Estimation of high suction values in unsaturated soils using conventional tensiometer

Estimation de grandes valeurs de succion dans les sols non-saturés en utilisant un tensiomètre conventionnel

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ABSTRACT

A simple method is proposed to estimate suction values in unsaturated soils ranging from 1,200 to 60,000 kPa in this paper using the conventional tensiometer results and the Kondner (1963) hyperbolic model. The proposed method uses the initial tangent value of suction versus time response in the suction range of 0 to 50 kPa for estimating the equilibration suction value. The model was tested on the published results of suction versus time response of high capacity tensiometers from the literature and an experimental program undertaken on compacted glacial till specimens with reasonably good results.

RÉSUMÉ

Une méthode simple est proposée, dans le présent article, pour estimer les valeurs de succion dans les sols non saturés allant de 1,200 à 60,000 kPa à l'aide de données obtenues grâce à un tensiomètre conventionnel et du modèle hyperbolique de Kondner (1963). La méthode proposée utilise la valeur initiale de la tangente la courbe de succion en fonction du temps dans la plage de succions allant de 0 à 50 kPa afin d'estimer la valeur de la succion à l'équilibre. Le modèle a été vérifié sur les résultats publiés de courbes de succion en fonction du temps obtenues à l'aide de tensiomètres de grande capacité ainsi qu'à partir d'un programme expérimental utilisant un tensiomètre conventionnel sur du till glacial avec des résultats raisonnablement bons.

Keywords : high suction measurement, tensiometer, hyperbolic model

1 INTRODUCTION

A framework for interpreting the engineering behavior of unsaturated soils in terms of two independent stress state variables, namely; net normal stress and soil suction is available (Fredlund & Rahardjo 1993). More recently, simple techniques of practical interest have been proposed to interpret and predict the bearing capacity (Vanapalli & Mohamed 2007; Vanapalli et al. 2007), modulus of elasticity (Oh et al. 2008), and shear modulus (Oh & Vanapalli 2009) of unsaturated soils. However, several difficulties are associated with the application of the mechanics of unsaturated soils in engineering practice due to a lack of economical and reliable means of measurement or estimation of soil suction.

The conventional tensiometers (i.e. jet fill tensiometer or small tip tensiometer; hereafter referred as CT) are regarded as the most reliable, simple and economical devices that can be used in the direct measurement of soil suction both in the laboratory and in the field. However, effective continuous measurements of soil suction using the conventional tensiometers is limited to 90 kPa or even lower due to problems associated with cavitation (Stannard 1990). The limitation of the conventional tensiometers could be overcome using the high capacity tensiometers (hereafter referred as HCT) (Ridley & Burland 1993; Guan & Fredlund 1997; Tarantino & Mongiovì 2003). The present HCTs are capable of measuring soil suction values up to 1,500 kPa (Ridley & Burland 1995). This is achieved by i) using high air-entry ceramic filter, ii) minimizing the volume of water in the tensiometer, and iii) pre-pressurizing the water in the tensiometer (Tarantino et al. 2008). However, they are not capable for measuring suction values greater than 1,500 kPa.

A method is proposed in the present study to estimate suction values in the range of 1,200 to 60,000 kPa. This method requires the experimental data measured from a conventional tensiometer and hyperbolic model that is commonly used in geotechnical engineering practice (Kondner 1963; Duncan & Chang 1970).

The response of conventional tensiometer versus time relationship (hereafter referred as TRT; Tensiometer Response versus Time) measured in the suction range of 0 to 50 kPa was used in the estimation of high soil suction values. This method was developed based on the assumption that the TRT is unique for each soil suction value. This assumption was found to be valid for the data published in the literature for several soils. In other words, there was a good comparison between the measured and estimated TRTs using the hyperbolic model for the entire range (i.e. 0 to suction value at equilibrium condition).

A series of tests were undertaken on a glacial till specimen compacted at several different water contents that are relatively low to achieve high suction values (i.e. in the range of 1,200 to 60,000 kPa). The suction measurements tests were performed using a conventional tensiometer and a psychrometer (i.e. WP4-T) to obtain TRTs in the low suction range (less than 50 kPa) and measure the suction values at equilibration condition of the soils, respectively. The WP4-T (chilled mirror dewpoint technique) can measure water potential in less than 5 min from 0 to 300 MPa with a resolution of 0.1 MPa. The effect of ambient temperature fluctuations on the measured results of suction are eliminated by maintaining a constant internal temperature.

The results summarized in this paper show that there is a unique relationship between the initial tangents of the TRTs and ultimate suction values. Therefore, high soil suction values can be estimated by calibrating the initial tangent value versus suction relationship for the soil of interest. The developed relationship can be used in the laboratory or in the field for estimating the high suction values of unsaturated soil using the limited TRT data in the suction range of 0 to 50 kPa, which typically requires less than 5 min.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-3426

2 HYPERBOLIC MODEL

The nonlinear soil behavior of soils such as the stress-strain relationship (Kondner 1963; Duncan & Chang 1970) and ultimate settlement in field conditions (Kodandaramaswamy & Narasimha Rao 1980) was estimated by hyperbolic model proposed by Kondner (1963).

$$y = \frac{x}{a + bx} \tag{1}$$

The ultimate value of *y* and the derivative at *x* equal to zero (i.e. initial tangent) can be obtained using Equations (2) and (3), respectively (Fig. 1).

$$y_{ult} = \lim_{x \to \infty} x = \frac{1}{b} \tag{2}$$

$$\left(\frac{dy}{dx}\right)_{x=0} = \frac{1}{a} \tag{3}$$

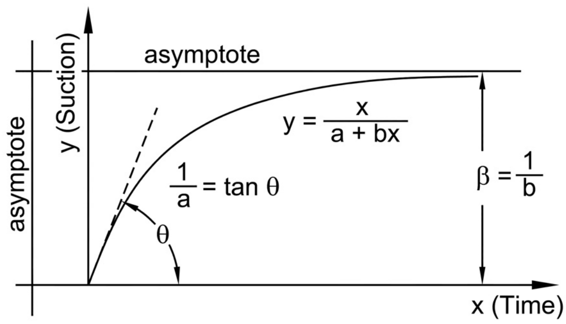

Figure 1. A typical hyperbolic relationship (after Kondner, 1963).

The two-constant hyperbolic relationship (i.e. Equation (1)) has been used in various geotechnical engineering fields. However, in some cases the hyperbolic relationship may not provide the exact fit for the entire range of the non-linear experimental data (Kondner 1963). Several studies, however, have shown that the initial tangent value (i.e. Equation (3)) can be used more reliably to estimate the ultimate value of the non-linear relationship. In the present study, the initial tangents obtained from TRTs in the suction range of 0 to 50 kPa were used to propose a method to estimate the equilibration soil suction values in unsaturated soil specimens that are relatively high.

The approach presented in this paper can be indirectly supported using the studies of Oliveira & Marinho (2008). These investigators suggested that the equilibration time (i.e. time at which suction readings are close to actual values) increases as the suction value increases. In other words, the TRT can be used as a tool to estimate the equilibrium suction value of a specimen. The equilibration time was defined as a time at which the average rate of suction change over an interval of ten seconds is less than 0.0025(s^{-1}) from the TRTs (Fig. 2).

3 APPLICATION OF HYPERBOLIC MODEL IN ESTIMATING HIGH SUCTION VALUE

Figs 3 and 4 show comparisons between the measured TRTs and the estimated non-linear behavior of TRTs using hyperbolic model (Equation (1)) for two different soils from the literature (Ridley & Burland 1993; Guan & Fredlund 1997). The results suggest that the TRT for the entire range (i.e. from zero to equilibration suction value) can be reasonably represented using the Kondner's (1963) hyperbolic model. In addition, these results also suggest that the initial tangent of the TRT (Equation (3)) is dependent on the suction value of the tested unsaturated soil.

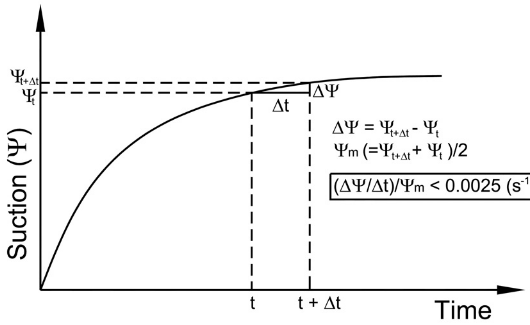

Figure 2. Illustrative diagram to define suction equilibration time measured with the HCT (after Oliveira & Marinho 2008).

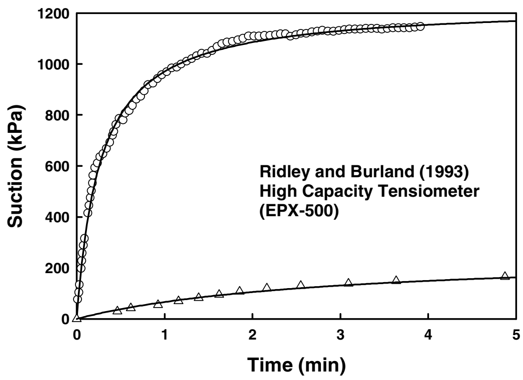

Figure 3. Comparison between the measured tensiometer response versus time (TRT) of Ridley & Burland (1993) data and the predicted response using hyperbolic model.

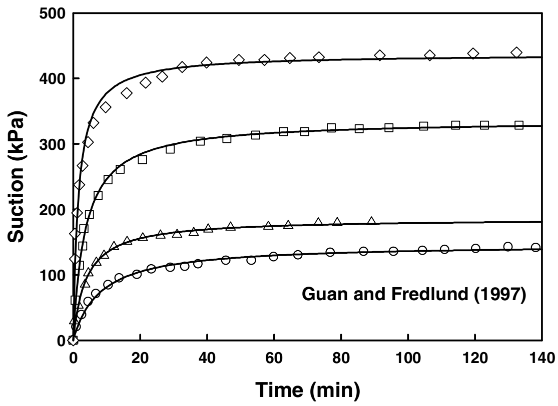

Figure 4. Comparison between the measured tensiometer response versus time (TRT) of Guan & Fredlund (1997) data and the predicted response using hyperbolic model.

4 TESTING PROGRAM

The testing program consists of three parts; i) compacting soil specimens, ii) measuring TRT using a CT in the suction range of 0 to 50 kPa, and iii) estimating ultimate suction values using a psychrometer. The initial tangents of the TRTs were calculated and then correlated with the ultimate suctions to develop a calibration model. This calibration model is useful in estimating soil suction value based on the information of initial tangent value. All the studies presented in this paper were undertaken in a laboratory under controlled environment with respect to both temperature and humidity conditions.

4.1 *Sample preparation*

A glacial till obtained from Indian Head, Saskatchewan was used for the present study (Plasticity index, I_P = 15.5%, Specific gravity, G_s = 2.72). The soil required for the testing program was air-dried and then subjected to gentle pulverization using a rubber mallet. The prepared soil was passed through a 2 mm sieve and mixed with five different water contents (i.e. 3.6, 5.3, 7.0, 9.3 and 11.2%) using distilled water.

The till/water mixtures were then placed in sealed polyethylene bags for a period of 2 days to ensure uniform distribution of moisture throughout the sample. The mixtures were statically compacted in a metal ring (i.e. 64 mm in diameter and 64 mm in height) using a compaction energy of 350 kPa to prepare soil specimens for testing.

4.2 *Suction measurements*

A cylindrical aperture (i.e. 5 mm in diameter and 9 mm in depth) was made into the prepared compacted soil specimens using a thin-wall tube to insert the ceramic cup of the CT (i.e. 5 mm in diameter and 7 mm in height) (Fig. 5(a)).

Take & Bolton (2003) showed that the measurements of suction values using tensiometers are significantly influenced by saturation effort of filter elements. However, in the present study the key objective is to measure the TRTs in the suction range of 0 to 50 kPa and estimate the equilibration suction value of the specimen rather than focusing on the filter element saturation. The response of variation of suction with respect to time was quick. Therefore, the suction response measurements of the CT were videotaped using a video camera with the real-time function (Fig. 5(b)).

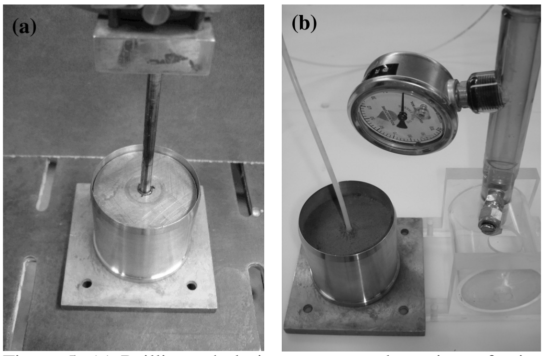

Figure 5. (a) Drilling a hole in a compacted specimen for insertion of conventional tensiometers ceramic cup; (b) Suction measurement using a conventional tensiometer.

After the TRT (in the suction range of 0 to 50 kPa or less) was measured using a CT, typically for a time period of less than 5 min, a small cylindrical piece from the compacted specimen was removed to measure the ultimate suction value of the compacted specimen using a psychrometer (WP4-T). The measurements of ultimate soil suction values using a psychrometer were obtained between 5 to 10 minutes depending on the suction values.

5 ESTIMATION OF HIGH SOIL SUCTION USING THE PROPOSED METHOD

The CT response versus time relationships (i.e. TRT) for a 5 minute period in the suction range of 0 to 50 kPa for five different compaction water contents are shown in Fig. 6 along with the ultimate suction values (Ψ) measured using a psychrometer. The fitting parameter, *a* value for the best-fitting curves using hyperbolic model (i.e. Equation (1)) for each suction value are summarized in Table 1. The initial tangents from a CT (i.e. Fig. 6) are relatively low in comparison with the results in Figs. 2 and 3 obtained using HCTs. The differences are attributed to i) the CTs are designed to measure the suction values less than 100 kPa and ii) the response is dependent of the sensitivity of the vacuum gage and the type of water used in the study (i.e. de-aired water or distilled water).

Figure 7 shows the relationship between the soil suction and inverse of the parameter, *a* (i.e. *1/a*) on an arithmetic scale plot. The value of *1/a* was assumed to be equal to zero at saturated condition. The results show that the suction value starts rapidly increasing in the suction range of 1,200 and 2,583 kPa. A suction of 1,500 kPa is commonly regarded as a residual suction value since it corresponds to the wilting point for many plants (van Genuchten 1980). The variation of suction in the soil specimen beyond this point is governed by vapor movement of water rather than capillary suction.

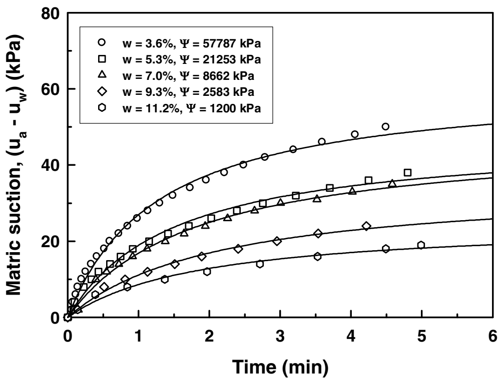

Figure 6. The suction versus time response relationship using conventional tensiometer for specimens compacted with different water contents.

Table 1. Summary of the parameter, *a* value for different compacted specimens using hyperbolic model.

Water content (%)	Suction (kPa)	*a*	*1/a*
3.6	57,787	0.0208	48.08
5.3	21,253	0.0318	31.45
7.0	8,662	0.0384	26.04
9.3	2,583	0.0612	16.34
11.2	1,200	0.0795	12.58

The results in Fig. 7 show a linear relationship (Equation 4) for the suction values studied in this study (i.e. 1,200 kPa $\leq \Psi \leq$ 57,787 kPa) when they are plotted on a logarithmic scale (Fig. 8).

$$\Psi(\text{kPa}) = 0.7771(1/a)^{2.9073} \quad (4)$$

The calibrated relationship summarized in Fig. 8 is useful in estimating the equilibration suction values (i.e. typically greater than 1,500 kPa) in the tested compacted glacial till specimens using CT readings in the suction range of 0 to 50

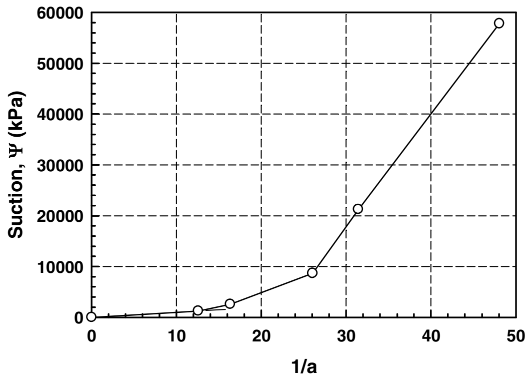

Figure 7. Variation of suction value with *1/a* (arithmetic scale plot).

kPa. The relationship for the suction values from 90 to 1,200 kPa was not investigated using chilled-mirror dewpoint psychrometer such as WP4-T since the measurement of suction in that range is not reliable (Bulut et al. 2002). The suction value in this range is influenced by the liquid phase flow. The relationship in that range can be obtained by measuring suction values using HCTs or axis-translation technique. This suction range was not addressed in this paper as the focus of the experimental results was towards estimating high suction values in unsaturated soils.

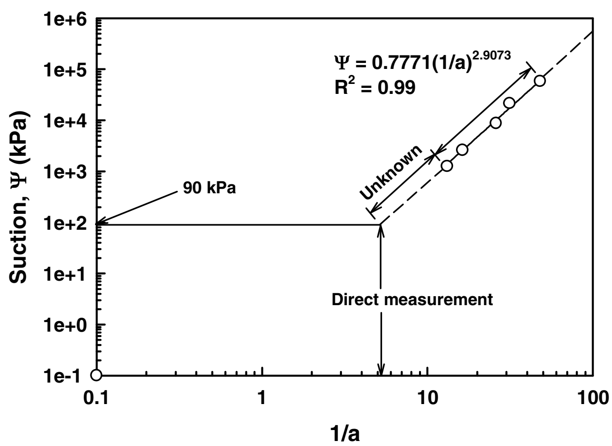

Figure 8. Variation of suction value with *1/a* (log scale plot).

6 PROCEDURE FOLLOWED FOR OBTAINING THE TRT

The calibrated Equation (4) for the TRT for the soil investigated in the present study is sensitive. This relationship can be influenced by the CT used and the techniques followed in the measurement of suction. The procedure followed in the present study for the TRT is summarized below;

i) The ceramic cup of the CT was saturated by submerging it in distilled water for a period of 24 hrs.
ii) The body of the tensiometer was filled with commercial distilled water. In this program, the de-aired water was not used to avoid possible inconsistencies between lab and field conditions.
iii) The service cap of the tensiometer should be securely tightened (Rahardjo & Leong 2006).
iv) The TRT can be influenced by the initial wetting condition of the surface of the ceramic cup (Ridley et al. 2003). Hence, the moisture on the surface of the tensiometer ceramic cup should be removed following standard protocols before the ceramic cup is driven into the specimen.

7 SUMMARY AND CONCLUSION

In this present study, a method is proposed to estimate high suction values of compacted glacial till specimens in the range of 1,200 kPa to 60,000 kPa using conventional tensiometer results in suction range of 0 to 50 kPa. The proposed method is based on the assumption that the response of a tensiometer versus time relationship (TRT) can be reasonably represented using hyperbolic model (Kondner 1963) and the initial tangents of TRTs are dependent on the equilibrium suction value of the specimen. A calibration equation should be developed using the procedures described in the paper for estimating high soil suctions for the required soil. For example, Equation (4) is the relationship developed for the compacted glacial till in the present study. Once the initial tangent (i.e. *1/a*) is determined using the TRTs measured with a CT, the suction value of the unsaturated soil can be estimated.

The relationship in Equation 4 is dependent of the CT used and the technical protocols followed for measuring TRTs. Hence, it is recommended to standardize the entire procedures to obtained reliable relationship between suction and (*1/a*).

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