Influence of suction on the pull-out capacity of grouted soil nails

Naresh Gurpersaud[1,3], Sai K. Vanapalli[2] & Siva Sivathalayan[1]
[1]*Department of Civil Engineering, Carleton University, Ottawa, Ontario, Canada*
[2]*Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada*
[3]*Geo-Foundations Contractors Inc., Acton, 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 suction. In this paper, a comprehensive experimental investigation was undertaken, using a specially designed equipment to understand the influence of suction on the pull-out capacity of soil nails placed in compacted sand. The results of the study show that the pull-out capacity of soil nails is significantly influenced due to the contribution of suction. A methodology is proposed for estimating the variation of the pull-out capacity of soil nails with respect to suction. The soil-water characteristic curve (SWCC) along with the saturated shear strength parameters are required in the proposed method. The proposed technique is simple and will allow for better optimization of the grout-soil adhesion and provide a reasonable estimate of the pull-out capacity of soil nails.

RÉSUMÉ
La conception de systèmes de sol clouté dans la pratique géotechnique est basée soit sur la mécanique des sols conventionnelle, our sur des procédures empiriques ignorant l'influence de la succion. Dans cet article, un programme expérimental détaillé a été entrepris, en utilisant de l'équipement spécialement conçu, afin de comprendre l' influence de la succion sur la capacité. d'arrachement des clous enfoncés dans un sable compacté. Les résultats de l'étude démontrent que la capacité d'arrachement des clous est influencée de manière significative par la contribution de la succion. On propose une méthodologie pour estimer la variation de la capacité d'arrachement de clous en fonction de la succion. La courbe de rétention d'eau (SWCC) ainsi que les paramètres de la capacité de résistance pour le sol saturé sont requis par la méthode proposée. La technique proposée est simple et permet de mieux optimiser l'adhésion sol-clou et fournir un estimé raisonnable de la capacité d'arrachement des clous.

1 INTRODUCTION

Soil nailing is a widely used ground stabilization technique for geotechnical engineering applications, utilizing passive elements (referred to as nails) for retaining soils and reducing soil movements. Typically soil nails are subjected to tension as movement of the retained soil occurs. The resisting tensile forces are generated into the ground through friction, mobilized at the grout/nail interface (Hong et al., 2003; Chu and Yin 2005; Su et al. 2008). 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 are utilized increasingly in recent years based on its technical and economic advantages. The equipment used for soil nailing facilitates quick and easy construction and contribute to significant savings (Powell and Watkins, 1990).

Soil nailing applications are best suited for their placement above the ground water table, where the soil is in a state of unsaturated condition. In most cases, soil nailed structures do not become saturated during their design service life and hence the mechanics of unsaturated soils should be used in the design of these structures. The changes in pore water pressures, which are sensitive to ground surface flux boundary have a significant influence on the mechanical behaviour of unsaturated soils (Fredlund and Rahardjo, 1993).

In this research program, the pull-out capacity of soil nails embedded in saturated and unsaturated compacted coarse grained soil were evaluated. Results obtained from this research program were analyzed to propose a framework for the interpretation of pull-out capacity by considering the influence of suction. In addition, a technique is proposed for predicting the pull-out capacity of soil nails with respect to suction. The soil-water characteristic curve (SWCC) along with the saturated shear strength parameters were used in the analysis. The present understanding of shear strength of unsaturated soils has been extended for the interpretation and prediction of the behaviour of soil nails (Vanapalli, 2009).

2 BACKGROUND

Limit equilibrium methods are typically used to estimate the total soil nail force required to achieve a specified factor of safety (Junaideen et al. 2004). Pull-out capacity is a key parameter for the design of soil nails. A factor of safety of three is generally used to calculate the allowable load for soil anchors based on the estimated capacity (CFEM, 2006). In most cases, the estimated pull-out capacity is 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 (Chai et al., 2004; Junaideen et al., 2004; Chu and Yin, 2005; Pradhan et al., 2006). However, the influence of suction on the pull-out capacity of soil nails did not receive significant research attention (Su et al., 2008; Zhang et al., 2009).

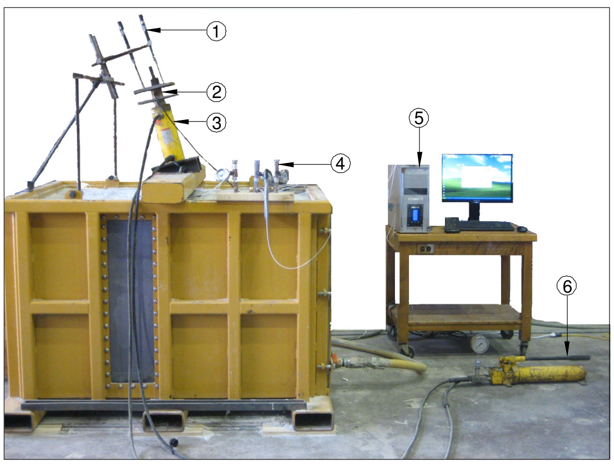
3 EQUIPMENT AND METHODOLOGY

3.1 General

Figure 1 illustrates the test box and set-up for testing. A test box was specially designed to serve the following objectives of this study:

i) To evaluate the contribution of suction towards the pull-out capacity of soil nails in compacted coarse-grained soil, under saturated and unsaturated conditions.
ii) To investigate the relationship between the (SWCC) and the pull-out capacity of soil nails in unsaturated soils.

The test box was constructed to internal dimensions of 1.5 m x 1.2 m in plan and 1.1 m in depth. Plumbing fixtures were added to simulate saturated and unsaturated conditions of the soil. Water supply and drainage valves were used to adjust the water table to the desired level within the box.



① LVDT ③ Jack ⑤ Computer with DAQ
② Load Cell ④ Tensiometer ⑥ Hydraulic pump

Figure 1. Test box and set-up for pull-out testing of nails

3.2 Details of equipment

The key features of the equipment are summarized as follows:

A clear distance of 5.5 times the diameter of the nail was achieved from the sides of the test box, thereby avoiding the influence of boundary effects during pull-out testing (Yin and Su, 2006). Materials used for the construction of the box consisted of 63.5 mm x 63.5 mm x 9.5 mm thick hollow steel section (HSS) as the frame and stiffeners, 9.5 mm thick steel plates and 203 mm x 203 mm x 9.5 mm thick HSS, which formed the base of the box. The materials used for the construction of the box were rigid enough to function as an independent reaction frame.

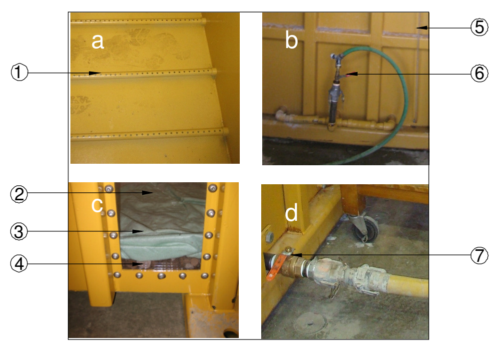
Sand was placed into the test box and compacted in layers of 150 mm with a 6.5 kg manual compactor. The compaction process was consistent for all the layers in the test box. An average dry density of 95% of the optimum was achieved.

A 330 mm x 870 mm x 25 mm thick transparent acrylic panel was installed within a section of the wall of the box to function as a window for observation. This window was used to observe changes in the water table.

Two piezometers comprising of 9 mm internal diameter transparent tubes were installed at diagonally opposite sides of the test box to monitor the elevation of the water table.

A 75 mm thick layer of clean aggregate was placed at the base area of the box and covered with a geotextile sheet. The geotextile fabric was used as a porous barrier between the soil and aggregate. The objective of this layer was to facilitate the free and gradual movement of water into the box. This barrier and gravel layer also facilitated the uniform saturation and de-saturation of the compacted sand, as desired by the testing requirements. Water was supplied to the box through a main line which then branched into three perforated pipes at the bottom of the box. A drainage pipe with a valve connected to the bottom of the test box was used to reduce the level of the water table. Both saturation and de-saturation conditions were achieved successfully from the bottom to the top of the soil surface by using this system. Several of the design features were improved on a similar test box that was designed and used by Mohamed and Vanapalli (2006), for determining the bearing capacity of model footings.

Figure 2 illustrates some key features of the test box.



① Perforated pipes ⑤ Piezometer
② Acrylic panel ⑥ Water supply valve
③ Geotextile fabric ⑦ Drainage valve
④ Gravel layer

Figure 2. Key features of the test box

3.3 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 suction. The hole was drilled to a depth of 800 mm from the surface of the compacted soil in the test box. The drilling process simulated the rotary method used in the field. 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).

3.4 Instrumentation

The applied force and displacement of the nail were recorded during the pull-out test through a data acquisition system (DAS). The DAS comprised of a NI PCI-6289 data logger and a NI SCB-68 channel box. Suction measurements were also taken during each pull-out test at various depths, relative to the location of the water table. 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. The HLP190 LVDT with a stroke length of 150 mm was used. This model was supplied with a spring loaded shaft, subjected to the fully extended position. The tensiometers used for the test program were soil moisture probe 2100F, having an operating range from -1 to 100 kPa to measure soil suction. Figure 3 illustrates some of the key instrumentation used for the test program.

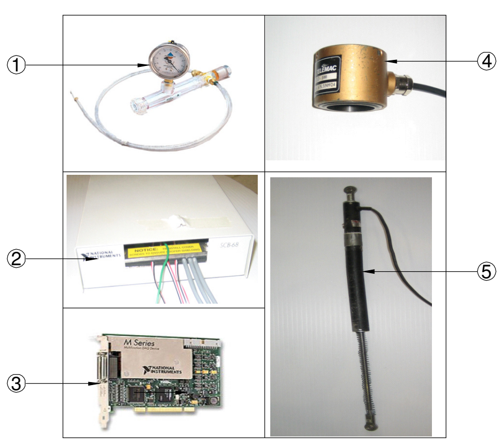


Figure 3. Instrumentation used for the test program

4 SOIL AND MATERIAL PROPERTIES

4.1 Soil Properties

The sand used can be classified as poorly graded sand as per the USCS. Some of the key properties of the sand are summarized in Table 1. The sand has approximately 1% of silt.

Table 1. Properties of the tested soil

PROPERTY	DESCRIPTION OR 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
Unified soil classification system (USCS)	SP
Soil friction angle (ϕ')	30.1^o
Grout–soil Interface friction angle (δ)	28.8^o
Dilation angle (ψ)	4.3^o

4.2 Nail Properties

Grouted soil nails of 100 mm diameter 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.

4.3 Grout Properties

Grout used for soil nails is typically neat cement grout, filling the annular space between the nail and ground. Type 10 Portland cement is generally used for most soil nailing applications. Grout characteristic has a strong influence on the ultimate bond strength at the grout-soil interface. According to Franzen (1998), grout characteristics will influence the nail surface area and the normal stress acting on the grouted nails. A grout mixture comprising of a water cement ratio of 0.45 was selected, which is also typical for most soil nailing application in the practice. The average compressive strength of the grout after 7 days was 28 MPa.

5 TEST PROGRAM

5.1 General

The objective of this study was to determine the pull-out capacity of soil nails in both saturated and unsaturated conditions, using prototype test nails in a laboratory environment. 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. The first test was performed under saturated condition and the later series tests under unsaturated conditions with average suctions of 1, 2, 3.7 and 5.3 kPa. Average suction of 1, 2, 3.7 and 5.3 kPa were achieved by water table depths of 150, 250, 550 and 800 mm respectively from the surface of the soil. The suction profile with the ground water table at 800 mm from the surface is illustrated in Figure 4.

5.2 Pull-out testing procedure

There are two general methods used to conduct the pull-out tests: displacement-rate controlled method and the force controlled method (FHWA, 1993). Displacement-rate controlled tests were used to establish the ultimate pull-out capacity of the test nails. Creep characteristics and a rough estimation of the peak capacity can be obtained from force-controlled tests. 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). Figure 2 shows the set-up used for pull-out testing of the nails. 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 Pull-out capacity under saturated condition

The compacted sand in the test box was saturated by gradually increasing the level of the water table from the bottom of the box. Gradual saturation was achieved from the aggregate layer at the bottom of box, such that water was advanced in an upward direction. This technique allowed the air from the compacted sand to be expelled at the surface. Readings from the tensiometers were zero when the water level reached the surface of the soil, confirming saturated condition (i.e., $u_a - u_w = 0$ kPa). The level of the water table was also verified by observing the stabilized level from both piezometers attached to the box.

5.4 Pull-out capacity under unsaturated conditions

The soil was saturated using a similar procedure as outlined in the previous section. The level of the water table was controlled by closely monitoring the stabilized level, as indicated by the piezometers. Suction value within the unsaturated zone was estimated based on the average of the three readings measured by the tensiometers. The gravimetric water contents were also measured by collecting specimens using small containers with perforations (Table 2.0). The small containers were embedded in the unsaturated zone and placed adjacent to the ceramic tip of the tensiometers. Figure 4.0 shows a cross-section of the test box, suction profile, locations of tensiometers and the small containers.

6 EXPERIMENTAL RESULTS

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

The SWCC was determined for use as a tool in the estimation 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 the suction, $(u_a - u_w)$, by using three different methods.

Table 2. Data from perforated cups embedded in the test box with the water table at 0.8 m from the surface

D (mm)	γ_t (kN/m^3)	e	w (%)	S (%)	AVR[1] $(u_a - u_w)$ (kPa)
150	15.8	0.73	5.6	20.2	8.0
400	16.9	0.73	12.4	45.0	6.0
650	18.8	0.72	24.2	89.3	2.0

[1]AVR = average value

D = depth from the soil surface of the test box (mm)
γ_t = total unit weight, kN/m^3
e = void ratio
w = gravimetric water content, %
S = degree of saturation, %
$(u_a - u_w)$ = matric suction, kPa

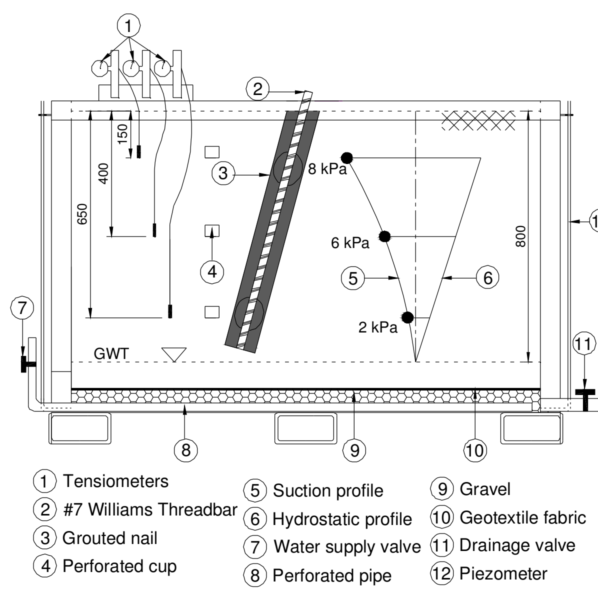


Figure 4. Section through the text box along with the suction profile

The first method for obtaining the SWCC entailed direct measurements from the test box. Cups with small perforations were used to obtain the water content from the box, as detailed in section 5.4. The corresponding suction for each water content measurement was taken by tensiometers. The gravimetric water content values were determined for the entire series of tests (i.e., 1, 2, 3.7 and 5.3 kPa average suction), after attaining equilibrium condition in the test box.

The second method was the direct measurement of the SWCC by using the Tempe cell apparatus in the laboratory. A pressure gauge with a sensitivity of measuring values of 0.2 kPa was connected to a pressure regulator. The drained water from the Tempe cell for different values of suction was collected in a bottle and its mass measured directly using an electronic scale.

The third method was a one-point prediction method, following the procedures outlined by Vanapalli and Catana (2005). This procedure can be used to estimate the SWCC for coarse-grained soils using parameters derived from the grain size distribution, volume mass properties and one measured point of suction versus gravimetric water content. For estimating the SWCC, the data set of water content (12.4%) and suction (6 kPa) was used.

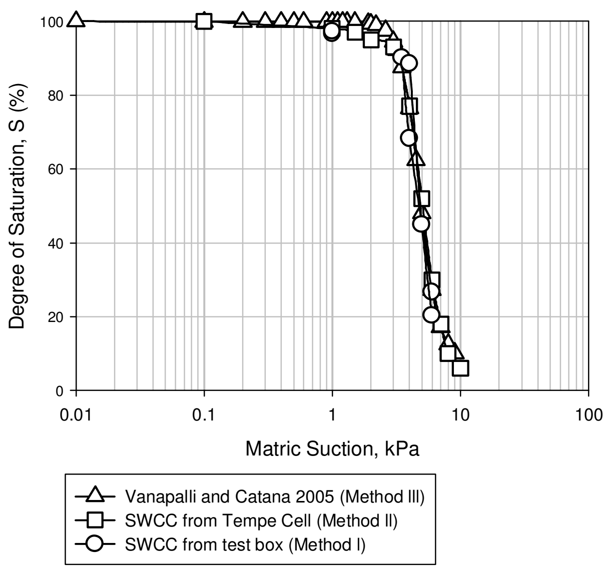


Figure 5. Measured and predicted SWCCs for the tested sand

There is a good comparison between the SWCCs using all the three different methods (Figure 5). The air-entry value is approximately in the range of 2.5 to 3 kPa from all the three methods. There is a steep transition zone in the suction range of 3 to 10 kPa. Such a behavior 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. This parameter was required for predicting the pull-out capacity of the soil nails in both saturated and unsaturated conditions. More details of this parameter are provided in a later section.

A dry sample of the sand was tamped into the bottom half of the direct shear box to a dry density value similar to the soil compacted in the test box. Cementitious grout was mixed at a water-cement ratio of 0.45 and poured into the upper half of the direct shear box and allowed to cure in place for 7 days. The sample was tested with the grouted section at the bottom. Shearing was done under saturated condition at a constant rate of 1.0 mm/min, which is the same rate used for pull-out testing of the soil nails. The results obtained for the residual shear stress is plotted in Figure 6, which shows a cohesion of 6 kPa. The residual values were used since the effect of dilatancy was also taken into account, in the analysis of the pull-out capacity of the nails.

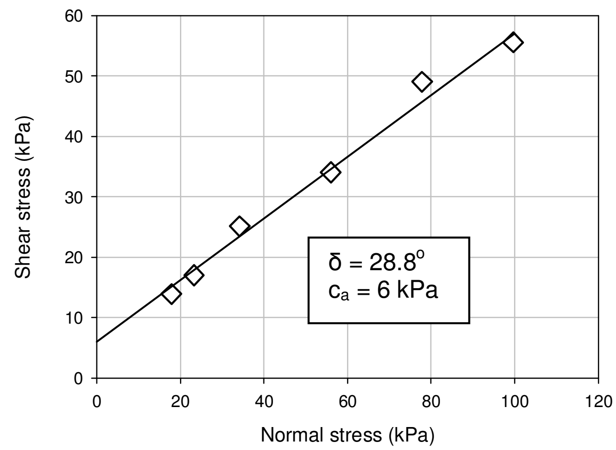


Figure 6. Interface direct shear test results

6.3 Laboratory pull-out test results

The results obtained from the laboratory pull-out tests were plotted to show the applied load against the displacement (Figure 7). The results indicated a progressive increase in the pull-out capacity with the increase in suction. Results obtained from this study are consistent with test results obtained by Su et al. (2008) for completely decomposed granite. There is a consistent trend in the post-peak pull-out capacity for cases where the soil experienced some level of suction.

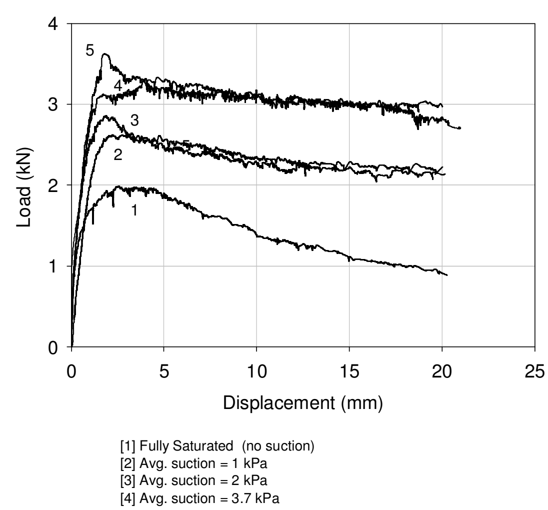


Figure 7. Load - displacement relationship under different average suction values

7 PROPOSED TECHNIQUE FOR ESTIMATION OF THE PULL-OUT CAPACITY OF SOIL NAILS IN BOTH SATURATED AND UNSATURATED SOILS

A detailed study was performed by Vanapalli et al. (2010), to investigate the influence of suction on the shaft capacity of jacked piles in coarse grained soils. The influence of suction towards the shaft capacity was significant: 35-40% of the total shaft capacity of silty sand. Using the results of this study, a technique was proposed to estimate the shaft capacity of piles in unsaturated coarse grained soils. In the present study, the equation proposed by Vanapalli et al. (2010) was modified to estimate the pull-out capacity of soil nails.

The general expression for pull-out capacity of soil nails in unsaturated sand, $Q_{f(us)}$, can be expressed as shown in equation [1]:

$$Q_{f(us)} = Q_f + Q_{(u_a-u_w)} \quad [1]$$

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

$$Q_{(u_a-u_w)} = \tau_{us} \times A_s \quad [2]$$

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

The contribution due to 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. The equation is provided below:

$$\tau = [c' + (\sigma_n - u_a)\tan\phi'] + (u_a - u_w)(S^{\kappa})(\tan\phi') \quad [3]$$

where: c' = effective cohesion, ϕ' = angle of internal friction, κ = fitting parameter used for obtaining a best-fit between the measured and predicted values and S = degree of saturation. The second part of equation [3] represents the shear strength contribution due to suction.

$$\tau_{us} = (u_a - u_w)(S^{\kappa})[(\tan\phi')] \quad [4]$$

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 follows:

$$f_s = c' + \beta\sigma'_z \quad [5]$$

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

$$\beta = k_\theta \tan(\delta + \psi) \quad [6]$$

where: k_θ = coefficient of lateral earth pressure with respect to nail inclination; δ = interface friction angle and ψ = dilation angle. The ultimate capacity of soil nails placed in saturated condition can be expressed as follows:

$$Q_f = f_s A_{surface} = (c_a + \beta\sigma'_z)\pi dL \quad [7]$$

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 $\sigma'_z = \frac{\gamma' L}{2}$, 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:

$$Q_{f(us)} = \left[(c_a + \beta\sigma'_z) + [(u_a - u_w)(S)^{\kappa}(\tan(\delta + \psi))]\right]\pi dL \quad [8]$$

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

8 ANALYSIS OF TEST RESULTS USING THE PROPOSED METHOD

The results obtained from pull-out test performed under saturated conditions and at average suctions of 1, 2, 3.7 and 5.3 kPa were analyzed by using the proposed method. The influence of suction on the pull-out capacity of the soil nails were significant even at low suction values of 1 and 2 kPa for the sand used in the present study.

The β value used in the analysis of the inclined nails was obtained by using the coefficient of earth pressure at rest (K_o) as recommended by CFEM (2006) and the interface friction angle (δ). The influence of the degree of inclination of the nail was taken into account and the K_o value was modified and referred as K_θ .

Dilatancy was also taken into account in the proposed method. The sand exhibited effects of dilatancy as indicated by results obtained from the interface direct shear test. The measured dilation angle was added to the interface friction angle as presented in equations [6] and [8]. A soil adhesion of 6 kPa was obtained from the interface direct shear test results (Figure 6). The soil adhesion value was based on the residual shear stress, since the effect of dilatancy was evaluated separately in the proposed technique. The peak values for the interface direct shear test were influenced by the effects of dilatancy.

9 DISCUSSION OF RESULTS

The pull-out capacity of soil nails in unsaturated condition is higher than the pull-out capacity of the same nail in a state of saturated condition (Figure 8). The SWCC (plotted on an arithmetic scale) and variation of the pull-out capacity with respect to matric suction is shown in Figure 8. This relationship demonstrates that there is a linear increase in the pull-out capacity up to the air-entry value, followed by a non-linear increase. There is a significant increase in the pull-out capacity of the nails due to the contribution of suction in the range from 1 to 5.3 kPa (i.e., the analysis is based on the average suction value in the proximity of the nail) for the tested coarse-grained soil. The trends of the pull-out capacity of soil nails in an unsaturated soil are similar to the shear strength behavior of unsaturated soils (Vanapalli et al., 1996).

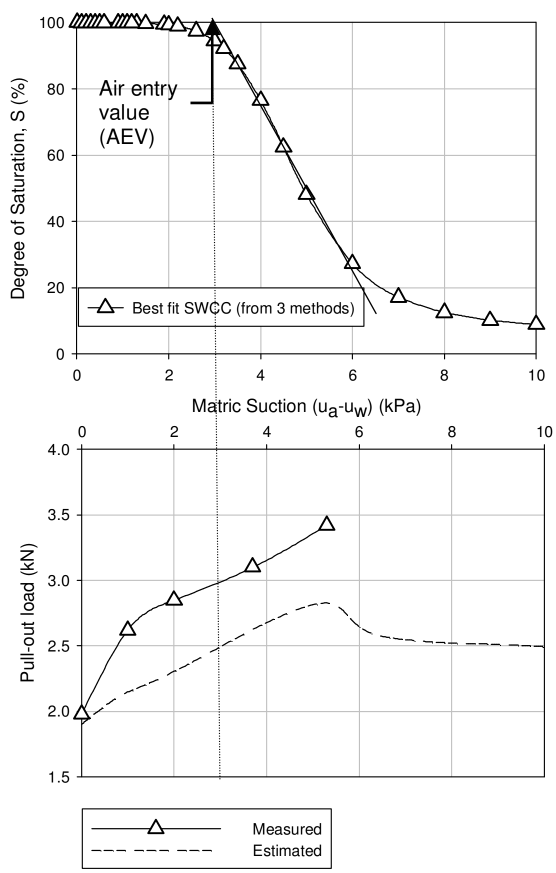


Figure 8. Variation of pull-out capacity with suction

The pull-out capacity of soil nails installed in compacted unsaturated coarse-grained soil measured in this study was observed to be 1.3 to 1.7 times higher than the pull-out capacity of the same soil under saturated condition. The results of this study are consistent with the observations of Zhang et al. (2009) and Su et al. (2008), who reported the pull-out capacity of soil nails in unsaturated soil to be significantly higher than the pullout capacity of the same soil under saturated conditions. A comparison of the measured and estimated values is presented in Figure 9.

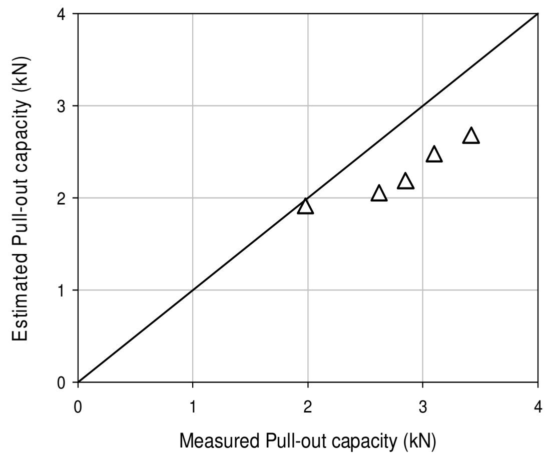


Figure 9. Comparison of measured and predicted pull-out capacity of soil nails

10 SUMMARY AND CONCLUSIONS

In this paper, an experimental program was performed 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 experimental studies demonstrate that suction has a significant influence on the pull-out capacity of soil nails in compacted, coarse-grained unsaturated soil.

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 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 fully 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. 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. The proposed technique is simple and also applicable to other geo-structural applications such as tie-backs, soil anchors and micropiles, embedded in unsaturated soils.

ACKNOWLEDGEMENTS

The authors are extremely grateful for the significant contribution provided by Geo-Foundations Contractors Inc., Acton, Ontario for the implementation of this research study. Instrumentation and technical support were provided by Stan Conley and members of the Civil Engineering Laboratory at Carleton University. The help provided by Jean Claude Celestin from the University of Ottawa Geotechnical Laboratory is also greatly appreciated.

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