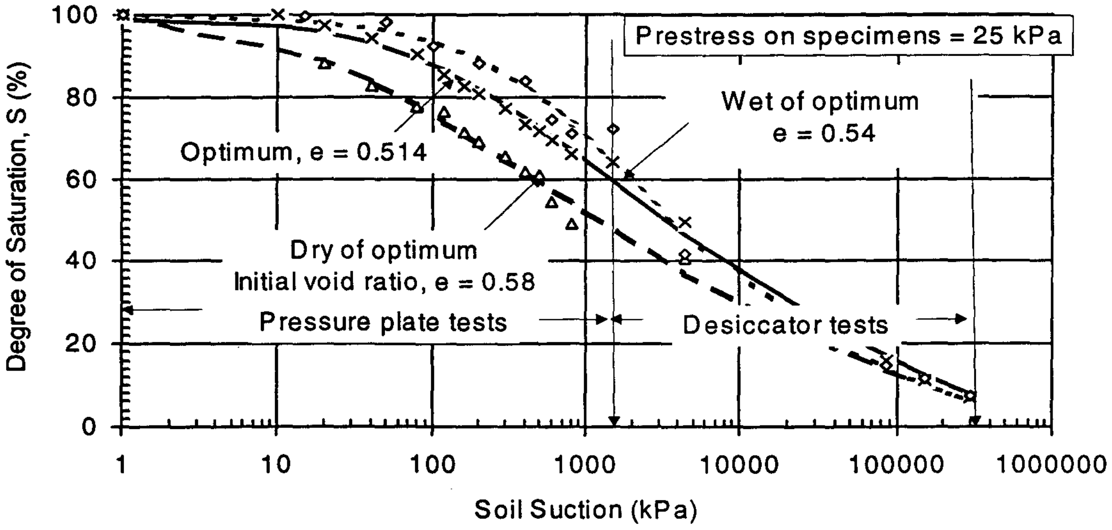

FIGURE 3. Soil-water characteristics of specimens with 25 kPa prestress

All specimens used to obtain the soil-water characteristic curves were subjected to a prestress of 25 kPa. It appears that the macro pore structure is more predominant for specimens compacted dry of optimum. This pore structure facilitates easier drainage of water (i.e., desaturation) under an applied soil suction. Thus, dry of optimum specimens desaturate without offering much resistance to flow particularly at small values of soil suction. This observation concurrs with that of Elsbury et al. (1990) who stated that "the interclod structure of dry of optimum specimens looked more like gravel". A wet of optimum water content specimen can be assumed to be relatively homogeneous, with virtually no visible evidence of interclod pores (Elsbury et al., 1990). In contrast to the dry of optimum specimens, the pore channels in the wetter specimens are generally disconnected and offer greater resistance to the water flow. The soil in this latter condition is less pervious since the micro structure dominates and provides resistance to the desaturation process. The slope of the soil-water characteristic curve for the wet of optimum conditions is much flatter in comparison to the dry of optimum water content specimens. The specimen prepared at optimum water content conditions lies between these two curves. However, the behavior is more like that of a soil compacted wet of optimum.

For all "initial" water contents (dry of optimum, optimum and wet of optimum) the soil-water characteristic curves are similar at higher suctions (i.e., 20,000 to 300,000 kPa). The interaggregate structure appears to be essentially the same for all specimens prepared at different "initial" conditions at these higher values of suctions.

SHEAR STRENGTH AND COEFFICIENT OF PERMEABILITY OF UNSATURATED SOILS

A framework for unsaturated soil behavior using the principles of stress state variables is available (Fredlund and Rahardjo 1993). The same framework can be extended to predict the properties of unsaturated soil using the soil-water characteristic curve and the properties of saturated soil. Fredlund and Xing (1994) proposed an equation for the soil-water characteristic curve which can be used to best-fit the experimental data of any soil for the suction range of 0 to 1,000,000 kPa (from saturated to dry conditions). The coefficient of permeability of unsaturated soils can be estimated using the Fredlund et al. (1994) equation, and shear strength of unsaturated soils can be estimated using the approach described by Fredlund et al. (1996) and Vanapalli et al. (1996b).

Figure 4 shows the variation of shear strength with respect to soil suction for the unsaturated soil specimens tested with various "initial" water content conditions when subjected to a net normal stress of 25 kPa. At any particular soil suction, the shear strength of the dry of optimum water content specimen is lower when compared to the optimum and wet of optimum water content specimens. Soil suction as a stress state variable appears to be more effective in contributing to shear strength for specimens with higher degrees of saturation. The variation in density from 1.73 to 1.80 Mg/m^3 (i.e., void ratio of 0.58 to 0.52) is considered to be too small to have any marked influence on the unsaturated shear strength behavior.

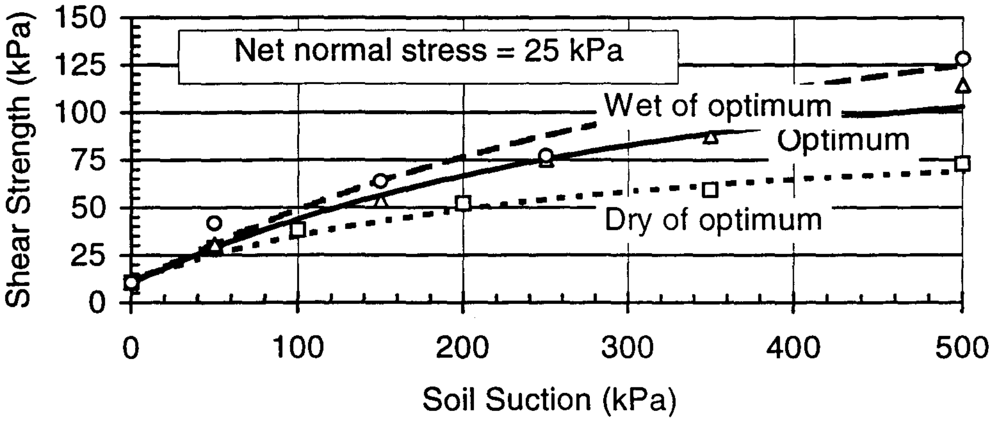

FIGURE 4. Predicted and measured shear strength versus suction for specimens tested with different "initial" water contents under 25 kPa net normal stress

Figure 5 shows the coefficients of permeability with respect to suction predicted by using the equation proposed by Fredlund et al. (1994). The specimens compacted wet of optimum have lower saturated hydraulic conductivity than the specimens prepared at dry of optimum conditions. The specimens dry of optimum begin to desaturate almost immediately indicating that the macro pores are more predominant and that they provide comparatively easy drainage of water at low values of suction. The difference in the coefficient of permeability at suctions around 200 kPa is several orders of magnitude. This emphasizes the effect of soil structure on the coefficient of permeability.

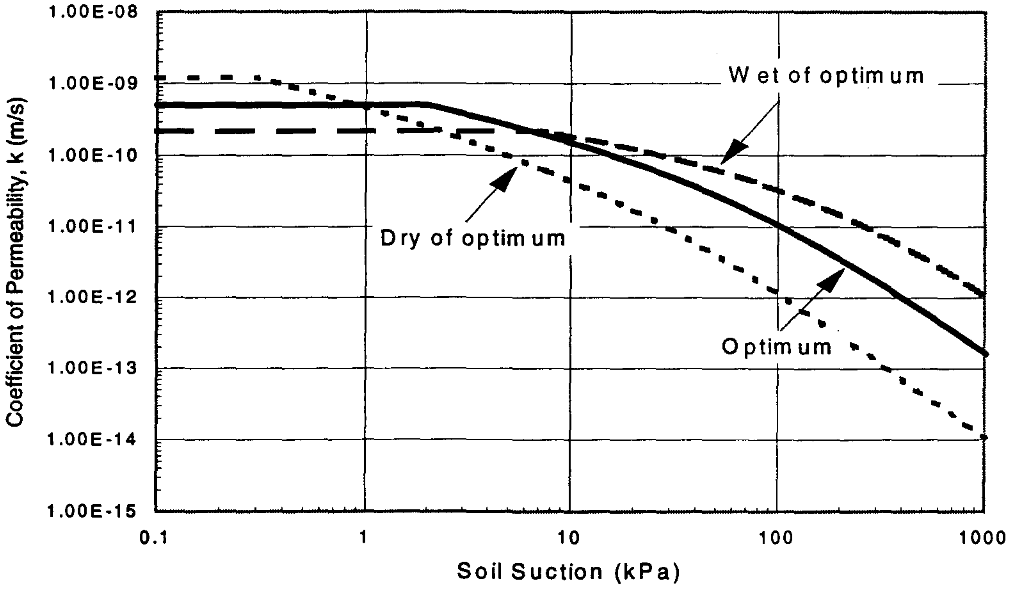

FIGURE 5. Predicted coefficient of permeability versus suction of specimens compacted with different "initial" water contents

SUMMARY

Soils compacted at various "initial" water contents and to various densities should be considered as "different" soils from a soil mechanics behavioral standpoint, even though their mineralogy, plasticity and texture are the same. The changes in engineering behavior from one specimen to another will vary due to differences in soil structure or aggregation.

The soil-water characteristic curve is dependent on soil structure or the aggregation, which in turn is dependent on the "initial" water content, the method of compaction and the stress state. The coefficient of permeability and the shear strength of an unsaturated soil are also influenced by these properties. The shear strength of the unsaturated specimens is lowest for the specimens compacted at dry of optimum conditions and highest for the specimens compacted at wet of optimum conditions. The coefficient of permeability of unsaturated soils for specimens compacted at dry of optimum conditions rapidly decreases with increasing suction in comparison to specimens compacted at wet of optimum conditions. This study suggests that preparation of specimens in the laboratory should closely represent the physical conditions and the stress state conditions that are likely to occur in the field if a proper assessment of the saturated-unsaturated soil properties of compacted fine-grained soils is to be made. However, the degree of accuracy required in engineering practice must be weighed against the reliability required for the engineering problem at-hand, and every attempt should be made to provide simpler solutions for practicing engineers. In that aspect, Fredlund et al. (1997) have recently proposed an approach for estimating the soil-water characteristic curve from the grain-size distribution, and volume-mass properties. The resulting equation can be best-fit by the soil-water characteristic curve equation proposed by Fredlund and Xing (1994). This method has been found to be particularly reliable for sands and reasonably accurate for silts. While clayey soils appear to give reasonable results in many cases, more research will have to be conducted to ensure greater reliability in the predicted results.

REFERENCES

ELSBURY, B.R., DANIEL, D.E., SRADERS, G.A., and ANDERSON, D.C. (1990). "Lessons learned from compacted clay liner," Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 11, pp. 1641-1660.

FREDLUND , D.G. (1989). "The character of the shear strength envelope for unsaturated soils," The Victor de Mello Volume, the XII International Conference on Soil Mechanics and Foundation Engg. (Rio de Janeiro, Brazil), pp. 142-149.

FREDLUND, D.G. and RAHARDJO, H. (1993). "Soil mechanics for unsaturated soils," John-Wiley & Sons Inc., New York, 517p.

FREDLUND, D.G. and XING. A. (1994). "Equations for the soil-water characteristic curve," Canadian Geotechnical Journal, Vol. 31, pp. 521-532.

FREDLUND, D.G., XING., A, and HUANG, S. (1994). "Predicting the permeability function for unsaturated soils using the soil-water characteristic curve," Canadian Geotechnical Journal, Vol. 31, pp. 533-546.

FREDLUND, D.G., XING, A., FREDLUND, M.D., and BARBOUR, S.L. (1996). "The relationship of the unsaturated soil shear strength to the soil-water characteristic curve," Canadian Geotechnical Journal, Vol. 33(3), pp. 440-448.

FREDLUND, M.D., FREDLUND, D.G., and WILSON, G.W. (1997). "Prediction of the soil-water characteristic curve from grain size distribution and volume-mass properties," N SAT'97, (ed.) T.M.P. de Campos & E.A. Vargas Jr., Vol. 1, pp. 13-23.

GAN J.K.M., (1986). "Direct shear strength testing of unsaturated soils," M.Sc. Thesis, Department of Civil Engineering., University of Saskatchewan, Saskatoon, Canada.

GAN, J.K.M. and FREDLUND D.G. (1988). "Multistage direct shear testing of unsaturated soils," American Society for Testing Materials, Geotechnical Testing Journal, Vol. 11, No. 2, pp. 132-138.

MITCHELL, J. K., (1976). "Fundamentals of soil behavior," New York, John Wiley & Sons Inc. 422p.

VANAPALLI, S.K. (1994). "Simple test procedures and their interpretation in evaluating the shear strength of an unsaturated soil," Ph.D. thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

VANAPALLI, S.K., FREDLUND, D.G., and PUFAHL, D.E. (1996a). "The relationship between the soil-water characteristic curve and the shear strength of a compacted glacial till," Geotechnical Testing Journal, GTJODJ, Vol. 19, No. 3, September 1996, pp. 259-268.

VANAPALLI, S.K., FREDLUND D.G., PUFAHL, D.E., and CLIFTON, A.W. (1996b). "Model for the prediction of shear strength with respect to soil suction". Canadian Geotechnical Journal, Vol. 33, No. 3, pp. 379-392.