Pull-out capacity of soil nails in unsaturated soils

Naresh Gurpersaud[1], Sai K. Vanapalli[2] & Siva Sivathayalan[3]
[1]*Geo-Foundations Contractors Inc., Acton, Ontario, Canada*
[2]*Dept. of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada*
[3]*Dept. of Civil Engineering, Carleton University, Ottawa, Ontario, Canada*

ABSTRACT
The design of soil nail systems used in engineering practice is either based on conventional soil mechanics or empirical procedures ignoring the influence of matric suction. A comprehensive experimental program was conducted to understand the influence of matric suction on the pull-out capacity of soil nails installed in compacted sand under both saturated and unsaturated conditions. Pull-out tests were performed on the nails installed vertically, horizontally and at an inclination of 15° to the vertical. A strong relationship was observed between the pull-out capacity and the soil-water characteristic curve (SWCC). A simple technique is proposed for the estimation of the pull-out capacity of soil nails by using the average matric suction value and the saturated soil parameters c' and ϕ'. There is a reasonably good comparison between the measured and estimated pull-out capacity of soil nails, both using the results of the present research program and as well as the data from the literature.

RÉSUMÉ
La conception de systèmes de sol clouté utilisés dans la pratique du génie est basée soit sur la mécanique des sols conventionnelle ou sur des procédures empiriques ne tenant pas compte de l'influence de la succion matricielle. Un programme expérimental a été entrepris pour comprendre l'influence de la succion matricielle sur la résistance à l'arrachement de clous installés dans du sable compacté dans des conditions saturées et non-saturées. Des essais d'arrachement ont été menés sur des clous installés à la verticale, à l'horizontale, et à un angle de 15° avec la verticale. Une relation marquée a été observée entre la résistance à l'arrachement et la courbe de rétention d'eau (CRE). Une technique simple est proposée pour estimer la résistance à l'arrachement de clous en utilisant la succion matricielle moyenne et les paramètres de sols saturés c' et ϕ'. Une bonne concordance a été observée entre les valeurs mesurées et estimées de résistance à l'arrachement des clous, tant en utilisant les résultats du programme de recherche que des données tirées de la littérature.

1 INTRODUCTION

Soil nailing is a widely used ground stabilization technique utilizing passive elements (referred to as nails) for retaining soils. The tensile forces generated in the soil nails are transferred to the soil through friction mobilized at the grout/soil interface, and hence the interface shear strength is of primary importance when designing soil nails. The load transfer mechanism and the ultimate pull-out capacity of soil nails depends primarily on the soil type, strength characteristics, installation technique, geometry of drilled hole and the grouting method. Soil nails have been utilized increasingly in recent years due to its technical and economic advantages.

Soil nailing applications are best suited for placement above the ground water table, where the soil is in a state of unsaturated condition. When the ground water table is deep, the stresses associated with the constructed infrastructures are distributed in the zone above the ground water table (Vanapalli and Oh, 2010). Shallow foundations, retaining walls and pavement structures are typical examples that fall in this category. Classical soil mechanics theories applicable to saturated soils are conventionally used in the design of such geotechnical structures, including soil nails by neglecting the contribution of matric suction or the negative pore-water pressures in the vadose zone (i.e., the zone above the ground water table) to the capacity. The key reason for this approach can be attributed to the lack of a simple framework for the analysis and design of geotechnical structures using the mechanics of unsaturated soils (Fredlund and Rahardjo, 1993; Vanapalli and Oh, 2010). In most cases, soil nail zones do not become saturated during their design service life and hence it is more appropriate to use the mechanics of unsaturated soils for the design of these structures. The difference between the pore air pressure, u_a (which is typically equal to atmospheric pressure) and the pore water pressure, u_w in unsaturated soils is known as matric suction, (u_a - u_w).

Determination of the shear strength of unsaturated soils is time consuming and requires trained personnel and elaborate testing equipment. In recent years, to alleviate some of the problems, several empirical, semi-empirical and analytical procedures have been proposed in the literature for estimation of the shear strength of unsaturated soils (Vanapalli et al., 1996; Fredlund et al., 1996; Oberg and Sallfours, 1997; Khalili and Khabbaz, 1998). Most of the proposed procedures utilize the soil-water characteristic curve (SWCC) as a tool for the prediction of the shear strength of unsaturated soils. The present understanding of shear strength of unsaturated soils has been extended for interpretation and prediction of the behaviour of soil nails.

The pull-out capacity is a key parameter for the design of soil nails. There are no specific design procedures or method specified to estimate the pull-out capacity of soil nails in the Canadian Foundation Engineering Manual (2006). The estimated pull-out capacity of soil nails is commonly verified by field pull-out tests during the construction stage. Several research studies have been conducted to investigate the behaviour of the soil/nail interface during pull-out (Junaideen et al., 2004; Chu et al., 2005; Yin and Su, 2006; Pradhan et al., 2006; Sivakumar and Singh, 2010). However, the influence of matric suction on the pull-out capacity of soil nails did not receive significant research attention (Su et al., 2008 and Zhang et al., 2009). Zhang et al. (2009) reported that matric suction is a key factor that contributes to the uncertainties in the estimation of the pull-out capacity of soil nails.

In this paper, the pull-out capacity of soil nails in saturated and unsaturated compacted coarse grained soil will be evaluated. Details of an extensive pull-out test program performed in a laboratory environment, and the test results are provided. The results obtained were analyzed to propose a framework for the interpretation of pull-out capacity of soil nails in both saturated and unsaturated soils by using the modified β method (Vanapalli et al., 2010).

2 THEORETICAL BACKGROUND

Shear strength is a key property required in the design of geotechnical structures such as foundations, earth retaining structures and the stability of slopes. The soils associated with these structures are typically in a state of unsaturated condition. Therefore, the mechanics of unsaturated soils is appropriate for the design and understanding of the performance of such structures. However, the influence of matric suction which contributes to the shear strength of unsaturated soils is typically ignored in the design of geotechnical structures. The soil is assumed to be typically in a state of saturated condition in conventional geotechnical practice because such an approach is considered to be conservative.

There are several equations proposed in the literature to estimate the pull-out capacity of soil nails (Potyondy, 1961; Cartier et al., 1983; Jewell et al., 1987; Jewell, 1990; Heyman et al., 1992; HA68/94, 1994; Mesci, 1997, Chu and Yin 2005; Zhang et al., 2009; Sivakumar and Singh, 2010). Limited information is available in the literature that examines the influence of matric suction on the pull-out capacity of soil nails within unsaturated soils. To the author's knowledge, there is only one equation in the literature that accounts for the contribution of matric suction towards the pull-out capacity of soil nails (Zhang et al. 2009).

The SWCC defines the relationship between soil suction and degree of saturation, S. The distribution of soil, water and air phases changes with the variation of stress state when a soil moves from a saturated state to drier condition or vice versa. The relationship between the different phases that take on different forms and influence the unsaturated soil behaviour can be derived from the SWCC (Barbour, 1999). For example, Vanapalli et al. (1996) used the relationship between the rates at which the shear strength changes with respect to matric suction as a function of the wetted area of contact between the soil particles using the SWCC as a tool to predict the shear strength. Figure 1 shows the zones of desaturation and the fundamental relationship between the SWCC with the shear strength of unsaturated soils. The SWCC has been as a tool to estimate or predict the different properties of the unsaturated soil such as the variation of coefficient of permeability, shear strength, bearing capacity of soils under drained and undrained loading conditions, modulus of elasticity of coarse-grained and fine-grained soils, design of pile foundations in coarse-grained soils and shear modulus (Vanapalli and Oh, 2010).

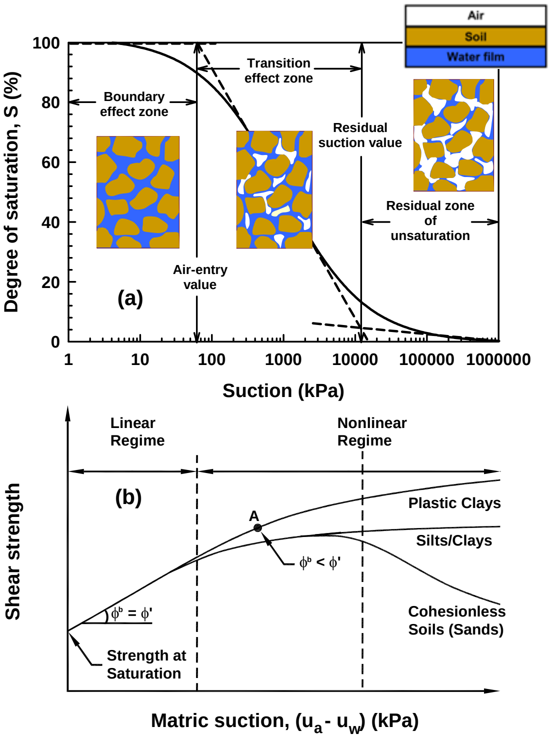

Figure 1. (a) SWCC illustrating zones of desaturation; (b) The relationship between the SWCC with shear strength of unsaturated soils (Vanapalli, 2009)

Vanapalli et al. (2010) recently investigated the influence of matric suction on the shaft capacity of jacked piles in coarse-grained soils. Results obtained from the study shows the contribution of matric suction towards the shaft capacity was significant (35-40% of the total shaft capacity of silty sand). In addition, they have also shown that there is a relationship between the SWCC and shaft capacity of piles in unsaturated soils. In the present study, the equation proposed by Vanapalli et al. (2010) was modified to estimate the pull-out capacity of soil nails installed in both saturated and unsaturated coarse-grained soils. This approach is useful in estimating the variation of pull-out capacity of soil nails with respect to suction using the SWCC and saturated shear strength parameters based on some reasonable assumptions.

3 EQUIPMENT AND METHODOLOGY

A test box was specially designed and constructed to determine the pull-out capacity of prototype grouted soil nails. The test box was outfitted with different accessories to conduct experiments to serve the following objectives of the study:

i) To evaluate the contribution of matric suction towards the pull-out capacity of soil nails in compacted coarse-grained soil under saturated and unsaturated conditions.
ii) To assess the pull-out capacity of soil nails installed at different orientations.
iii) To evaluate the relationship between the SWCC and the pull-out capacity of soil nails
iv) To develop a simple technique to estimate the pull-out capacity of soil nails by using the average matric suction and the saturated shear strength parameters.

3.1 Details of equipment

The test box was constructed to internal dimensions of 1.5 m x 1.2 m in plan and 1.1 m in depth. General details of the test box, including features to allow for variation of matric suction and soil compaction are presented in Gurpersaud et al. (2010). A clear distance of 5.5 times the diameter of the nail was allowed from the sides of the test box to avoid the influence of boundary effects during pull-out testing (Yin and Su, 2006). Figure 2 shows the key features the test box and its assembly that was used for testing the pull-out capacity of soil nails. The salient features of this test box are similar to the test set-up used by Mohamed and Vanapalli (2006) and Vanapalli et al. (2010) to model the performance of shallow foundations in unsaturated soils and determining the bearing capacity of model piles respectively.

3.2 Drilling and installation of the test nails

The influence of inclined soil nails were studied in this paper as they are conventionally done in the field. An electric core drilling machine was used to drill the holes at a diameter of 100 mm. The steel tendon was installed and then grouted in the drilled hole. Prior to drilling, the water table was dropped below the target elevation of the hole to prevent collapse of the soil and to ensure stable drilling conditions, by utilizing the contribution of matric suction.

The hole was drilled to a depth of 800 mm from the surface of the compacted soil in the test box. The drilling system and method of installation was carefully selected to maintain a reproducible procedure for the entire test series. Each test nail was installed with two centralizers and a tremie grout tube. The tremie grout tube was removed upon completion of grouting.

Grouting of the nail was performed by mixing Type 10 Portland cement at a water cement ratio of 0.45. The grout was thoroughly mixed using an electric drill with a paddle mixer and batching was done by weight. The specific gravity of grout used for each soil nail was measured using a Baroid mud balance in accordance with API 13B-1 (1990).

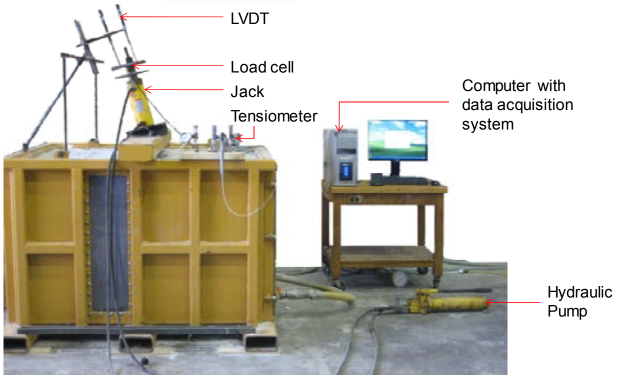

Figure 2. Test box and set-up for pull-out testing of soil nails

3.3 Instrumentation

The applied force and displacement of the nail were recorded during the pull-out test through a data acquisition system (DAS). Matric suction measurements were also taken with soil moisture probe 2100F tensiometers. The pull-out force was measured with an ANCLO load cell located between the hollow core hydraulic jack and the restraining plate. Two linear variable displacement transducers (LVDT) were installed at the nail head to measure the pull-out displacement.

4 SOIL AND MATERIAL PROPERTIES

4.1 Soil and nail properties

The sand used can be classified as poorly graded sand (SP) as per the USCS. Some of the key properties of the sand are summarized in Table 1. Grouted soil nails of 100 mm diameter x 800 mm long were used for this experimental program. Williams Form Hardware - 22 mm (#7) threaded bar with a minimum yield stress of 517 MPa was used as the central reinforcement for the soil nails.

Table 1. Properties of the tested soil

Property	Value
Specific Gravity, G_s	2.65
D_{60} (mm)	0.27
D_{30} (mm)	0.2
D_{10} (mm)	0.16
Coefficient of uniformity, C_u	1.7
Coefficient of curvature, C_c	0.93
Soil friction angle (ϕ')	30.1°
Grout–soil Interface friction angle (δ)	28.8°
Dilation angle (ψ)	4.3°

4.2 Grout Properties

Type 10 Portland cement is generally used for most soil nailing applications. Characteristics of the grout will influence the nail surface area and normal stress acting on the grouted nails (Franzen, 1998). A grout mixture comprising of Type 10 Portland cement at a water cement ratio of 0.45 was selected for the present study. This mixture is commonly used in most soil nailing applications in practice.

5 TEST PROGRAM

5.1 General

The tests were performed in compacted sand and each test nail was installed under identical conditions (i.e., similar degree of compaction), for both saturated and unsaturated cases. A total of 10 pull-out tests were performed during this study.

5.2 Pull-out testing procedure

Pull-out tests can be conducted either under displacement-rate controlled loading or force controlled loading (FHWA, 1993). Displacement-rate controlled tests allow for the determination of peak, and ultimate pull-out capacity. Creep characteristics and a rough estimation of the peak capacity can be obtained from force-controlled tests. However, force controlled tests cannot yield a true measure of the post peak response. Force controlled tests are easier to conduct and commonly utilized for field testing. A pull-out rate of 1.0 mm/min was used for tests performed for this study, as recommended by FHWA (1993). Pull-out testing was performed seven days after installation of the nails, allowing the grout to cure to a suitable strength. This guideline is also consistent with the protocols followed in determining the pull-out capacity for field testing of soil nails.

5.3 Saturated and unsaturated conditions

The compacted sand in the test box was saturated by gradually increasing the level of the water table from the bottom of the box. This technique allowed the air from the compacted sand to be expelled toward the surface. Three tensiometers were used to measure the matric suction in the soil at different depths. The matric suction value within the unsaturated zone was estimated based on the average of the three readings. Water table was raised to the top surface for the saturated tests. Readings from the tensiometers when the water level reached the surface of the soil confirmed saturated condition (i.e., $(u_a - u_w) = 0$ kPa). The gravimetric water contents were also measured by collecting specimens using small containers with perforations (Figure 3). Details of the locations of the perforated cups and tensiometers are provided in Gurpersaud et al. (2010).

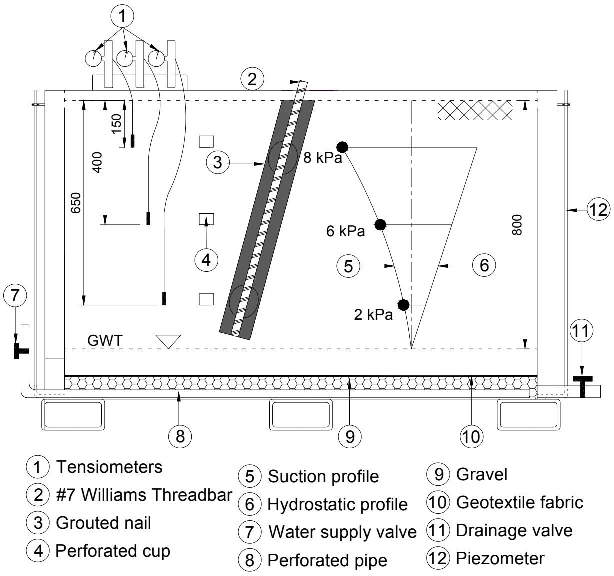

Figure 3. Section through the text box along with the matric suction profile

6 EXPERIMENTAL RESULTS

6.1 Determination of the soil-water characteristic curve (SWCC)

The SWCC was determined for use as a tool in the prediction of the pull-out capacity of soil nails, installed in unsaturated soils. The SWCC (drying curve) was plotted as a relationship between the degree of saturation, S and matric suction, $(u_a - u_w)$, by using three different methods:

i) Direct measurements from the test box
ii) Using the Tempe cell apparatus
iii) One-point prediction method, following the procedures outlined by Vanapalli and Catana (2005)

The details of each method are provided in Gurpersaud et al., 2010. There is a good comparison between the SWCCs using the three methods. The air-entry value is approximately in the range of 2.5 to 3 kPa from the three methods. There is a steep transition zone in the suction range of 3 to 10 kPa. Such behaviour is consistent with the nature of the poorly graded sand used in the research study.

6.2 Interface direct shear test

The interface friction angle (δ) between the compacted sand and grout was measured using the direct shear test apparatus. More details of this parameter are presented in Gurpersaud et al., 2010.

6.3 Laboratory pull-out test results

The results indicated a progressive increase in the pull-out capacity with the increase in matric suction within the transition zone (i.e. between the air entry value and the residual suction value). Results obtained from this study are consistent with test results obtained by Su et al. (2008) for completely decomposed granite with variation in the degree of saturation. A summary of the pull-out test results is presented in Table 2:

Table 2: Pull-out tests performed during the present study

Test No.	Nail inclination	Avg. matric suction (kPa)	Measured pull-out capacity (kN)
1	15° to vertical	0	1.98
2	15° to vertical	1	2.62
3	15° to vertical	2	2.85
4	15° to vertical	3.7	3.10
5	15° to vertical	5.3	3.42
6	15° to vertical	7	2.72
7	Vertical	0	1.69
8	Vertical	2	2.56
9	Horizontal	0	2.25
10	Horizontal	2	2.93

7 PROPOSED TECHNIQUE TOESTIMATE THE PULL-OUT CAPACITY OF SOIL NAILS

The proposed method to estimate the pull-out capacity or soil nails in unsaturated soils is an extension of the β method used to estimate the shaft capacity of piles (Vanapalli et al., 2010). The ultimate unit shaft skin friction (f_s) is expressed as below:

$$f_s = c' + \beta\sigma'_z \qquad [1]$$

where: c' = effective cohesion intercept; β = Bjerrum-Burland coefficient and σ'_z = effective overburden stress

$$\beta = K_0 \tan(\delta + \psi) \qquad [2]$$

where: K_0 = coefficient of lateral earth pressure; d = interface friction angle and ψ = dilation angle.

The main variable is the estimation of the β value by using an analytical method (Figure 4). Results obtained by Vanapalli et al. (2010) showed a similar variation of the β values used to estimate the shaft capacity of jacked steel tube piles. There is a wide range of recommendations for β values which can be found in the literature (McClelland, 1974; Meyerhof, 1976; Briaud and Tucker, 1997). Factors which influence the β value are in-situ stress conditions, frictional resistance, compressibility of the soil, nail type, shape and mode of installation.

The results were re-evaluated by using an empirical approach, where the computed β value for a vertical element under saturated conditions was applied to all orientations of the nail in this study (i.e. vertical, inclined at 15° and horizontal). For the case of the soil being in a state of unsaturated condition prior to nail pull-out, β values were increased by a factor of two. This increase in the β value is directly related to the changes in in-situ stress conditions and higher grout to ground adhesion due to the contribution of matric suction. The β values were estimated as shown below in eq. [3] and eq. [4].

$$\beta_{sat} = K_0 \tan(\delta + \psi) \qquad [3]$$

$$\beta_{us} = 2 \times \beta_{sat} \qquad [4]$$

The ultimate capacity of soil nails placed in saturated condition can be expressed as follows:

$$Q_f = f_s A_s = (c_a + \beta_{sat}\sigma'_z)\pi dL \qquad [5]$$

where: c_a = soil adhesion; L = length of nail, d = diameter of nail

Assuming a linearly increasing stress distribution along the nail, the average vertical stress can be estimated as $\sigma'_z = \gamma' L/2$, in which γ' is effective unit weight of the soil. A general equation for estimating pull-out capacity of grouted soil nails in unsaturated soils is given below:

$$Q_{f(us)} = \left[(c_a + \beta_{us}\sigma'_z) + (u_a - u_w)(S^{\kappa})\tan(\delta + \psi)\right]\pi dL \qquad [6]$$

The fitting parameter κ value equal to 1 can be used for non-plastic soils such as sands (Vanapalli and Fredlund, 2000).

The grout-soil interface shear strength in the unsaturated zone was taken into account to evaluate the contribution due to matric suction as follows (Hamid and Miller, 2009):

$$Q_{(u_a - u_w)} = \tau_{us} \times A_s \qquad [7]$$

where: τ_{us} = shear strength of unsaturated soils; A_s = surface area of nail in the unsaturated zone

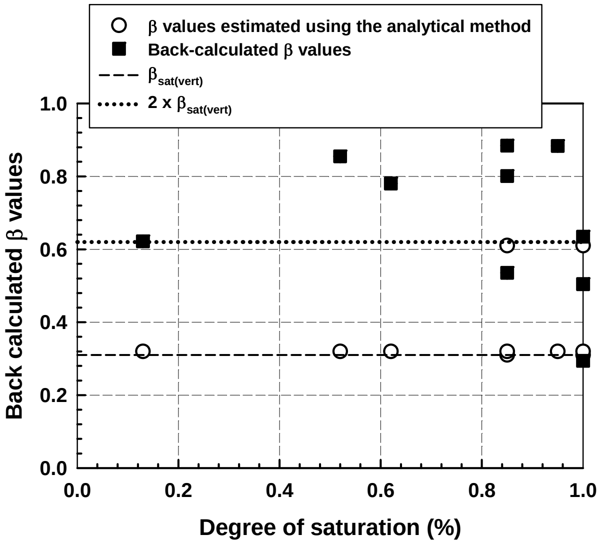

Figure 4. Comparisons of estimated β values using the analytical and empirical methods

The contribution due to matric suction $Q_{(u_a - u_w)}$ was estimated by extending the approach proposed by Vanapalli et al. (1996) and Fredlund et al. (1996) for predicting the shear strength of unsaturated soils. This equation utilizes the SWCC as a tool for predicting the shear strength of unsaturated soils, along with the effective shear strength parameters, κ.

8 ANALYSIS OF TEST RESULTS USING THE PROPOSED TECHNIQUE

The lower pull-out capacity at an average suction of 7 kPa (Table 2) can be attributed to the soil approaching residual stage of desaturation. In the residual stage of desaturation, the shear strength generally decreases, especially for sand and silts (Vanapalli et al., 1996; Vanapalli et al., 1998). The water content in the residual stage is typically low for sands and silts and may not transmit suction effectively to the soil particle or aggregate contact points.

The influence of dilatancy was taken into account by adding the dilation angle (ψ) to the interface friction angle (δ). The dilation angle was calculated based on results obtained from the interface direct shear test. A dilation angle of 4.3° was obtained from the vertical displacement versus the horizontal displacement during the interface direct shear test. Dilatancy effects are predominant under low stresses and can be accounted by increasing the internal friction angle, ϕ' (or δ – interface friction angle) by 10 to 15% (Steensen-Bach et al., 1987; Oh and Vanapalli, 2011). The Danish Code of Practice (DS 415) recommends that the dilation angle can also be estimated by using 10% of the value of the angle of internal friction irrespective of the relative density. A similar approach was also adopted by Vanapalli and Mohamed (2007); Oh and Vanapalli (2010) for the interpretation of the bearing capacity of unsaturated sands.

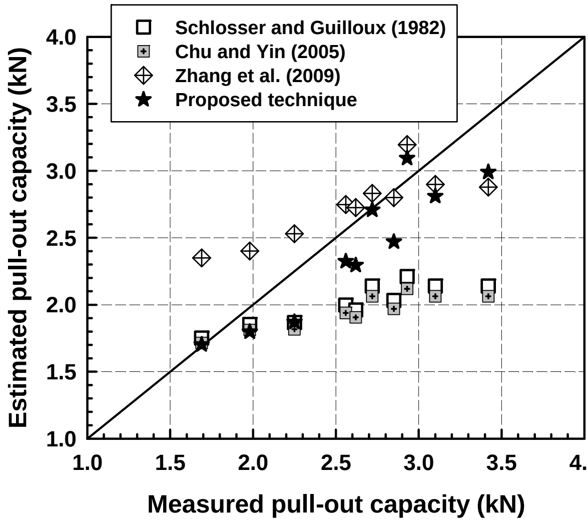

Figure 5. Comparison between the estimated and measured values for the test nails by using the proposed technique and other methods available in the literature

The technique proposed in section 7 produced a good match with the measured pull-out capacities in comparison with other methods available in the literature as indicated in Figure 5.

The proposed technique was used to analyze results obtained by Pradhan (2003) for pull-out testing of soil nails installed in completely decomposed granite (CDG). A reasonably good match is obtained by using the proposed technique as illustrated in Figure 6.

9 DISCUSSION OF RESULTS

A gradual increase in the pull-out capacity is evident from a low suction value (i.e. 1 kPa) up to 5.3 kPa followed by a decline at an average suction value of 7 kPa (i.e. soil approaching residual conditions). A decrease in pull-out capacity with the degree of saturation and hence decreasing matric suction from the optimum moisture content to the saturated condition was also observed by Pradhan (2003) and Chu and Yin (2005). Pradhan (2003) contended that the behaviour in the pull-out capacity is related to the decrease in apparent soil cohesion. The decrease is the soil cohesion is also directly related to the reduction in matric suction.

A strong relationship exists between the SWCC and the pull-out capacity with respect to matric suction (Gurpersaud et al., 2010). This relationship demonstrates a linear increase in the pull-out capacity up to the air-entry value, followed by a non-linear increase. The behaviour of the pull-out capacity matches the different phases of the SWCC where a gradual increase in strength occurs in the boundary effect zone and the transition zones (i.e. primary and secondary), followed by a decline in the residual zone (i.e. average matric suction of 7 kPa). The behaviour of the pull-out capacity of soil nails with matric suction resembles the behaviour of the shear strength of unsaturated soil during the different phases (i.e. boundary effects zone, transition zone and residual phase).

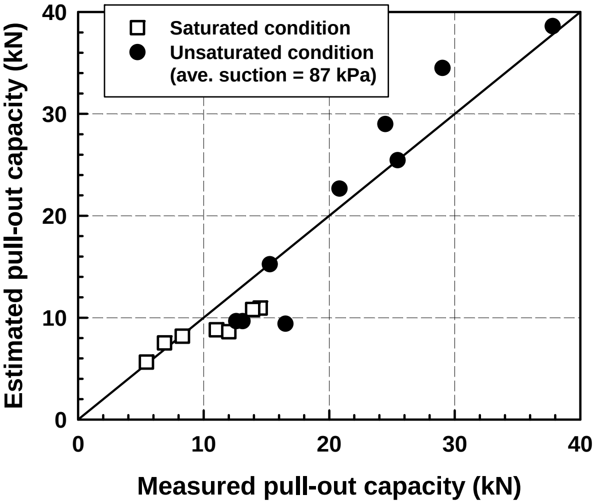

Figure 6. Comparison between estimated and measured pull-out capacity (Pradhan, 2003)

10 SUMMARY AND CONCLUSIONS

In this paper, a comprehensive experimental program was undertaken to determine the pull-out capacity of soil nails in both saturated and unsaturated compacted coarse-grained soil using specially designed equipment in a laboratory environment. The pull-out capacity of soil nails under unsaturated conditions increases almost linearly up to the air-entry value. There is a non-linear increase in the pull-out capacity beyond the air-entry value. The measured pull-out capacity of the soil nails used for this study in the compacted coarse grained soil under unsaturated conditions was found to be 1.3 to 1.7 times higher than the pull-out capacity under saturated conditions. In addition, these results show that there is a strong relationship between the SWCC and the pull-out capacity of soil nails installed in the coarse-grained soil used for this research program. A simple technique was proposed to predict the variation of pull-out capacity with respect to matric suction by using the average matric suction value and the saturated shear strength parameters (c' and ϕ').

The proposed technique was compared with other equations available in the literature by evaluating the test results from the present study. A reasonably good match to the measured values was obtained by using the proposed technique in comparison with other methods available in the literature. Additionally, data available in the literature was evaluated to verify the application of the proposed technique. The analysis shows that the technique provides estimated values which are close to the measured values for completely decomposed granite (CDG). However, additional testing and analysis is required to verify the suitability of this technique for other soil types.

The results of this experimental program suggest that conventional procedures for the estimation of the pull-out capacity of soil nails used in the engineering practice is conservative when it is applied to unsaturated soils.

ACKNOWLEDGEMENTS

The authors are extremely grateful for the significant support provided by Geo-Foundations Contractors Inc., Acton, Ontario for the execution of this research study. Additional support was provided by the Natural Sciences and engineering Research Council through its discovery grants program, Stan Conley and other members of the Civil Engineering Laboratory at Carleton University for providing the required instrumentation and technical support throughout the testing program. The help received from Jean Claude Celestin and Dr. Won Taek Oh is also greatly appreciated.

REFERENCES

American Petroleum Institute (API). 1990. 13B-1 Recommended standard procedure for field testing water-based drilling fluids, API, Dallas.

Barbour, S.L. 1999. Nineteenth Canadian Geotechnical Colloquium: The soil-water characteristic curve - A historical perspective. *Canadian Geotechnical Journal* 35: 873–894.

Briaud, J.L. and Tucker L. 1997. Design and construction guidelines for downdrag on uncoated and bitumen-coated piles. Report 393, National Cooperative Highway Research.

Canadian Foundation Engineering Manual. 2006. Canadian Geotechnical Society, Richmond, British Columbia.

Cartier, G. and Gigan, J.P. 1983. Experiments and observations on soil nailing structures. Proceedings of the 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, 473-476.

Chu, L. M. and Yin, J.H. 2005. Comparison of interface shear strength of soil nails measured by direct shear box tests and pullout tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(9): 1097-1107.

DS415. 1984. The Danish code of practice for foundation engineering. Danish Society of Civil Engineering.

FHWA. 1993. Recommendations clouterre 1991 (English translation). Report on the French national research project clouterre, FHWA-SA-93-026. Federal Highway Administration, Washington, DC.

Franzen, G. 1998. Soil nailing - a laboratory and field study of pull-out capacity. PhD dissertation, Department of Geotechnical Engineering, Chalmers University of Technology, Goteborg, Sweden.

Fredlund, D.G. and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley and Sons Inc., New York.

Fredlund, D.G., Xing, A., Fredlund, M.D. and Barbour, S.L. 1996. Relationship of the unsaturated soil shear strength to the soil-water characteristic curve. *Canadian Geotechnical Journal*, 33(3): 440–448.

Gurpersaud, N., Vanapalli, S.K. and Sivathalayan, S. 2010. Influence of matric suction on the pull-out capacity of grouted soil nails. Proceedings of the 63rd Canadian Geotechnical Conference, 12-16 September, 2010, Calgary, AB,1748-1755

HA68/94. 1994. Design methods for the reinforcement of highway slopes by reinforced soil and soil nailing technique. Road Authorities in England, Welsh, Scotland and Northern Ireland.

Hamid, T. and Miller, G.A. 2009. Shear strength of unsaturated soil interfaces. *Canadian Geotechnical Journal*, 46(5): 595-606.

Heymann, G., Rohde, A.W., Schwartz, K. and Friedlaender, E. 1992. Soil nail pull-out resistance in residual soils. Proceedings of the International Symposium on Earth Reinforcement Practice, Fukuoka, Japan, 487-492.

Jewell, R.A. and Wroth, C.P. 1987. Direct shear tests on reinforced sand. *Géotechnique*, 37:53-68.

Jewell, R.A. 1990. General Report – Soil Nailing. Proceedings of the International Reinforced Soil Conference, Glasgow, 197-202.

Junaideen, S.M., Tham, L.G., Law, K.T., Lee, C.F. and Yue, Z.Q. 2004. Laboratory study of soil-nail interaction in loose completely decomposed granite. *Canadian Geotechnical Journal*, 41(2): 274-286.

Khalili, N. and Khabbaz, M.H. 1998. A unique relationship for χ for the determination of the shear strength of unsaturated soils. *Géotechnique,* 48(5): 681–687.

McClelland, B. 1974. Design of deep penetration piles for ocean structures. Journal of Geotechnical Enineering Division ASCE 100(GT 7): 705-747.

Mecsi, J. 1997. The load bearing capacity and the load elongation diagram of soil anchors. Proceedings of the European Conference on Soil Mechanics and Foundation Engineering, Hamburg, 1327-1330.

Meyerhoff, G.G. (1976). Bearing capacity and settlement of pile foundations. *Journal of Geotechnical Engineering Division*, ASCE 102(GT3):195-228.

Mohamed, F.M.O and Vanapalli, S.K. 2006. Laboratory investigations for the measurement of the bearing capacity of an unsaturated coarse-grained soil. Proceedings of 59th Canadian Geotechnical Conference, October 1 – 4, 2006, Vancouver, B.C.

Öberg, A.L. & Sallfors, G. 1997. Determination of shear strength parameters of unsaturated silts and sands based on the water retention curve. Geotechnical Testing Journal, 20(1): 40–48.

Oh, W.T., and Vanapalli, S.K. 2011. Modelling the applied vertical stress and settlement relationship of foundations in saturated and unsaturated sands. *Canadian Geotechnical Journal*. 48(2):425-438

Potyondy, J.G. 1961. Skin friction between various soils and construction materials. *Géotechnique*, 11(4): 339.

Pradhan, B. 2003. Study of the pull-out behaviour of soil nails in completely decomposed granite fill. M.Pill thesis, The University of Hong Kong.

Pradhan, B., Tham, L.G., Yue, Z.Q., Junaideen, S.M., and Lee, C.F. 2006. Soil-nail pullout interaction in loose fill materials. *International Journal of Geomechanics*, 6(4): 238-247.

Schlosser, F. and Guilloux, A. 1982. “Le frottement dens les sols. Revue Francaise de.” *Géotechnique*. 16:65-77 (1981).

Sivakumar, G.L. and Singh, V.P. 2010. Soil nails field pull-out testing: evaluation and applications. *International Journal of Geotechnical Engineering*, 4: 13-21.

Steensen-Bach, J.O., Foged, N., and Steenfelt. J.S. 1987. “Capillary induced stresses – Fact or fiction?.” Proceedings of the 9th European Conf. on Soil Mechanics and Foundation Engineering, Budapest, August 31, 83-89.

Su, L.J., Chan, T.C.F., Shiu, Y.K., and Cheung, T. and Yin, J.H. 2008. Influence of degree of saturation on soil nail pullout resistance in compacted completely decomposed granite fill. *Canadian Geotechnical Journal*, 44(11): 1314-1328.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal,* 33(3): 379–392.

Vanapalli, S.K., Sillers, W.S., and Fredlund, M.D. 1998. The meaning and relevance of residual water content to unsaturated soils. Proceedings of the 51st Canadian Geotechnical Conference, Edmonton, pp. 101-108.

Vanapalli, S.K., and Fredlund, D.G., 2000. Comparison of different procedures to predict the unsaturated soil shear strength of unsaturated soils, Geo-Denver 2000. American Society of Civil Engineers, Geotechnical Special Publication. No. 99,195-209.

Vanapalli, S.K. and Catana, M.C. 2005. Estimation of the soil-water characteristic curve of coarse grained soils using one point measurement and simple properties. Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics June 27 – 29, 2005, Trento, Italy, 401-407.

Vanapalli, S.K. and Mohamed, F.M.O. 2007. Bearing capacity of model footings in unsaturated soils. Experimental Unsaturated Soil mechanics. Springer, New York, 483-493.

Vanapalli, S.K. 2009. Shear strength of unsaturated soils and its applications in geotechnical engineering practice. Keynote Address. Proceedings of the 4th Asia-Pacific Conference on Unsaturated Soils. New Castle, Australia. Nov. 23-25, 2009. Edited by O. Buzzi, S. Fityus and D. Sheng. 2010 Taylor & Francis Group, London , 579-598.

Vanapalli, S.K. and Oh, W.T. 2010. Bearing capacity of a compacted unsaturated fine-grained soil under constant water content conditions. Keynote address. 3rd International Conference on Problematic Soils, 7-9 April, 2010, Adelaide, Australia, editors Cameron, D.A and Kaggwa, pp. 35-52.

Vanapalli, S.K., Eigenbrod, K.D., Catana, C., Taylan, Oh, W.T. and Garven, E. 2010. A technique for estimating the shaft resistance of test piles in unsaturated soils. 5th International Conference on Unsaturated Soils, Barcelona, Spain. September 6-8, 2010. Paper accepted for publication.

Yin, J.H. and Su, L.J., 2006. An innovative laboratory box for testing nail pull-out resistance in soil. ASTM *Geotechnical Testing Journal*, 29: 1 – 11

Zhang, L.L., Zhang, L.M., and Tang, W.H. 2009. Uncertainties of field pullout resistance of soil nails. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(7): 966-973.