THE INFLUENCE OF MATRIC SUCTION ON THE PULL-OUT CAPACITY OF GROUTED SOIL NAILS

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by

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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 better understand the influence of matric suction on the pull-out capacity of soil nails installed in compacted sand under both saturated and unsaturated conditions.

The testing program was undertaken in the laboratory using a specially designed test box with dimensions of 1.5 m x 1.2 m in plan and 1.1 m height. A single prototype soil nail was installed in the test box and tested under saturated and various average matric suction values. The size of the test box was sufficiently large to avoid influence of any boundary effects. The results of the study demonstrated that the pull-out capacity of soil nails is significantly influenced by the contribution of matric suction. The pull-out capacity of the tested nails under unsaturated conditions for the tested compacted sand ranged from 1.3 to 1.7 times higher in comparison to its capacity under saturated state.

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 with the pull-out test results and the soil-water characteristic curve (SWCC) for a series of nails pulled out at 15° using a wide range of matric suction values. A technique is proposed for the estimation of the pull-out capacity of soil nails by considering the influence of matric suction, nail inclination and dilatancy. The pull-out capacity can be predicted by using the saturated soil parameters (c' and ϕ') and the SWCC in the proposed model. Pull-out test data available in the literature for both saturated and unsaturated conditions were also

analyzed using the proposed technique. There is a reasonably good comparison between the measured and estimated pull-out capacity of soil nails tested in the present research program and also using the data from the literature.

The proposed technique is simple, allows for better optimization of the grout-soil adhesion and provides a better understanding of the long term performance of the pull-out capacity of soil nails in different environmental conditions.

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$(u_a - u_w)$	matric suction
$(\sigma_n - u_a)$	net normal stress
A_s	surface area of the nail
D_{eq}	equivalent width of flat reinforcement
K_s	coefficient of lateral earth pressure
$Q_{(u_a-u_w)}$	capacity of soil nails due to the contribution of matric suction
Q_f	capacity of soil nails installed in saturated soils
$c^{'}$	soil cohesion
c_a	soil adhesion at the grout/soil interface
d_i^d	minimum grain diameter of the corresponding fraction
d_i^g	maximum grain diameter of the corresponding fraction
k_θ	coefficient of lateral earth pressure with respect to soil nail inclination
q_s	shaft capacity of piles
δ	interface friction angle
θ_s	saturated volumetric water content
μ^*	coefficient of apparent friction of soil ($\mu^* = \tan\phi^{'}$ and $c^{'}= 0$ for granular soil)
$\sigma_N^{'}$	effective normal stress
$\sigma_v^{'}$	vertical stress calculated at the mid-depth of the nail in the resistance zone
$\sigma_z^{'}$	effective overburden stress
τ_{us}	shear strength of unsaturated soils
$\phi^{'}$	angle of internal friction of soil
ϕ^b	the angle of shearing resistance with respect to matric suction
Δg_i	fraction weight in parts of the total weight
c_u	coefficient of uniformity

D	nail diameter (m)
d_e	dominant particle size diameter, *mm*
e	void ratio
f_b	coefficient of roughness
f_c	coefficient defined by c_a/c'
f_s	coefficient defined by δ/ϕ
L_s	embedment depth of soil nail (m)
m	soil parameter related to residual water content
n	soil parameter related to the slope at the inflection point of the SWCC
P	nail perimeter
S_r	residual degree of saturation
$T_{pull\text{-}out}$	failure load at which pull-out failure occurs (kN)
w_r	residual gravimetric water content
w_s	saturated gravimetric water content
w_w	gravimetric water content
ψ	dilation angle.
$C(\psi)$	correction factor that forces the SWCC through a suction of 1,000,000 kPa and zero water content.
S	degree of saturation
β	a combined shaft resistance factor
θ	volumetric water content
κ	fitting parameter used for obtaining a best-fit between the measured and predicted values.
λ	pull-out factor
χ	a parameter dependent on the degree of saturation (varies from 0 to 1)

LIST OF ABBREVIATIONS

ASTM	American Society of Testing Materials
CALTRANS	California Department of Transportation
SW	Well-graded sand
SP	Poorly graded sand
CDG	Completely decomposed granite
CFEM	Canadian Foundation Engineering Manual
CU	Consolidated undrained
DAS	Data Acquisition System
FHWA	Federal Highway Administration
GSD	Grain size distribution
GWT	Ground-water table
HAED	High Air Entry Disk
HSS	Hollow Steel Section
LVDT	Linear Variable Displacement Transducer
NATM	New Austrian Tunneling Method
M	Silty sand
SPT	Standard penetration test
SWCC	Soil-water characteristic curve
TYP	Typical
USCS	Unified soil classification system
WWM	Welded wire mesh

CHAPTER 1

INTRODUCTION

1.1 Statement of the problem

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. The soil nails are typically subjected to tension when the retained soil moves. The fundamental design principle of soil nails consists of transferring the resisting tensile forces generated in the soil nails into the ground through friction, mobilized at the grout/soil interface. 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.

The soil nailing technique has been found to be suitable for excavation shoring, tunnel portals, slope stabilization, bridge abutments and several other civil engineering projects. Soil nails have been utilized increasingly in recent years due to 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 placement above the ground water table, where the soil is in a state of unsaturated condition. Approximately 33% of the earth's surface constitute of arid or semi-arid regions where the soils are typically unsaturated (Dregne, 1976). Compacted soils and soils in regions other than arid and semi-arid regions are also found 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 without considering the contribution of 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 structures 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 changes in pore water pressures, which are sensitive to ground surface flux boundary (i.e. net infiltration or net evaporation at the ground surface) have a significant influence on the mechanical behavior of unsaturated soils (Fredlund and Rahardjo, 1993). In other words, the influence of negative pore water pressures in the vadose zone also plays an important role on the load carrying capacity of soil nails. The difference between the pore air pressure, u_a (which is typically equal to atmospheric pressure conditions) and the pore water pressure, u_w in unsaturated soils is known as matric suction, $(u_a - u_w)$.

Vanapalli (2009) summarized the developments over the past 50 years of our present understanding of the shear strength behavior of unsaturated soils and their applications in geotechnical engineering practice. The developments over this period are significant but a lack of simple techniques was discouraging for practicing engineers in the implementation of the present understanding related to the shear strength of unsaturated soils. Determination of the shear strength of unsaturated soils is time consuming and requires trained personnel and elaborate testing equipment. Several factors such as the soil type, soil gradation, stress state, soil structure, density, rate of strain, stress state and soil mineralogy influence the shear strength of unsaturated soils. 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 (Fredlund et al., 1996; Vanapalli 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. Measurement of the SWCC is typically performed with a pressure plate in low suction and vapor pressure technique in high suction range (Fredlund and Rahardjo, 1993; Vanapalli et al., 2004). The present understanding of shear strength of unsaturated soils can be extended for interpretation and prediction of the behavior of soil nail structures.

The pull-out capacity is a key parameter for the design of soil nails. 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). There are no specific design procedures or method of estimation for the pull-out capacity of soil nails in the Canadian Foundation Engineering Manual (2006). However, the manual specifies that the allowable load for soil anchors should be reduced by a factor of three based on the estimated capacity. 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 behavior of the soil/nail interface during pull-out (Chai et al., 2004; Junaideen et al., 2004; Chu et al., 2005; Yin et al., 2006; Pradhan et al., 2006; Zhou et al., 2007; Zhou et al., 2008, 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). It was reported by Zhang et al. (2009) 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 research program, the pull-out capacity of soil nails in saturated and unsaturated compacted coarse grained soil was evaluated. The test program implemented for this research study was performed in a specially constructed test box. A series of tests were performed to investigate the influence of matric suction on the pull-out capacity of soil nails. The testing of prototype soil nails under varying suction values was considered meaningful towards better understanding of the pull-out resistance behavior. Results obtained from this research program were analyzed to propose a framework for the interpretation of pull-out capacity in both saturated and unsaturated soils by using the modified β method (Vanapalli et al., 2010).

1.2 Objectives of the thesis

The key objectives of this research study are as follows:

i) To design and construct a test box for the testing of prototype soil nails.

ii) 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 by undertaking a comprehensive experimental program.

iii) To investigate the relationship between the soil-water characteristic curve (SWCC) and the pull-out capacity of soil nails in unsaturated soils.

iv) To propose a framework for the interpretation of the pull-out capacity of soil nails in compacted coarse grained soils based on the experimental program implemented for this research.

v) To develop a technique for reliably predicting the pull-out capacity of soil nails installed in saturated and unsaturated coarse-grained soils.

vi) To verify the proposed approach for other pull-out test results published in the literature.

1.3 Scope of the thesis

A comprehensive experimental program was undertaken using a coarse grained soil in a test box to evaluate the pull-out capacity of prototype soil nails. The test nails were installed vertically, horizontally and at 15° to the vertical in both saturated and unsaturated conditions. A complete series of pull-out test was performed with nails installed at 15° to the vertical in order to capture the variation in the pull-out capacity with the SWCC. This angle of inclination was selected since it was more convenient to assess the variation of matric suction over a wider range within the specially designed test box. The generalized technique can also be applied to all nail inclinations. Commercial tensiometers were located in the unsaturated zone to measure the suction values. A methodology was proposed for estimating the average suction variation within the test box for each pull-out test. The results obtained from the experimental program were used to develop a technique to predict the pull-out capacity of soil nails in both saturated and unsaturated soils by using the modified β method.

1.4 Outline of the thesis

The research program undertaken is summarized in this thesis under seven main chapters. These chapters are organized as follows:

This Chapter, "Introduction" summarizes the background information and provides details of the key elements of the research program.

Literature review forms the second chapter in which a detailed review of soil nail pull-out capacity, interface behavior and the mechanics of unsaturated soils are succinctly summarized. General background of soil nailing technique, applications, behaviour, mechanism and factors influencing the pull-out capacity are also included in this chapter. Additionally, methods used to estimate the pull-out capacity of soil nails and previous research where matric suction was considered are summarized.

The third chapter entitled, "Theoretical background" presents an overview of equations and concepts related to the SWCC, shear strength of unsaturated soils, unsaturated soil interfaces and other factors that contributes towards the pull-out capacity of soil nails.

Equipment design forms the fourth chapter of the thesis. In this chapter, details of the specially constructed test box, instrumentation and materials that were utilized for this research program are outlined.

The fifth chapter is titled "Testing program and results," where the testing procedures are presented along with the results obtained.

The sixth chapter is comprised of the "Discussion of the test results," where a detailed evaluation of the results is provided. The measured and estimated results from the proposed technique are compared. The technique proposed to estimate the pull-out capacity of soil nails, in both saturated and unsaturated coarse grained soils was used to analyze other test results found in the literature.

Chapter seven presents the "Summary and conclusions" of this research program along with recommendations for future research.

Appendix - A paper published from this research

CHAPTER 2

LITERATURE REVIEW

2.1 Soil nailing

Soil nailing technique has been extensively used in recent years for several geotechnical projects such as excavations support, slopes and retaining walls stabilization and bridge abutments. The success stories of different projects have encouraged several research studies in various parts of the world to explore the use of soil nails for addressing other geotechnical problems (Banyai, 1984; Ortigao et al., 1990; Gassler, 1990; Barley, 1992; Bruce and Jewell, 1986; Chu and Yin, 2005; Su et al., 2008; Sivakumar and Singh, 2010).

The two key engineering considerations in the design of soil nails are the pull-out capacity of the nails and how the interface friction develops during various stages of loading. Soil nails are typically placed in a zone where the soil is in a state of unsaturated condition. Therefore, the engineering behavior of soil nails is significantly influenced by matric suction. However, the influence of matric suction on the pull-out capacity did not receive much research attention (Su et al., 2008 and Zhang et al., 2009).

In this chapter, a brief review of the soil nailing concepts is provided along with discussions on techniques used for estimating the pull-out capacity. In addition, the need for using the mechanics of unsaturated soils towards the rational interpretation of soil nails behavior and developing a simple technique for its estimation is justified.

2.1.1 Historical background

The soil nailing technique was developed as an extension of the New Austrian Tunneling Method (Rabcewicz, 1964, 1965). The first recorded application of soil nailing was completed in France in 1972 (Singala, 1999). The soil nailing projects were completed in shorter periods of construction compared to conventional methods and proven to be cost-effective. Some of the pioneering work in this research field was conducted in Germany from 1975 to 1981 by the University of Karlsruhe and Bauer Construction Company (Lazarte et al., 2003). The French engineers have also significantly contributed to this field through a major experimental program called "Clouterre" between 1986 and 1990. The main objectives of the Clouterre program were to provide better understanding of the soil nail walls behavior and their limitations in addition to providing elaborate design recommendations including dimensioning (Plumelle et al., 1990).

The first documented application of soil nailing in North America was the support of a 13.7 m deep foundation excavation in dense silty lacustrine sand for a project in Portland, Oregon, USA in 1976 (Bryne et al., 1998). This project was completed in approximately half the time in addition to contributing to 15% of savings in comparison to the cost of conventional support systems.

2.1.2 The soil nailing concept

The main features of soil nails are as follows:

- Provides an increase in the normal force and hence the shear resistance of the soil is also increased along potential slip surfaces in frictional soils.

- The driving force along potential slip surfaces is reduced in both frictional and cohesive soils.

A facing is typically applied to soil nails by the application of shotcrete reinforced with welded wire mesh (WWM). Soil nails are installed horizontally or sub-horizontally the excavated soil or slope. The nails support the soil by resisting the destabilizing forces and increasing the normal loads on potential sliding surfaces. Figure 2.1 illustrates the soil nailing concept.

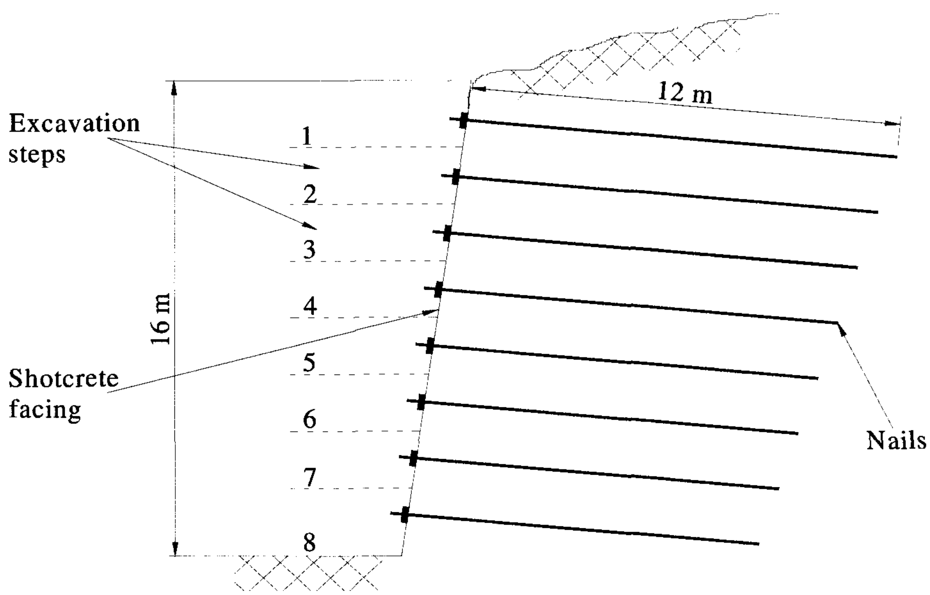

Figure 2.1 Soil nailing concept (modified after Bryne et al., 1998)

2.1.3 Applications of soil nailing

The soil nailing technique is well suited for several applications that require vertical or near vertical cuts. The following are some common applications where soil nail retaining walls have been successfully used (Porterfield et al., 1994; Bryne et al., 1998; Lazarte et al., 2003):

- Roadway cut excavations
- Widening under an existing bridge
- Tunnel portal cut stabilization
- Repair and construction of existing retaining structures
- Temporary or permanent excavations in an urban environment
- Slope stabilizations
- Bridge abutments

2.1.4 Ground conditions suitable for soil nails

The technique used for the construction of soil nails is dependent on the existing ground conditions at the site. In certain cases, a conventional method may be more appropriate and economical in comparison to soil nailing technique. For the economical implementation of soil nailing projects, the excavated ground should have the capacity to remain unsupported in a vertical or sloped cut of 1 to 2 m depth for a period of 1 to 2 days (Bryne et al., 1998). Soil nails are generally located above the ground water table to prevent sloughing and have a stable face after excavation. Therefore, the host soils for most soil nailing projects are predominantly placed in a state of unsaturated condition that has apparent cohesion from the contribution of matric suction. The standard penetration test (*SPT*) is a common method of identifying suitable soil profiles based on the '*N*' values obtained. The '*N*' value from the *SPT* is the number of blows required to achieve a penetration depth of 305 mm.

The following ground types are considered favourable for soil nailing applications (FHWA, 1991; Bryne et al., 1998; Lazarte et al., 2003):

- Stiff to hard fine-grained soils: Fine grained soils include stiff to hard clays, clayey silts, sandy clays and sandy silts.
- Dense to very dense granular soils with some apparent cohesion: These soils include sand and gravel with *SPT* - '*N*' values greater than 30 with some fines or with weak natural cementation that provide cohesion.
- Residual soils and weathered rock without zones of low strength structure.
- Glacial soils: Glacial outwash and glacial till materials are typically suitable for soil nailing applications as these soils are typically dense, well graded material with a limited amount of fines.

Soil nailing can also be utilized in the following intermediate soil conditions:

- Engineered fill: Soil nails can be installed in engineered fill consisting of a mixture of well graded granular material and fine grained soil with low plasticity.
- Residual soils: Residual soils can also be considered an acceptable material for soil nailing.

2.1.5 Components of a soil nail

The main components of a soil nail are: a steel tendon, centralizers and cementitious grout. Typical diameter of pre-drilled holes for soil nails range from 100 to 300 mm in diameter. Centralizers are used to keep the nail tendon in position in order to provide a minimum specified grout cover. A bearing plate is attached to the nail head and functions as the means for pressure transfer from the facing to the nail. Figure 2.2 shows the basic elements of a typical grouted soil nail.

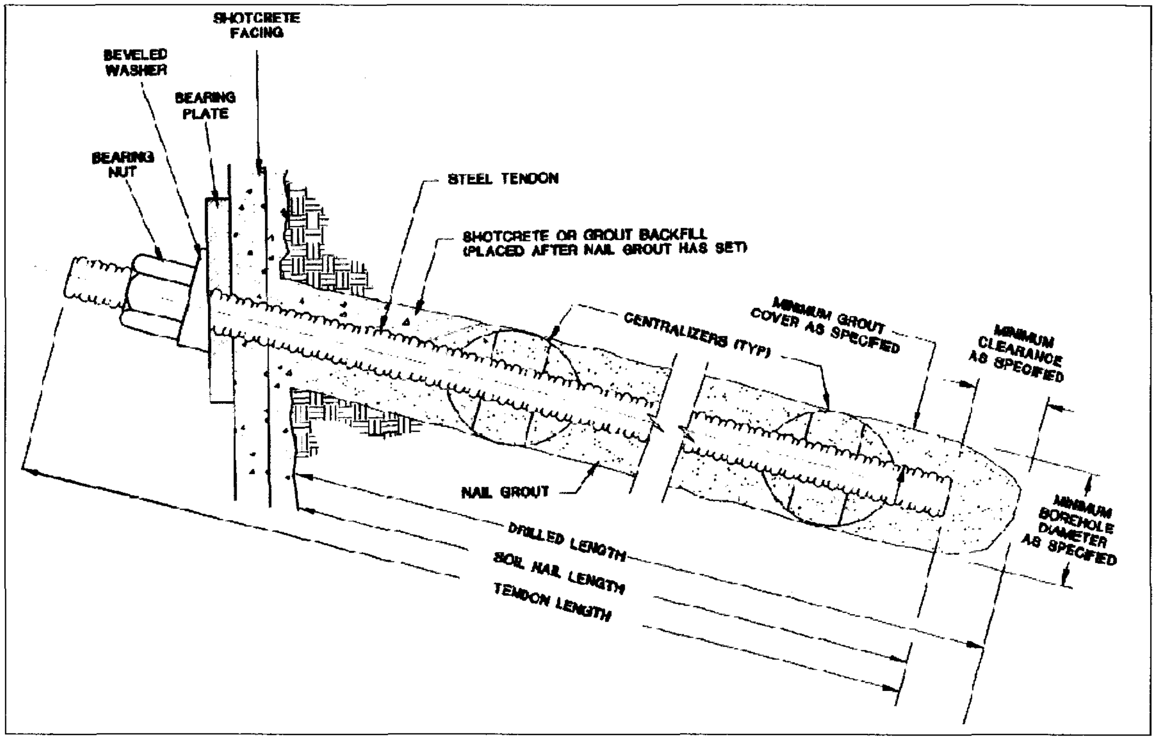

Figure 2.2 Details of a typical soil nail (Porterfield et al., 1994)

2.1.6 Effects of groundwater on soil nails

Soil nailing is generally not recommended for areas below the ground water table unless dewatering measures are assured both during construction and for the service life of the structure (FHWA, 1991). Stability problems will occur if soil nailing is performed below the ground water table due to flow of water through the structure. A detailed subsurface investigation is necessary to identify any lenses or pockets of granular soil filled with water, which can also lead to instability.

2.1.7 Design approaches for soil nail walls

The limit equilibrium design approach is typically used for the design of soil nail walls, where the total required reinforcing load to achieve a specified global safety margin is established (Junaideen et al., 2004). The design methods for soil nail structures are derived by extending conventional slope stability analyses approaches to include the tensile forces developed by the nails. Methods of analysis to assess the factor of safety along the assumed failure surfaces include the following:

German method: This method assumes a bilinear failure surface passing through the toe of the excavation. The failing soil mass can be broken into two parts namely, the nailed soil mass and the active earth pressure wedge behind the soil nailed wall. This method also considers the tensile resistance of the nails crossing the failure surface (Stocker et al., 1979).

Davis (Original Shen) method: A parabolic failure surface that passes through the toe of the wall is used for analysis by the Davis method (Shen et al., 1981). The sliding surface either passes entirely through the nails or intersects the ground surface somewhere beyond the reinforced zone. The pull-out resistance of the nails crossing the failure surface is considered as the governing stabilizing forces.

French method (Talren): This method assumes a circular failure surface passing through the toe of the wall. Shear and bending contribution of the nails are also considered in this method (Schlosser, 1982).

There are two more methods of analysis in the form of software packages namely, SNAIL design method by California Department of Transportation (CALTRANS) and the GoldNail design method by Golder Associates, both of which are more widely used (Bryne, et al., 1998). These two methods are considered as improvements to the previous methods since they design the soil nail wall as a system.

2.2 Pull-out behaviour of soil nails

Numerous field and laboratory tests have been performed to investigate the pull-out behaviour of soil nails by several investigators. These tests were fully instrumented and involved full scale models, modified direct shear box tests or pull-out tests. Pull-out testing studies on grouted soil nails were also conducted to investigate the interface shear strength (Franzen, 1998; Pradhan, 2003; Chu and Yin, 2005; Su et al., 2008; Sivakumar and Singh, 2010).

Design charts were proposed to estimate the pull-out capacity of gravity grouted and driven nails in various types of soils based on a number of field pull-out test results performed during the French National Research Project – "Clouterre" (FHWA, 1993). Several researchers also conducted studies to evaluate soil–nail interaction by using a large direct shear box (Barr et al., 1991; Davies et al., 1992) and laboratory pull-out tests

(Milligan et al., 1997; Franzen, 1998; Junaideen et al., 2004; Pradhan, 2003, Chu and Yin, 2005; Sivakumar and Singh, 2010). Milligan et al. (1997) attempted to study the effects of initial stress in the soil, grouting pressure and stress changes during the pull-out test. Franzen (1998) used a large scale laboratory setup to study the pull-out capacity of driven nails in dry, poorly graded, fine sand. Junaideen (2001) studied the behaviour of different types of embedded steel bars in completely decomposed granite soil and provided a framework for further investigation of grouted soil nails.

Pull-out failure as per the California Transportation Department (Caltrans, 1997) occurs when movement of the test nail increases without an increase in load or the creep rate exceeds 2 mm between 6 and 60 minutes. The pull-out test is widely used by designers and researchers since it is the simplest and also well established testing technique.

2.2.1 Mobilization of nail force

A small movement of the active zone in a soil nail structure will result in both axial and lateral displacement. The axial displacement will result in an axial force (tension force) in the nail. The mobilization of the axial stresses will occur in a progressive manner when the structure is loaded. Axial stresses will be limited by the maximum shear capacity which can be developed between the soil and the nail (Barley et al., 1997).

Load-displacement curves are conventionally used to determine the pull-out force during loading of soil nails. The pull-out capacity is dependent on the stiffness of the soil nail and the deformation properties of the soil. Studies conducted by Milligan et al.

(1997) indicated that the pull-out force of soil nails installed in fine-sand develop at relatively small displacements (between 1 to 5 mm). The small displacements are associated with the rapid mobilization of full interface shear strength. The interface shear strength remained constant or increased when nails were pulled further.

2.2.2 Pull-out capacity of soil nails

In most cases, the pull-out capacity of a soil nail is estimated based on previous experience with similar soil conditions and verified by pull-out test during the construction phase. The pull-out capacity for the preliminary design of soil nails is estimated based on analytical or empirical approaches and verified during the construction phase.

Chu and Yin (2005) highlighted the lack of data in the literature to understand the concepts of interface shear for soil nails. They suggested that the interface shear strength which is used to estimate the pull-out capacity of soil nails is approximately equal to the critical state shear strength of the soil. However, there may be variations in interface strength and the pull-out capacity due to uncertainties in the selection and verification of the shear strength parameters. The pull-out resistance of soil nails in Hong Kong is typically assumed to be the same as the shear strength of the soil.

There are several empirical or semi-empirical and analytical methods available in the literature to estimate the pull-out capacity of soil nails (Franzen, 1998). More details of these methods are discussed later in the Chapter.

2.2.2.1 Empirical approach

Several attempts have been made by researchers to correlate the pull-out capacity of soil nails with soil properties obtained from in-situ tests. A correlation between pull-out capacity and standard penetration test (*N* values) was done for soil nails in Brazil by Ortigao and Palmeria (1997). Heymann (1993) contended that the shear stress between nail and residual soil can be limited to 2*N* kPa. A correlation with pressuremeter tests were done for grouted and driven nails in various soils by Schlosser et al. (1991). Design charts were developed during the Clouterre program to provide preliminary estimates of the pull-out capacity of soil nails (FHWA, 1993).

2.2.2.2 Analytical approach

A number of researchers have suggested different approaches to analytically estimate the pull-out capacity of soil nails (Table 2.1). There are differences in the equations outlined in Table 2.1 but they are all based on four main variables: the normal stress acting on the nail surface (σ_n'), coefficient of friction between nail and soil (μ), adhesion between nail and soil (c_a) and nail perimeter (θ).

Table 2.1 The pull-out capacity of soil nails according to various researchers

References	Equations	Equation #
Zhang et al. (2009)	$T_L = \pi D\,[c' + (u_a - u_w)\tan\phi^b] + \dfrac{2D\,\sigma_v'\tan\phi'}{1 - \left[\dfrac{2(1+v)}{(1-2v)\,(1+2K_0)}\right]\tan\phi'\tan\psi}$	2.1
Chu and Yin (2005)	$T_L = Pc' + 2D\sigma_v'\tan\delta"$	2.2
Mecsi (1997)	$T_L = P\sigma_N' f_b \tan\delta$	2.3
HA68/94 (1994)	$T_L = \lambda(c' + \sigma_N' \tan\phi'$	2.4
Heymann et al. (1992)	$T_L = P(c' + \sigma_N'\ tan\,\phi')$	2.5
Jewell (1990)	$T_L = P\sigma_N'\ f_b\ tan\,\phi$	2.6
Schlosser and Guilloux (1981)	$T_L = Pc' + 2\,D_{eq}\sigma_v'\,\mu^*$	2.7
Potyondy (1961)	$T_L = f_c\,c' + \sigma_N'\tan\,(f_b\ \phi)\,P$	2.8

where:

c' = soil cohesion

P = nail perimeter

D_{eq} = equivalent width of flat reinforcement

σ_v' = effective overburden stress at mid-depth of reinforcing meml

μ^* = coefficient of apparent friction

λ = pull-out factor

ϕ' = angle of internal friction of soil

σ_N' = effective normal stress

f_b = coefficient of roughness

δ = soil/nail interface friction angle

c_a = soil/nail interface adhesion

f_c = coefficient defined by c_a/c'

f_s = coefficient defined by δ/ϕ

v = coefficient defined by δ/ϕ

ψ = dilation angle

K_0 = coefficient of earth pressure at rest

ϕ^b = internal friction angle with respect to soil suction

f_s = coefficient defined by δ/ϕ

$\delta"$ = interface friction angle for the normal stress on a strip

$(u_a - u_w)$ = matric suction

2.2.2.3 Normal stress acting on soil nails

The normal stress acting on a soil nail is dependent on several factors such as soil properties, nail properties and time factors. Dilation occurs in dense sand during shearing which can result in an increase in normal stress acting on soil nails during pull-out. If dilation is partly restrained by surrounding soils, the effect is referred to as restrained dilatancy and results in normal stress increase up to four times the initial stress (Schlosser et al., 1991).

The effect of dilatancy on soil nail pull-out capacity was also demonstrated by Wang and Richwien (2002). The pull-out capacity of soil nails will be reduced with an increase in pore pressure (i.e. reduction in matric suction), which reduces the effective normal stress. Heymann (1993) studies show that the normal stress acting on the nail surface depends on the initial stress and the stress increase is based on the soil stiffness and particle size.

The normal stress acting on soil nails is greatly influenced by the method of installation. The profile of the drilled hole for grouted nails will also influence the normal stress acting on the nail. A smooth cylindrical borehole will have normal stress equal to the stress prevailing during drilling (almost zero) and the resulting pull-out capacity will be low. An irregular drilled hole will develop a rib effect during grouting and mobilize restrained dilatancy effect, causing an increase in normal stress (Plumelle et al., 1990).

Kimmerling et al. (1993) studies suggest that the pull-out force of a soil nail is not constant over time. The variation of pull-out force with time can be attributed to the changes of pore- water pressure (i.e. variation in matric suction), chemical bonding, stress relaxation, aging and greater normal stress caused by slope movement.

2.2.2.4 Soil nail interface coefficient

Soil-nail interface coefficient depends on the properties of soil and nail surface characteristics. Franzen (1998) stated that an increase in the angle of internal friction, ϕ' of the soil will result in greater mobilized friction between the nail-soil interface and hence results in an increase the normal stress during pull-out. An increase in the coefficient of uniformity of the soil will generally result in an increase in the angle of internal friction, ϕ'. The relative density is another factor affecting the angle of internal friction, ϕ'. Soils with a higher value of relative density have a greater tendency to dilate and contribute to an increase in the angle of internal friction (Franzen, 1998).

Schlosser et al. (1983) studies show that ultimate internal friction angle ϕ'_{cv} will be obtained from direct shear box test (since no volume change occurs) at failure. However, during pull-out tests some volume change occurs contributing to dilatancy and the mobilized angle of internal friction, ϕ' will be greater than ϕ'_{cv}. Studies from direct shear box tests by Jewell and Wroth (1987) show that the maximum interface angle of friction in direct shear, δ between a rough reinforcement and sand is limited by the angle of internal friction of soil in direct shear, ϕ'_{ds}.

Potyondy (1961) showed that interface angle of friction, δ between smooth concrete and sand decreased by about 5° when the water content was increased from completely dry to full saturation. Soil comprising cohesion and friction components was highly influenced by the variation in degree of saturation (i.e. variation in matric suction values). Schlosser et al. (1983) reported a reduction of 50% if the pull-out capacity on ribbed strips in clayey gravel when the water content was increased from optimum water content to full saturation. The increase in the pull-out capacity by 50% at the optimum water content in comparison to saturation conditions can be attributed to the contribution of matric suction.

The texture of the soil nail surface will also influence the interface friction angle, ϕ'. A ribbed nail or extremely rough surface will fail by pull-out within the soil outside the nail and the angle of the internal friction, ϕ' for the soil, will be the governing parameter. A completely smooth nail will fail at the soil-nail interface and the angle of internal friction, ϕ' for the soil is governed by soil-nail interface friction, δ (Schlosser and Elias, 1979). Pull-out failure for most soil nails can be expected to occur partly as soil/soil and partly as soil/nail interface and the actual interface friction angle varies between $\tan\,\delta$ and $\tan\,\phi'$. Potyondy (1961) showed that the interface friction angle is greatly influenced by the type of construction material and the results indicated that the roughness played a major role.

2.2.2.5 Soil nail surface area

The soil nail surface area is required for the estimation of pull-out capacity of nails. The nail surface area is treated as area of inclusion for driven nails and borehole surface area for grouted nails. Grout characteristic will a strong influence on the surface area of the nail.

Penetration of grout into the soil depends on the relation between the soil and grout particle sizes. Grout with high water/cement ratio spreads easily and fills all irregularities in boreholes and grout with low water/cement ratio will produce stiff mortar, which will not fill all the voids (Winterkorn et al., 1991). The water/cement ratio is often recommended to be 0.4-0.6 to obtain an economical and good quality soil nail (Schlosser et al., 1991).

2.2.3 Direct shear test comparison with pull-out test

The shear strength failure envelopes for pull-out tests and interface shear tests show trends similar to soil-soil direct shear test. The peak interface friction angle, δ from the soil-grout interface shear tests is generally close to that of the soil nail pull-out tests. Based on results obtained by Chu and Yin (2005), the interface friction angle, δ of grouted nails can be estimated by using soil-grout interface shear tests. The direct shear box test is considered as a simple and reliable method to measure the interface shear strength parameters. Pradhan et al., 2005 observed that the mobilization of shear stress in the direct shear test is similar to that of the laboratory pull-out test until the first slip occurs for completely decomposed granite (CDG). Figure 2.3 shows a comparison of results obtained from pull-out tests and direct shear test for CDG.

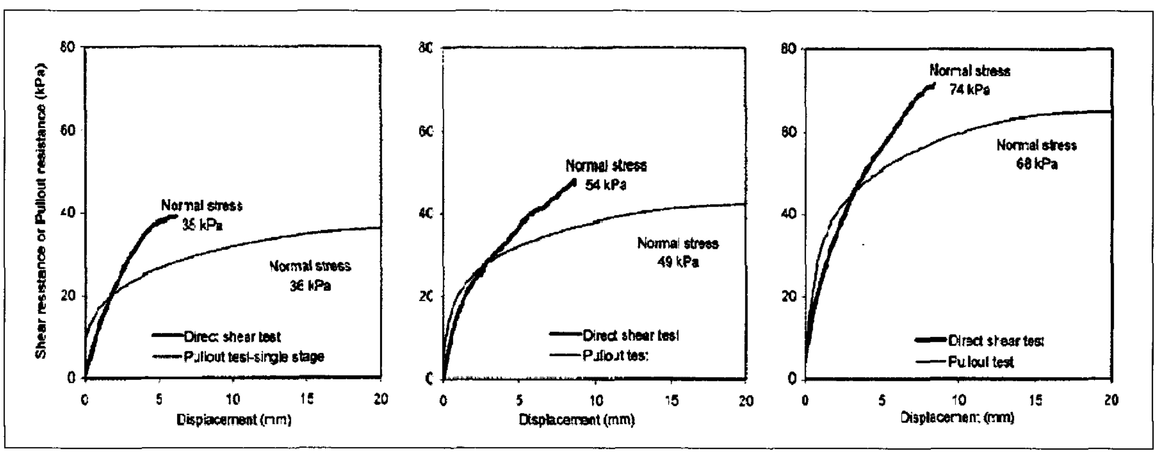

Figure 2.3 Comparison of pull-out test and direct shear box test results (Pradhan et al., 2005)

2.2.4 Effect of degree of saturation

The variation in the degree of saturation associated with the changes in matric suction plays a major role towards the pull-out capacity of soil nails. A series of laboratory pull-out tests were performed by Su et al., 2008 in completely decomposed granite (CDG) at different degrees of saturation. The test results show that the peak pull-out strength of the soil nails was strongly influenced by the degree of saturation of the soil. Peak pull-out shear strength values were obtained between degrees of saturation of 50% and 75% (Su et al., 2008). These results indirectly show a relationship to the shear strength of unsaturated soils where the peak shear strength values typically occurs within the transition zone (Vanapalli et al. 1996). A degree of saturation of approximately 50% typically falls within the transition zone for many unsaturated soils. The decrease in the pull-out capacity with an increase in the degree of saturation (i.e. associated with a decrease in matric suction) from optimum moisture content to the saturated condition was also observed by Pradhan (2003) and by Chu and Yin (2005) for CDG. The shearing plane also migrated from the nail-soil interface to further into the CDG as the degree of saturation increases. Displacements at peak pull-out shear strength for soils under saturated conditions were higher than that for unsaturated conditions. Figure 2.4 illustrates the relationship between peak pull-out shear resistance and degrees of saturation for CDG with overburden pressure at (a) 40 kPa, (b) 120 kPa, (c) 200 kPa, and (d) 300 kPa. The degrees of saturation at which pull-out tests were performed are 98%, 75%, 50% and 38% with corresponding matric suction values of 0, 6, 68 and 87 kPa respectively.

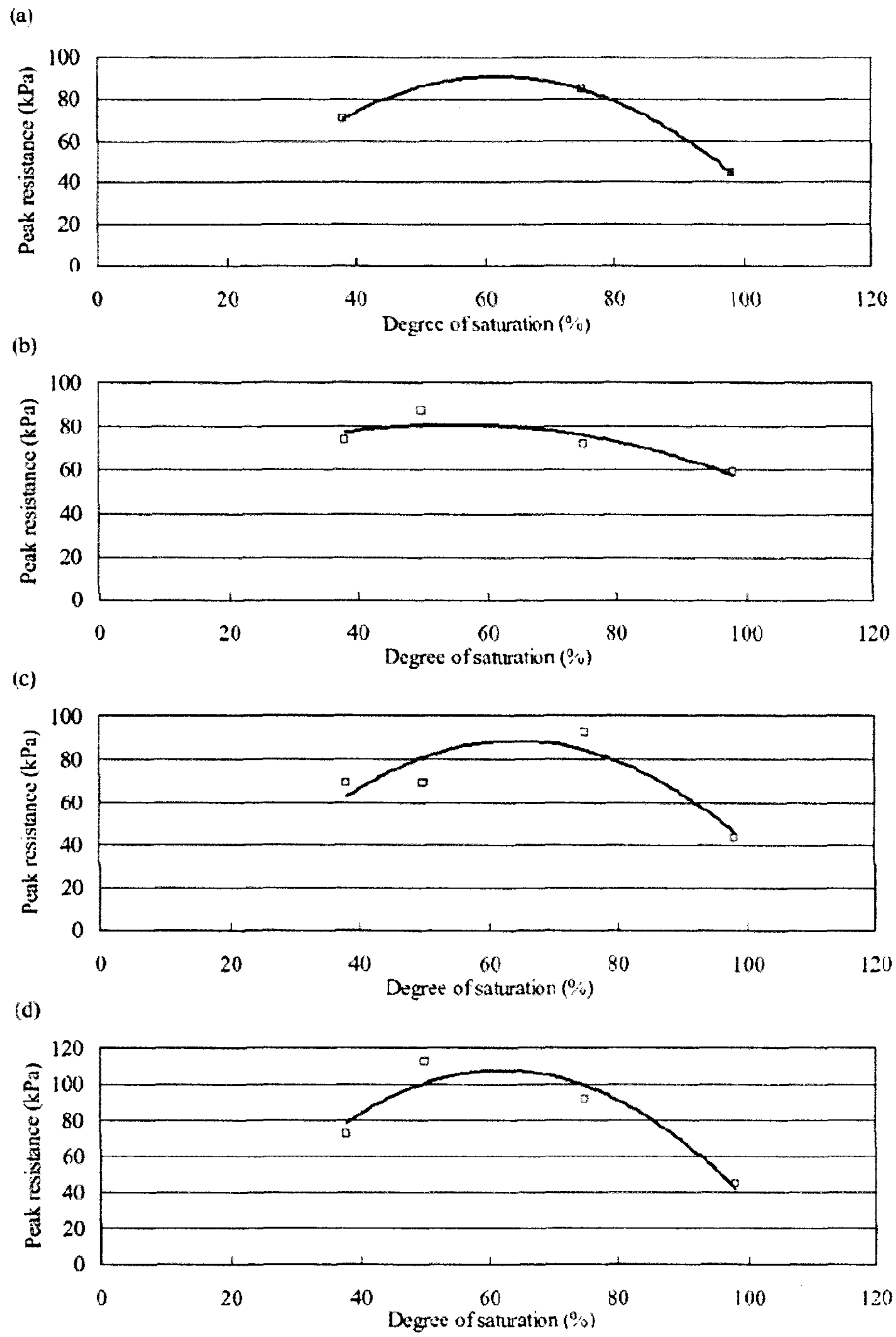

Figure 2.4 Relationship between peak pull-out shear resistance and degrees of saturation for CDG with overburden pressure at (a) 40 kPa, (b) 120 kPa, (c) 200 kPa, and (d) 300 kPa

2.3 Suction profile within a soil nail cut

The matric suction at a specific location of a soil nail cut will be dependent on both the natural and the surrounding environment. Figure 2.5 shows typical variation of in-situ profile of pore-water pressure (matric suction) which may vary from time to time depending on various factors including ground condition, environmental conditions, vegetation, ground-water table and permeability of the soil (Fredlund and Rahardjo, 1993).

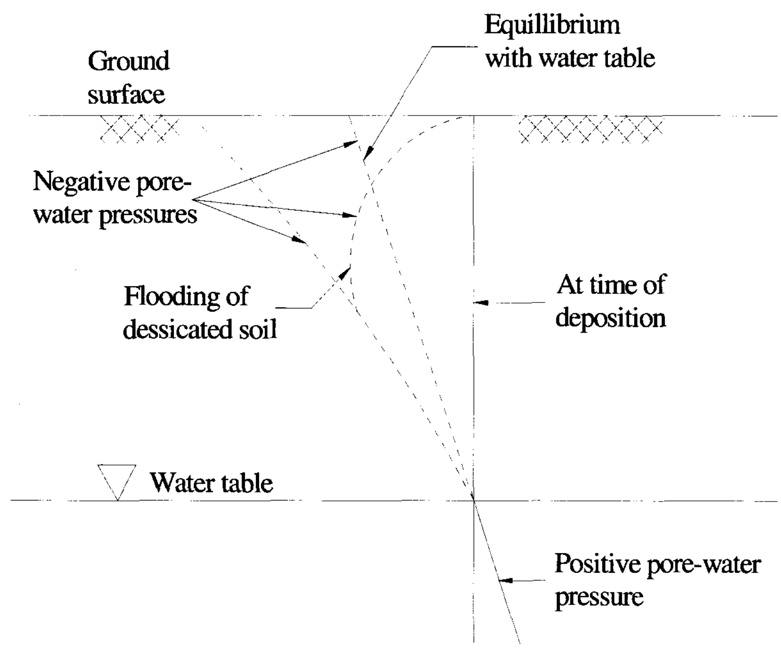

Figure 2.5 Typical pore-water pressure profile (modified after Fredlund and Rahardjo, 1993)

2.4 Unsaturated soil interfaces

The mechanical behavior of unsaturated soil interfaces is a key parameter for the design of geotechnical structures such as retaining walls, foundations and soil nails.

Structural elements are commonly found in contact with unsaturated soils through a contact zone (i.e. the unsaturated interface), where a transfer of stress occurs. An accurate analysis of the behaviour of unsaturated soil interfaces is crucial for the design and performance of numerous civil engineering applications. Little research attention has been given to study the influence of matric suction on the behaviour of interfaces for unsaturated soils. Recent research by Hamid and Miller (2009) suggest the peak shearing resistance of both smooth and rough unsaturated soil interfaces is significantly influenced by both matric suction and the net normal stress. Additional details and discussions on this topic are presented and discussed in the next chapter.

2.5 Effects of matric suction on bond strength

In order to study the uncertainties in the measured and actual pull-out capacity of soil nails, Zhang et al. (2009) analyzed a large number of in-situ pull-out tests data in completely decomposed granite (CDG) in Hong Kong. The field measurements were compared with estimated values and the effects of overburden pressure, grout length, soil suction and soil dilatancy were analyzed quantitatively. The grouted length of the soil nail was considered as the most important parameter that governs the pull-out capacity. The second most important factor is the matric suction (Zhang et al., 2009).

Studies performed by Su et al., (2008) indicated that the effect of the degree of saturation (i.e. a parameter which is influenced by matric suction) on soil nail pull-out capacity is significant and should be carefully addressed in the design of soil nailing system. The peak pull-out shear strength for tests at matric suction of 6 kPa was found to be two times that for saturated tests for CDG. Matric suction influences the unsaturated soil interface for numerous civil engineering applications, including piles and soil nails (Vanapalli et al. 2010). All the above discussions support using the mechanics of unsaturated soils in the design of soil nails.

2.6 Soil conditions under which matric suction can be maintained

The effect of negative pore-water pressure (matric suction) is generally ignored as there is a perception among geotechnical engineers that rainfall infiltration will dissipate any negative pore water pressure that exists. The infiltration of rainfall on unsaturated slopes is dependent on the saturated coefficient of permeability, permeability function and the water storage capacity of the soil (Zhang et al., 2004). Studies have shown that matric suction can be maintained over a much larger time period than the rainfall period. Measurements of insitu matric suction were presented by Sweeney (1982) from a slope instrumented with tensiometers in Hong Kong. The results indicated that matric suction between 5 and 17 m depth remained constant throughout the year, which demonstrated the water storage capacity of the soil and its role in maintaining matric suction. Slope cover and surface recompaction are some common methods to minimize the rainfall infiltration and maintain matric suction in soils. Figure 2.6 illustrates the suction measurements in a weathered Rhyolite in Hong Kong.

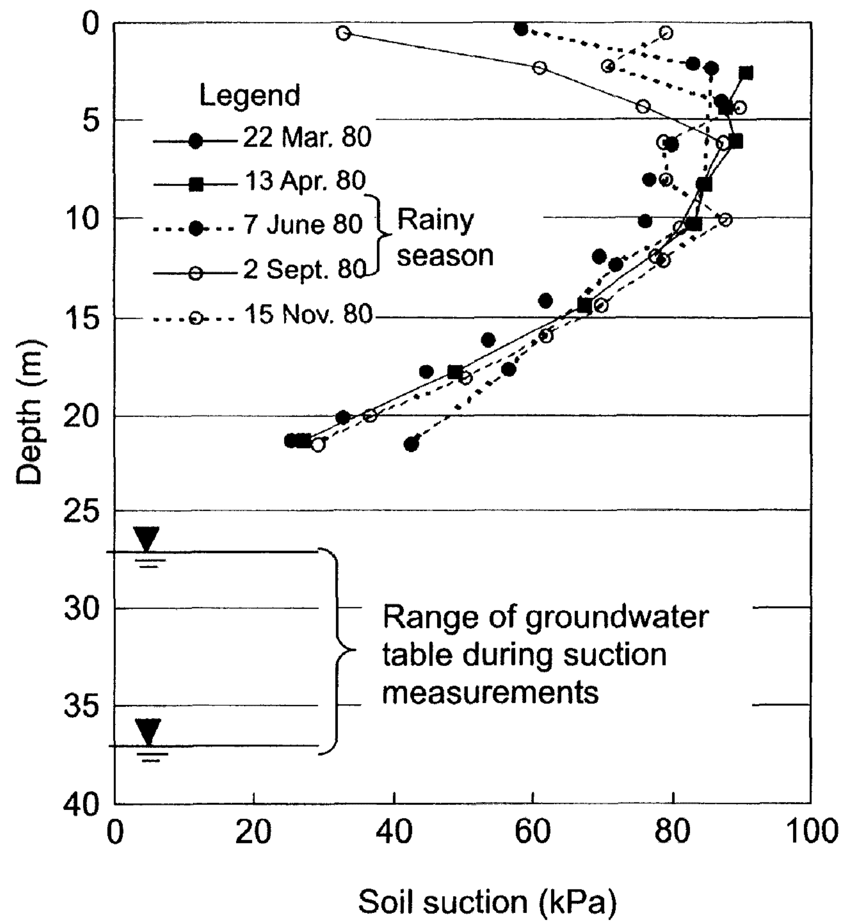

Figure 2.6 Suction measurements in a weathered Rhyolite in Hong Kong (Sweeney, 1982)

2.7 Methodology for the estimation of the pull-out capacity of soil nails

The parameters governing the pull-out capacity of soil nails are similar to that of friction piles; which are normal stress, surface area and friction parameters. The influence of matric suction on the shaft capacity of piles was investigated by Vanapalli et al. (2010). A test program was performed to evaluate the shaft resistance of jacked open end pipe piles under saturated and unsaturated conditions in sandy soils. The contribution of matric suction was found to be 50% of the shaft capacity of piles installed in silty sand under unsaturated conditions for both compression and tension. Vanapalli et al. (2010)

also proposed a method to estimate the shaft resistance of piles in unsaturated soils. This method incorporates the influence of matric suction into the conventional β method. In the present research program, this method was extended to investigate the influence of matric suction on the pull-out capacity of soil nails. More details about this methodology are available in the next chapter.

2.8 Summary

The influence of matric suction in typically neglected in the analysis of the pull-out capacity of soil nails. Recent studies have shown that the pull-out capacity of soil nails in unsaturated soils is typically much higher than the pull-out capacity for soil in a state of saturated condition (Su et al., 2008, Zhang et al. 2009). However, there are limited investigations that are reported in the literature, which attempt to provide a theoretical framework for interpreting the pull-out capacity of soil nails installed in unsaturated soils. Matric suction is one of the key parameters which influences the pull-out capacity and should be considered since soil nailing is performed conventionally in soils that are in a state of unsaturated condition.

The background literature summarized in this chapter clearly demonstrates that a need exists for developing a simple technique to interpret the pull-out capacity of soil nails by taking account of matric suction. The next chapter, entitled, "Theoretical Background" provides the details of such a technique. This technique is simple and will encourage the practicing geotechnical engineers to implement the mechanics of unsaturated soils into practice in the estimation of the pull-out capacity of soil nails.

CHAPTER 3

THEORETICAL BACKGROUND

3.1 Introduction

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 soil associated with these structures such as slopes, retained backfills or the soils on which structures such as pavements and foundations are placed, typically are unsaturated and may not reach saturated conditions during their entire design service life. 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.

In this chapter, established concepts related to our present understanding of the shear strength of unsaturated soils are succinctly summarized. A technique is presented by extending the concepts of shear strength of unsaturated soils for estimating the pull-out capacity of soil nails placed in coarse-grained soils. This approach is simple and can be extended for soils both in unsaturated and saturated conditions. The required parameters for using this approach include the saturated shear strength parameters, (c' andϕ') and the soil-water characteristic curve (SWCC).

3.2 Shear strength of unsaturated soils

The stress state variable approach is used both in the interpretation of the shear strength of saturated and unsaturated soils. While the saturated soils require one stress state variable, $(\sigma - u_w)$; two independent stress state variables; namely, net normal stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$ are necessary for the interpretation of the shear strength behavior of unsaturated soils.

Bishop (1959) and Fredlund et al. (1978) provided two different techniques for the interpretation of the shear strength behavior of unsaturated soils using the two stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$. The approach presented by Bishop (1959) is an extension of conventional shear strength of saturated soils using only the angle of internal friction, ϕ' introducing a non-dimensional parameter χ into the shear strength equation, which is a function of degree of saturation, S [3.1].

$$\tau = c' + [(\sigma_n - u_a) + \chi\,(u_a - u_w)]\tan\phi' \qquad [3.1]$$

where:

τ = shear strength of unsaturated soil

c' = effective cohesion

ϕ' = effective internal friction angle

$(\sigma_n - u_a)$ = net normal stress

$(u_a - u_w) =$ matric suction

$\chi =$ a parameter dependent on the degree of saturation (varies from 0 to 1)

Fredlund et al. (1978) suggested using the independent stress state variables approach which leads to two frictional parameters, ϕ' and ϕ^b which are respectively the shear strength contribution due to the angle of internal friction and matric suction [3.2].

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad [3.2]$$

where:

ϕ^b = the angle of shearing resistance with respect to matric suction

There is a smooth transition between the variations of shear strength with respect to matric suction to a saturated condition using both these interpretation techniques which are based on experimental results. Experimental studies of the shear strength of unsaturated soils are however costly, time consuming, require elaborate equipment and highly trained personnel.

Significant advances were made during the past 50 years regarding the measurement, interpretation and estimation of the shear strength of unsaturated soils (Vanapalli, 2009). In recent years, the soil-water characteristic curve (SWCC) has been used as a tool along with the saturated shear strength parameters (c' and ϕ') to predict or estimate the shear strength of unsaturated soils. Such models alleviate the need for measuring the shear strength and are attractive to the practicing engineer to implement our present understanding of the mechanics of unsaturated soils. There are several such empirical or semi-empirical models in the literature proposed by various researchers; some of the widely used ones in the literature were proposed by Vanapalli et al., 1996a; Fredlund et al., 1996; Oberg and Salfours, 1997 and Khallili and Khabbaz, 1998.

Soil nailing techniques are being widely used in all regions of world towards improving the performance of various geotechnical structures. There are several equations proposed in the literature to estimate the pull-out capacity of soil nails which are summarized in an earlier chapter (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). There is limited information available in the literature that discusses the influence of matric suction on the pull-out capacity of soil nails installed in unsaturated soils. The only equation found in the literature that takes the contribution of matric suction into account towards the pull-out capacity of soil nails was proposed by Zhang et al., 2009.

3.3 The soil-water characteristic curve (SWCC)

The SWCC defines the relationship between soil suction and degree of saturation *(S)*. Alternatively, the SWCC can also be expressed as a relationship between soil suction and either gravimetric water content *(w)*, or the volumetric water content (θ). 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). In other words, the SWCC can be used as a tool to estimate or predict the different properties of the unsaturated soils. For example, the variation of coefficient of permeability (Van Genuchten, 1980; Fredlund et al., 1994), shear strength (Vanapalli et al., 1996, Fredlund et al., 1996), bearing capacity of soils under drained and undrained loading conditions

(Vanapalli and Mohamed, 2007; Vanapalli and Oh, 2010), modulus of elasticity of coarse-grained and fine-grained soils (Oh et al., 2009, Vanapalli and Oh, 2010), design of pile foundations in coarse-grained soils (Vanapalli et al., 2010) and shear modulus (Oh and Vanapalli, 2010) variation with respect to matric suction were either estimated or predicted using the SWCC as a tool.

Figure 3.1 shows a typical SWCC and highlights the various features of the SWCC.

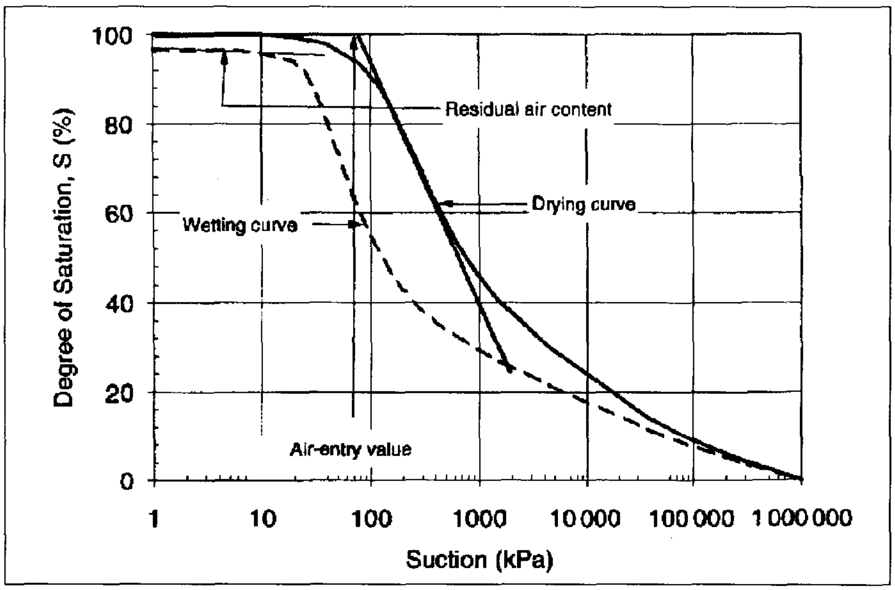

Figure 3.1 Typical soil-water characteristic curve for drying and wetting of a soil (Vanapalli et al., 1996)

The variation of the wetted area of contact between soil particles along which matric suction acts and contributes to the shear strength decreases with an increase in matric suction due to desaturation of the soil. The relationship that exists between the rate at which shear strength changes with respect to matric suction is a function of the wetted area of contact between the soil particles and can be derived from the SWCC (Vanapalli et al., 1996a). Figure 3.2 shows the different zones of desaturation and the fundamental relationship between the SWCC with the shear strength of unsaturated soils.

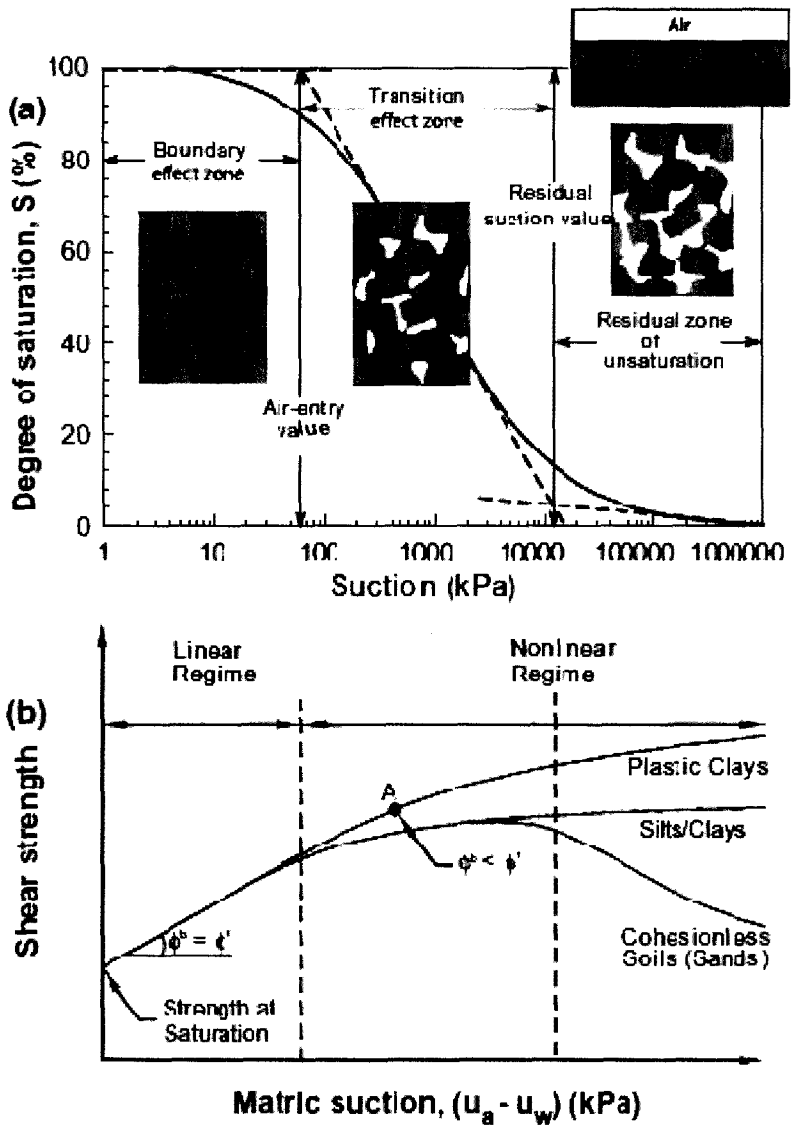

Figure 3.2 (a) SWCC illustrating different zones of desaturation; (b) The relationship of the SWCC with shear strength of unsaturated soils (Vanapalli, 2009)

3.3.1 Mathematical representation of the SWCC

Different soils exhibit different shapes for the SWCC behaviour depending on the percentage of various sizes of soil particles and other parameters such as the stress history, soil structure, clay mineralogy (Vanapalli et al., 1999). Several investigators have provided mathematical equations for representing the SWCC behaviour (Gardner, 1958; Van Genucthen, 1980; Mualem, 1986; Fredlund and Xing, 1994). Of the many equations available in the literature, the equation [3.3] derived by Fredlund and Xing (1994) based on the soil pore size distribution is found to be more suitable for fitting the SWCC data of various soils over the entire range of suction from zero (representing saturated conditions) to 1,000,000 kPa (representing dry condition of the soil).

$$\theta = C\,(\psi)\left\{\frac{\theta_s}{ln\left[\left(e+\left(\frac{\psi}{a}\right)^n\right]^m\right.}\right\} \quad [3.3]$$

where:

θ = volumetric water content

θ_s = saturated volumetric water content

a = suction related to an air entry value of the soil

n = soil parameter related to the slope at the inflection point of the SWCC

ψ = suction

m = soil parameter related to residual water content

e = natural number (2.71828)

$C\ (\psi)$ = correction factor that forces the SWCC through a suction of 1,000,000 kPa and zero water content.

The correction factor is defined as:

$$C(\psi) = \left[1 - \frac{ln\left(1+\frac{\psi}{c_r}\right)}{ln\left(1+\left(\frac{1\,x\,10^6}{c_r}\right)\right)}\right] \qquad [3.4]$$

where: c_r = suction value corresponding to residual water content, θ_r.

The normalized form of equation [3.3] is shown below

$$\Theta = [C\ (\psi)]\left[\frac{1}{ln\left(e+\left(\frac{\psi}{a}\right)^n\right)}\right]^m \qquad [3.5]$$

The normalized volumetric water content, Θ is defined as:

$$\Theta = \frac{\theta}{\theta_s} \qquad [3.6]$$

The degree of saturation S, is also equal to the normalized volumetric water content, $\Theta = S$

Equations [3.3] or [3.5] can be used to best-fit the SWCC data for the entire range of suction (i.e. from 0 to 1,000,000 kPa).

3.3.2 Prediction of the SWCC

Vanapalli and Catana (2005) proposed a method for estimating the SWCC of coarse-grained soil from the grain size distribution (GSD) and volume mass properties using one data point of the measured SWCC. The equation proposed by Fredlund and Xing (1994) was used to develop relationships between fitting parameters and parameters derived from GSD data and volume-mass properties. The equation proposed by Vanpalli and Catana (2005) was used in the present study to predict the SWCC for the coarse-grained soil that was used to establish the pull-out capacity of prototype soil nails. This method is quick and reliable for the estimation of the SWCC in comparison to other methods that use only the GSD data.

The equation proposed by Vanapalli and Catana (2005) is given below [3.7]:

$$w_w = w_r + (w_s - w_r)\left(\frac{1}{ln\,(f)}\right) \qquad [3.7]$$

where:

w_w = gravimetric water content

w_s = saturated gravimetric water content

w_r = residual gravimetric water content

$$f = \left(e + \left(\frac{\psi}{1.33/de^{0.86}}\right)^{7.78/(C_u\, x\, e)^{1.14}}\right)^{mf} \qquad [3.8]$$

where:

e = void ratio

d_e = dominant diameter, *mm*

c_u = coefficient of uniformity

ψ = soil suction, kPa

m = fitting parameter

The dominant particle size diameter is obtained from the equation given below by Vukovic and Soro (1992):

$$\frac{1}{d_e} = \sum_{i=1}^{i=n} \Delta g_i \frac{ln\left(\frac{d_i^g}{d_i^d}\right)}{(d_i^g - d_i^d)} \qquad [3.9]$$

where:

d_e = dominant particle size diameter in mm

Δg_i = fraction weight in parts of the total weight

d_i^g = maximum grain diameter of the corresponding fraction

d_i^d = minimum grain diameter of the corresponding fraction

The fraction weights and corresponding grain diameters are computed by subdividing the GSD curve as shown in Figure 3.3.

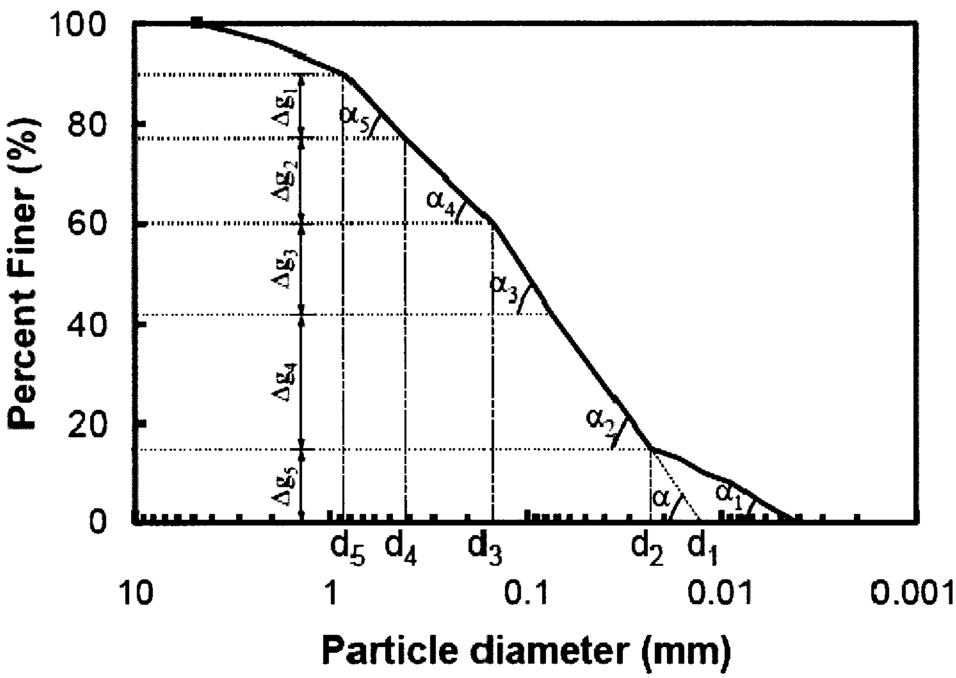

Figure 3.3 The procedure for calculating the dominant particle size diameter according to Zamarin (Vukovic and Soro, 1992)

3.3.3 Equation used to predict the shear strength of unsaturated soils using the soil-water characteristic curve (SWCC) and saturated shear strength parameters

Vanapalli et al. (1996a) and Fredlund et al. (1996) proposed a semi-empirical equation for predicting the shear strength of unsaturated soils using the equation below:

$$\tau = [c' + (\sigma_n - u_a) \tan\phi'] + (u_a - u_w)\,[(S^{\kappa})(\tan\phi')] \qquad [3.10]$$

where:

κ = fitting parameter used for obtaining a best-fit between the measured and predicted values.

S = degree of saturation

Equation [3.10] is consistent with eq. [3.2]. The second part of the eq. [3.10] is the shear strength contribution due to matric suction which can be derived from the SWCC as follows:

$$\tau_{us} = (u_a - u_w)\,[(S^{\kappa})(\tan\phi')] \qquad [3.11]$$

Equation [3.10] can be used to predict the shear strength of unsaturated soils over the entire range of suction values from 0 to 1,000,000 kPa using a fitting parameter, κ. Vanapalli and Fredlund (2000) provided a relationship between the fitting parameter, κ and plasticity index, I_p that can be used for predicting the shear strength using eq. [3.10]. This relationship was based on limited data set of results using only six soils. Garven and Vanapalli (2006) extended the data base and provided a more refined relationship between κ and I_p. Most of the data used in these relationships is based on shear strength data that was developed using statically compacted soils. Both these relationships suggest that a fitting parameter κ value of 1 can be used for predicting the shear strength for non-plastic soils such as coarse-grained soils, for which compaction technique did not influence the shear strength behavior.

A second equation was proposed by Vanapalli et al. (1996) to predict the shear strength of unsaturated soils without using the fitting parameter, κ. The equation [3.12] is given below:

$$\tau = [c' + (\sigma_n - u_a)\tan\phi'] + (u_a - u_w)\left[(\tan\phi')\left(\frac{S-S_r}{100-S_r}\right)\right] \qquad [3.12]$$

where:

S_r = residual degree of saturation

The residual degree of saturation, S_r, can be determined from the SWCC.

In the present research, eq. [3.11] is used to develop a technique for the prediction of the pull-out capacity of soil nails by extending the conventional β method. Equation [3.11] can also be used without any implications.

3.4 Shear strength of unsaturated soil interfaces

The soil-structure interface behaviour is necessary in the design of some features of foundations, retaining walls, buried pipes, soil nails and other geotechnical structures. The soil interface is defined as a layer of soil where stresses are transferred from soil to structure and vice versa. Limited studies are reported in the literature with respect to soil-structure interface behavior of unsaturated soils. Hamid and Miller (2009) modified a conventional direct shear device to perform interface tests by controlling the matric suction. The results from this study suggest that matric suction contributes significantly towards the peak shear strength of unsaturated interfaces. The SWCC was used to develop failure envelope, which captured the nonlinear influence of matric suction on the shear strength of soil and various interfaces. Hamid and Miller (2009) also highlighted the importance of understanding of the mechanical behaviour of unsaturated interfaces and its application for the reliable and efficient design of geotechnical structures.

Figure 3.4 illustrates the typical behaviour observed during shearing of a rough interface and Minco silt with the variation of matric suction for a net normal stress of 105 kPa.

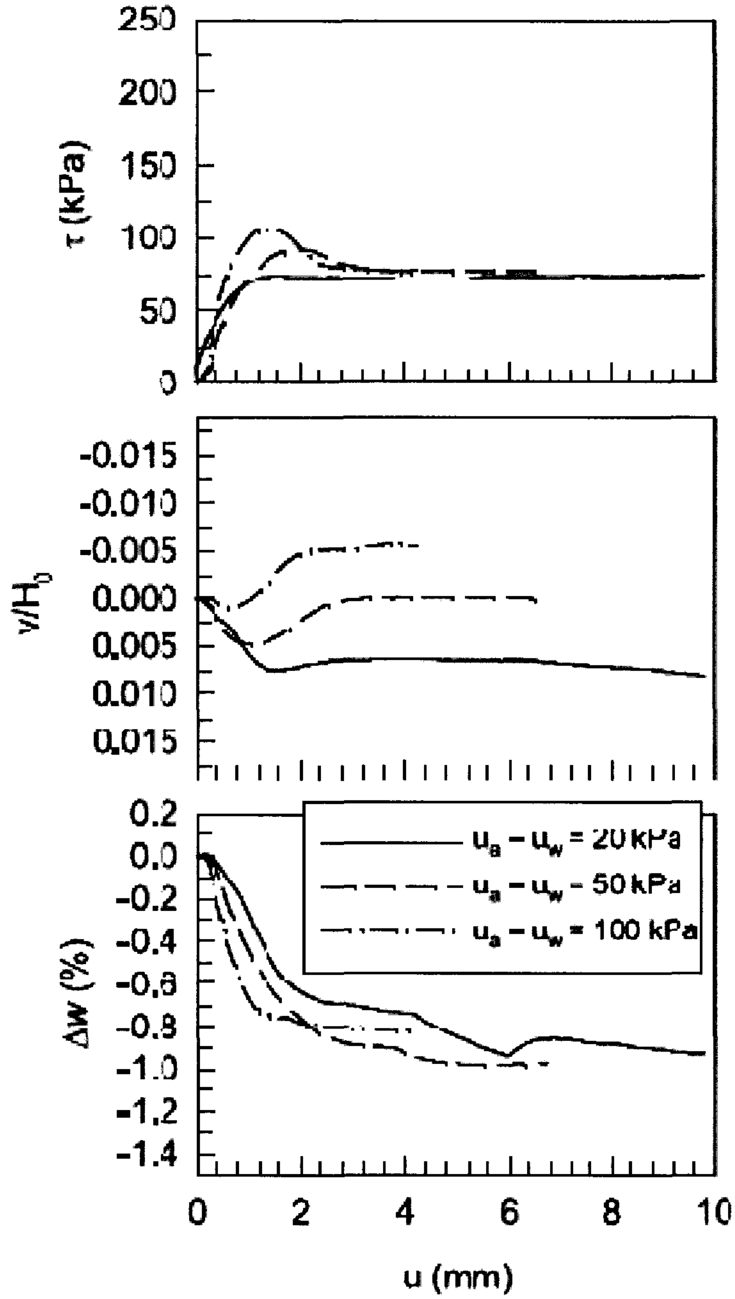

Figure 3.4 Typical behaviour observed during shearing of the rough interface for a net normal stress of 105 kPa; u = displacement; v/H_0 = vertical or volumetric strain; τ = shear stress and Δw = change in gravimetric water content (from Hamid and Miller, 2009)

3.5 Proposed technique to estimate the pull-out capacity of soil nails in unsaturated soils

Vanapalli et al. (2010) recently investigated the influence of matric suction on the shaft capacity of jacked piles in coarse-grained soils. The results of the study show the contribution of matric 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 model 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.

The general expression for pull-out capacity of soil nails in unsaturated sand, $Q_{f(us)}$, can be expressed as shown in equation [3.13]:

$$Q_{f(us)} = Q_f + Q_{(u_a - u_w)} \qquad [3.13]$$

where:

Q_f = capacity of soil nails installed in saturated soils

$Q_{(u_a - u_w)}$ = capacity of soil nails due to the contribution of matric suction

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):

$$Q_{(u_a - u_w)} = \tau_{us} \times A_s \qquad [3.14]$$

where:

τ_{us} = shear strength of unsaturated soils

A_s = surface area of nail in the unsaturated zone

The contribution due to matric suction $Q_{(u_a-u_w)}$ was estimated by extending the approach proposed for predicting the shear strength of unsaturated soils (eq. [3.10]).

The proposed method to estimate the pull-out capacity of 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:

$$f_s = c' + \beta\sigma_z' \qquad [3.15]$$

where:

c' = effective cohesion intercept

β = Bjerrum-Burland coefficient (Burland, 1973)

σ_z' = effective overburden stress

The β value in equation [3.15] can be expressed as follows:

$$\beta = k_\theta \, tan(\delta + \psi) \qquad [3.16]$$

where:

k_θ = coefficient of lateral earth pressure with respect to soil nail inclination

δ = interface friction angle at residual state

ψ = dilation angle.

The dilation angle (ψ) can be defined as a measure of the change in volumetric strain with respect to the change in shear strain (Budhu, 2007).

Residual values from the interface direct shear test was used to establish the interface friction angle since the dilation angle is also considered separately. The ultimate capacity of soil nails placed in saturated condition can be expressed as follows:

$$Q_f = f_s A_{surface} = (c_a + \beta\sigma_z') \pi dL \qquad [3.17]$$

where :

c_a = soil adhesion at the grout/soil interface

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. Equation 3.17 can be extended to include the contribution of matric suction, and will then yield a general equation for estimating pull-out capacity of grouted soil nails in unsaturated soils as given below:

$$Q_{f\,(us)} = \left[(c_a + \beta\sigma_z') + [(u_a - u_w)(S^{\kappa}) \tan(\delta + \psi)]\right] \pi dL \qquad [3.18]$$

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

3.5.1 The Modified β method

The conventional β method (Burland 1973) is typically used to estimate the shaft capacity of piles. In the case of cohesionless soil, the unit shaft friction at any depth *(z)* along a pile is given as follows:

$$q_s = \sigma_v^{'} K_s \tan\delta = \beta \sigma_v^{'} \qquad [3.19]$$

where:

$q_s =$ shaft capacity

σ_v' = vertical effective stress adjacent to the pile at depth, z

K_s = coefficient of lateral earth pressure

δ = the interface friction angle (i.e. pile and soil)

β = a combined shaft resistance factor

3.5.2 β as a function of inclination

The β used in equation [3.17] is intended for vertical piles or soil nails, and can be expressed as follows:

$$\beta = K_s \tan\delta \qquad [3.20]$$

The influence of soil nail inclination on the β value is taken into account by using an earth pressure coefficient K_θ which is a function of the inclination of the nail. The coefficient of earth pressure, K_s is influenced by the angle of shearing resistance, the method of installation, the compressibility, degree of overconsolidation and original stress in the ground, as well as the material size and shape of the pile. The Canadian Foundation Engineering Manual – CFEM (2006) recommends that the value of K_s for bored piles can be assumed to be equal to the coefficient of earth pressure at rest K_0.

The lateral earth pressure coefficient at rest K_0 is the ratio of the horizontal stress to the vertical stress, and can be substituted for K_s to yield reasonably accurate results for the case of vertical nails (CFEM).

$$K_0 = \sigma_h / \sigma_v \qquad [3.21]$$

For the case of a vertical soil nail:

$K_\theta = K_0$, where $\theta = 0$, therefore $K_\theta / K_0 = 1$

For the case of inclined soil nail at an angle θ, the coefficient K_θ can be expressed as:

$$K_\theta / K_0 = 1 + (1 - K_0)/2K_0 \times (1 - \cos 2\theta) \qquad [3.22]$$

3.5.3 The interface friction angle *(δ)*

The value of interface angle, δ is based on the surface roughness of the nail, the mean particle size of the soil, the normal stress at the gout-soil interface and the method of installation. Direct shear tests are commonly used to obtain the interface friction angle, δ. The value of δ ranges from 0.5 to 1.0 ϕ' as outlined in the Canadian Foundation Engineering Manual (CFEM, 2006).

3.5.4 Dilatancy

The influence of dilatancy was also taken into account towards the pull-out capacity of soil nails used for this study. The dilation angle was added to the interface friction angle of the soil according to Coulomb's Model.

Figure 3.5 shows the relationship of the average pull-out stress with (a) pull-out displacement and (b) dilation angle.

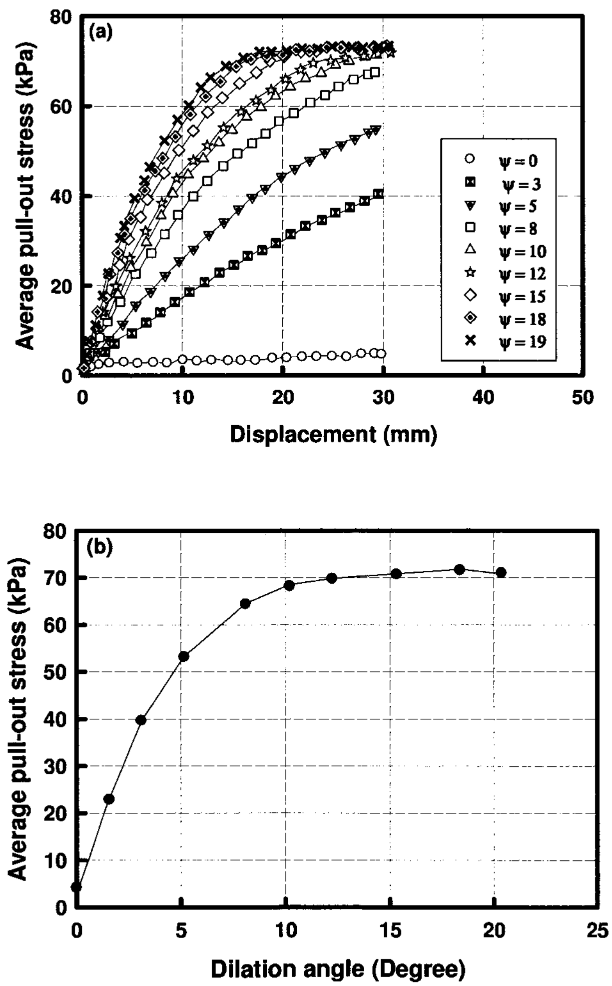

Figure 3.5 Relationship of the average pull-out stress with (a) pull-out displacement and (b) dilation angle (Su et al., 2007)

Results in Figure 3.5 clearly show that the pull-out resistance initially increases quickly with the dilation angle. For dilation angles greater than 10°, the pull-out resistance increases and then remains constant.

Pradhan (2003) studies show that the soil particles around the nail will dilate when the shear stress is applied on the soil nail interface during pull-out. This phenomenon leads to an increase in the normal stress. Numerical simulation of the effects of dilatancy on soil nail pull-out resistance was performed by Su et al. (2007). The results suggest that soil dilatancy has a significant influence on the soil nail pull-out resistance.

3.6 Summary

A technique is proposed in this Chapter to estimate the pull-out capacity of soil nails installed in both saturated and unsaturated coarse-grained soils. This technique is developed by extending the conventional β method used for the estimation of the shaft capacity of piles. The β method is modified to allow for the contribution of matric suction at the grout/soil interface by applying the concepts of shear strength of unsaturated soils. The SWCC, saturated shear strength parameters (c' and ϕ') and the soil-structure interface friction angle, δ are required for using the proposed technique to estimate the pull-out capacity of soil nails with the variation of the degree of saturation (i.e. variation of matric suction).

The various parameters that influence for the proposed equation are also briefly discussed in this chapter along with the concepts of the shear strength of unsaturated soils as applicable to the pull-out capacity of soil nails. A test box was specially designed and a comprehensive test program was undertaken to check the validity and limitations of the proposed approach summarized in this chapter. Details of the equipment design, results and analysis are provided in later chapters.

CHAPTER 4

EQUIPMENT DESIGN

4.1 Introduction

This Chapter presents the details of the equipment that was specially designed and constructed to determine the pull-out capacity of prototype grouted soil nails placed in inclined, vertical and horizontal orientations under both saturated and unsaturated conditions. This equipment had special provisions with different accessories to conduct experiments and understand the influence of the variation of matric suction on the pull-out capacity of soil nails. The objective of conducting these experiments using the specially designed equipment is twofold. First, the equipment is useful to undertake a comprehensive experimental program, collecting all the required information for understanding the influence of matric suction on the soil-nail pull-out capacity. Second, the collected data can be useful for validation of the model that was developed in Chapter 3. The design of soil nails can be optimized in terms of being more economical and feasible if the pull-out capacity can be reliably estimated. These details will be summarized in the next Chapter.

This chapter describes the features of the specially designed equipment, material properties and instrumentation used for the test program.

4.2 Test box used for soil-nail pullout testing

A test box forms the key element of the soil-nail pullout testing equipment. The equipment as previously noted is specially designed for the present research project 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 both saturated and unsaturated conditions.

ii) To assess the pull-out capacity of soil nails installed at different orientations

iii) To investigate the relationship of the pull-out capacity of soil nails with respect to matric suction from the measured data and the estimated capacity using the technique developed in Chapter 3 that uses the soil-water characteristic curve (SWCC) and the saturated shear strength parameters.

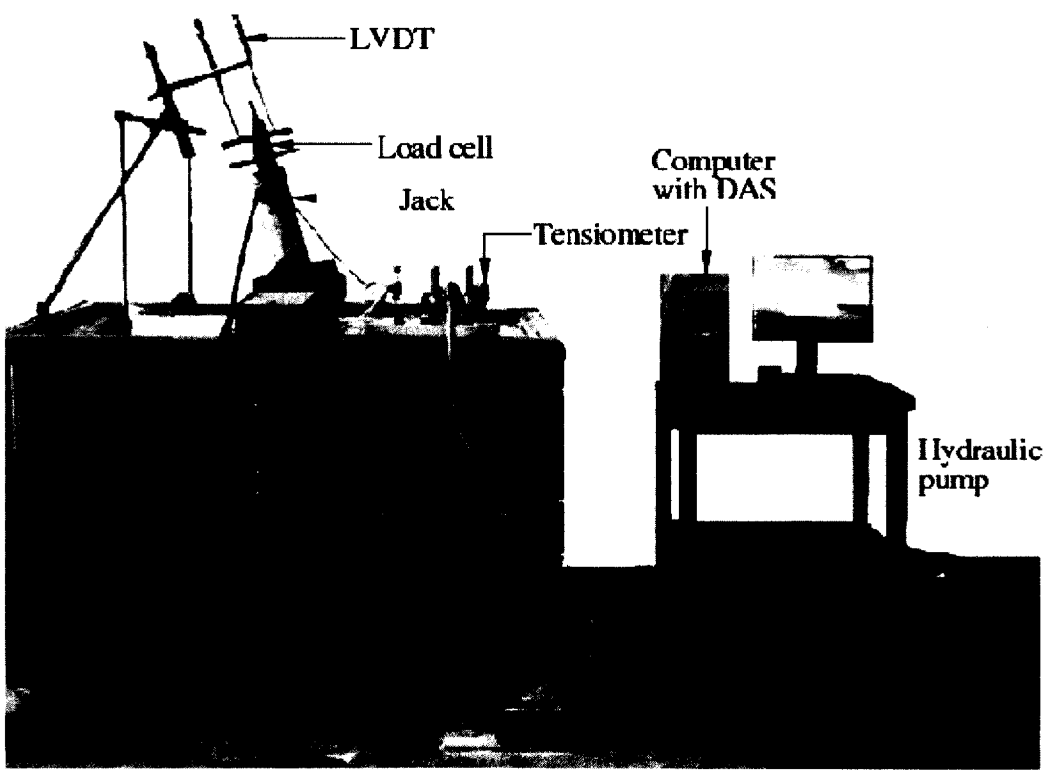

Figure 4.1 Test box and set-up for pull-out testing of soil nails

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 both allow or drain water from the test box to simulate both saturated and unsaturated conditions of the soil compacted. Figure 4.1 shows the key features of test box and its assembly that was used for testing the pull-out capacity of soil nails.

4.2.1 Key features of the test box

The key features of the equipment are summarized as follows:

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). The size of the grouted nails used in the present study was equal to 100 mm in diameter and 800 mm long for the inclined nail, and 780 mm for the vertical and horizontal nails. 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. A 25 mm thick transparent acrylic panel (330 mm x 870 mm) was installed within a section of the wall of the box to function as a window for observation. 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 placed above it and the 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. 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 dry density was achieved. More details on the compaction process are provided under section 5.3.1. 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 desaturation 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 4.2 shows a schematic of the test box used for the present study. The salient features of this test box are similar to the test set up used by Vanapalli et al., (2010) and Mohamed and Vanapalli (2006) for determining the bearing capacity of model piles and model shallow foundations respectively. Figure 4.3 illustrates the bearing capacity used by Mohamed and Vanapalli (2006). The test pit used for the study that was conducted by Vanapalli et al., 2010 is illustrated in Figure 4.4. The key features of the test box are depicted in Figure 4.5.

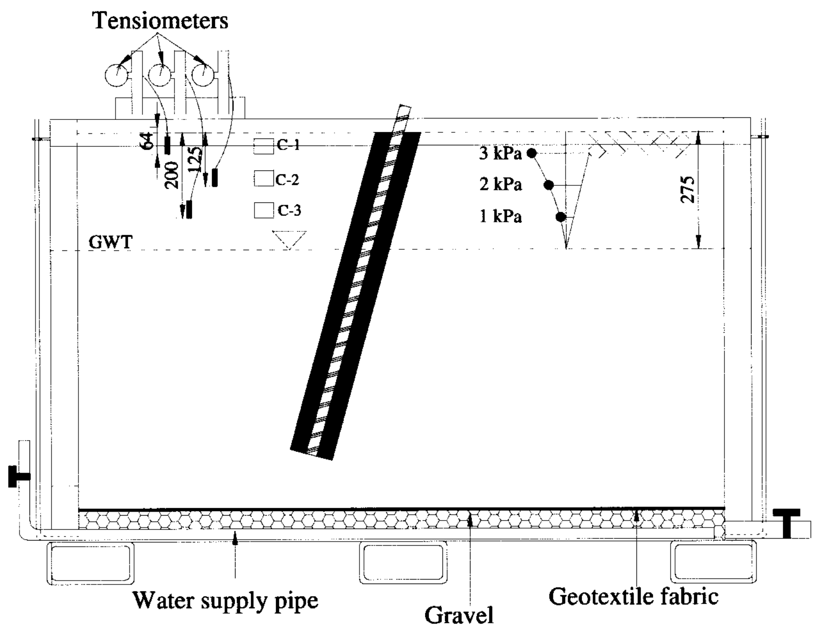

Figure 4.2 Schematic of the test box for the present study

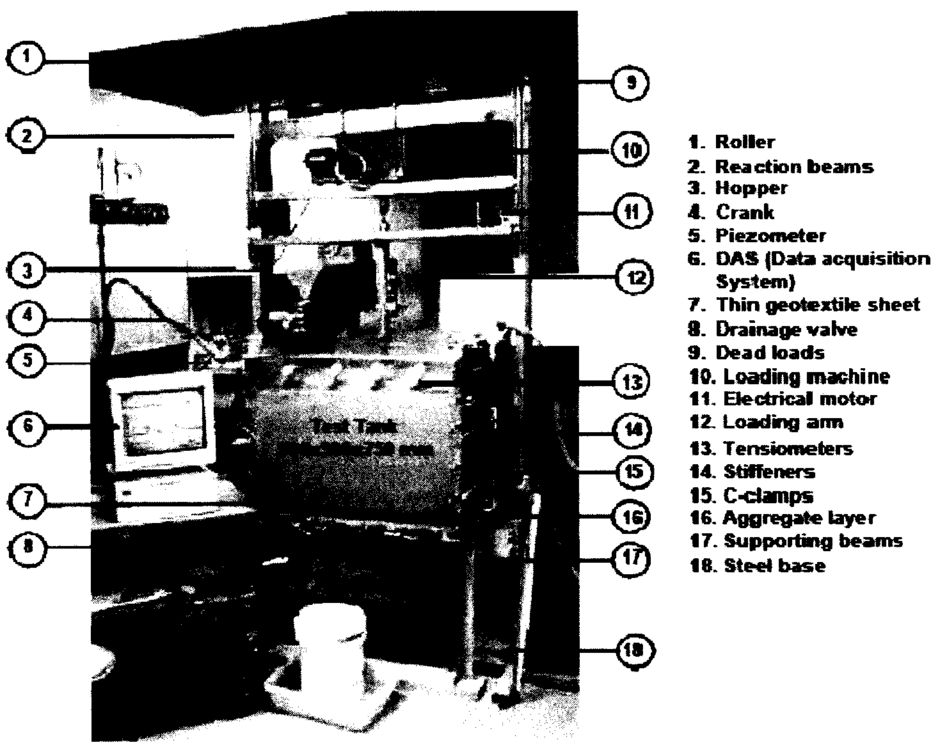

Figure 4.3 Bearing capacity equipment used by Mohamed and Vanapalli (2006)

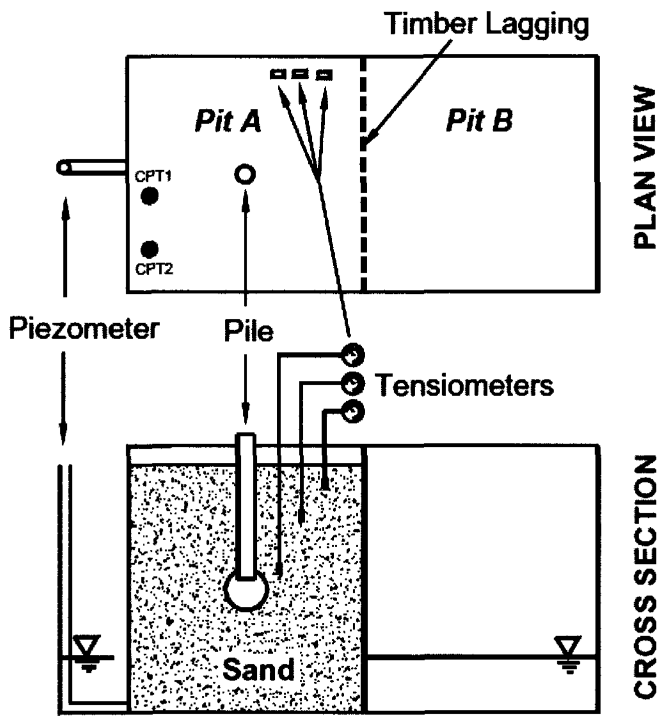

Figure 4.4 Schematic of the test pit used by Vanapalli et al. (2010)

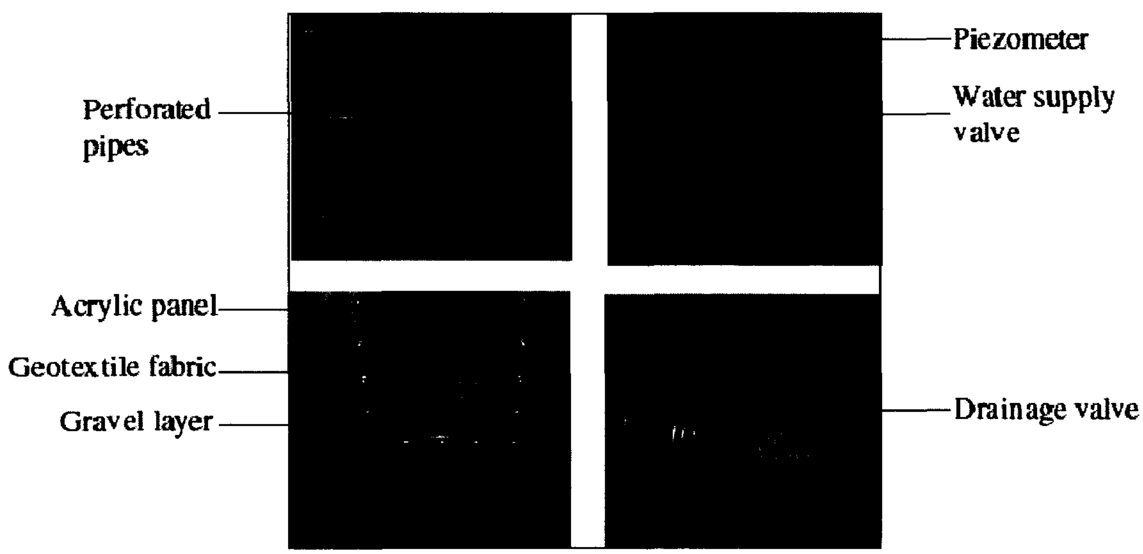

Figure 4.5 Key features of the test box used for the present study

4.2.2 Loading frame and pull-out device

The test box was used as the reaction frame for the application of the pull-out force in tension for the soil nails. The test hydraulic jack was mounted on a reaction beam (203 mm x 203 mm x 9.5 mm thick HSS) at an inclination of 15° as shown in Figure 4.5. The reaction beam was also used to test vertical nails and a special frame was used for testing of the horizontal nails. The reaction force was transferred to the wall of the test box for each test. The pull-out load testing was performed by using a calibrated Enerpac jack which was operated with a hand pump. The capacity and stroke of the jack are 267 kN and 300 mm, respectively. The test load was applied axially. Figure 4.6 shows details of the complete set-up for load testing of nail inclined at 15°.

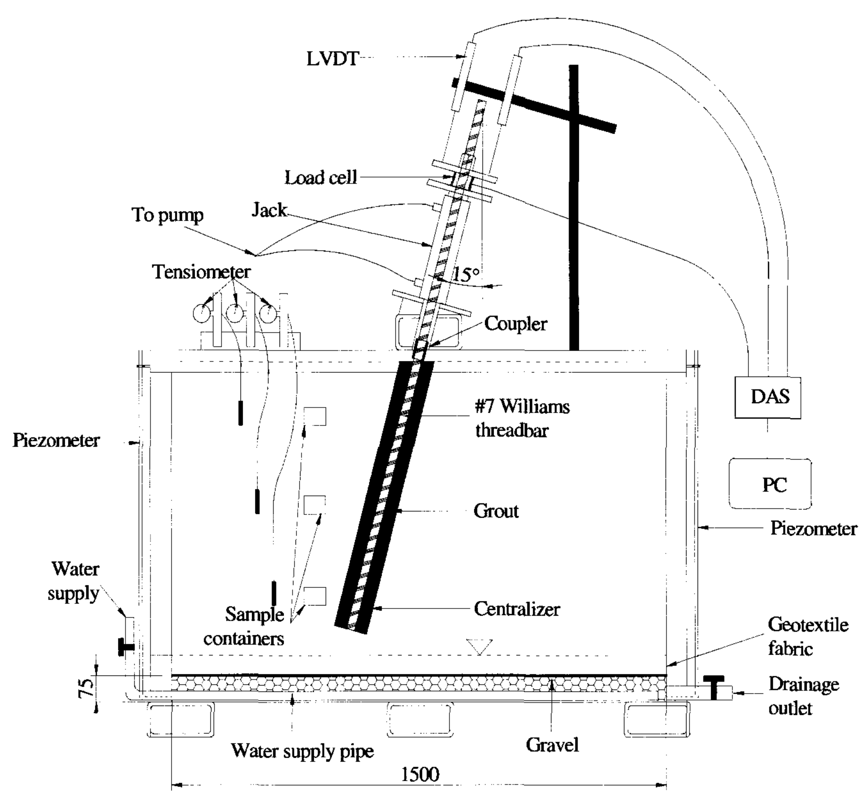

Figure 4.6 Set-up used for testing of nails inclined at 15 degrees

4.2.3 Arrangement for drilling and grouting

The holes for the installation of the soil nails were 100 mm in diameter. Drilling of the holes was done with an electric coring machine, mounted at the top of the test box. The set-up used for drilling the holes inclined at 15° is illustrated in Figure 4.7. The arrangement for drilling the horizontal holes is shown in Figure 4.8.

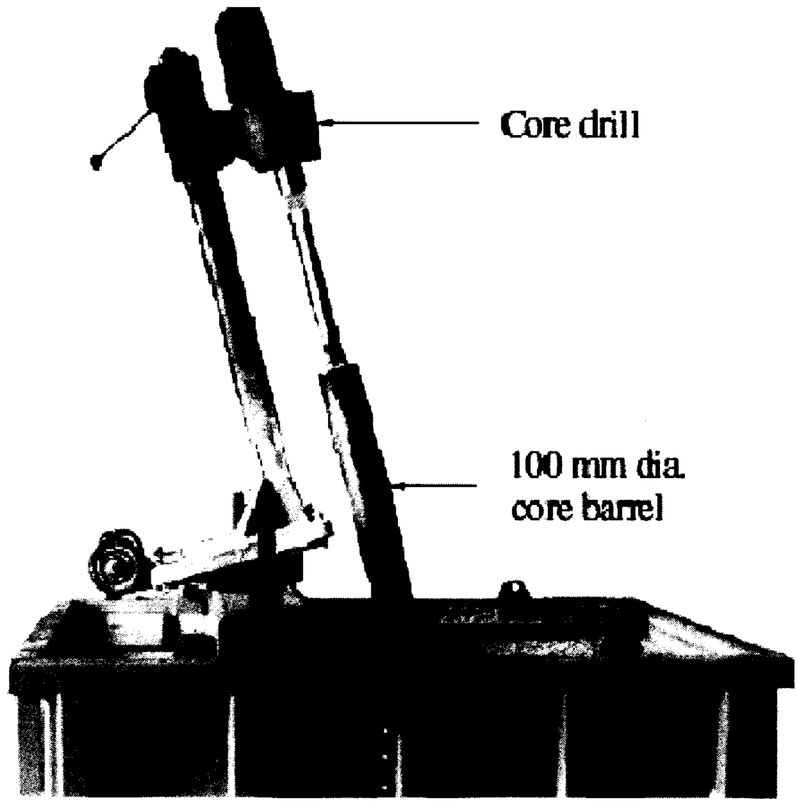

Figure 4.7 Drilling set-up for soil nails inclined at 15 degrees

Figure 4.8 Drilling set-up for horizontal soil nails

A tremie tube was temporarily attached to the bottom to the bar during installation. Grout was injected through the tremie tube by using a large funnel and gravity flow. Figure 4.9 shows the set-up used for grouting.

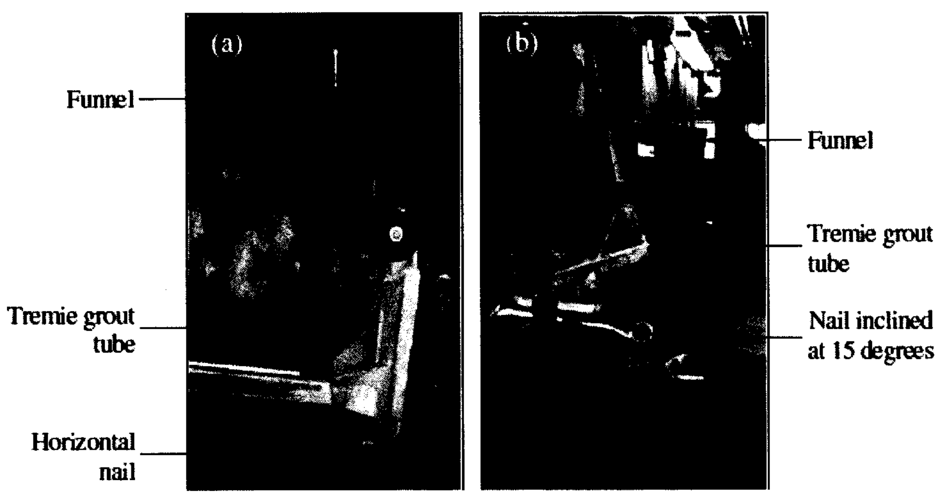

Figure 4.9 (a) Set-up for grouting of horizontal nails; (b) Set-up for gouting of nails inclined at 15 degrees

4.3 Nail properties

Grouted soil nails of 100 mm diameter were used for this experimental program. Williams Form Hardware #7 threaded bar (yield stress = 517 MPa) was used as the central reinforcement for the soil nails. The general properties of the central reinforcement are provided in Table 4.1

Table 4.1 Properties of the central reinforcement

Bar designation	#7
Nominal diameter (mm)	22
Minimum net area through threads (mm^2)	387
Minimum ultimate strength (kN)	267
Minimum yield strength (kN)	200
Nominal weight (kg/m)	3.04
Approximate thread diameter (mm)	25.4

4.4 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. The water/cement ratio for grout used for soil nails typically ranges from 0.4 to 0.5 (Lazarte et al., 2003). Grout characteristic has a strong influence on the ultimate bond strength at the grout-soil interface. According to Franzen (1998) the grout characteristics will influence the nail surface area and normal stress acting on the grouted nails. Grout comprising of a high water/cement ratio will spread easily and fill all irregularities in the drilled hole. The water content of the grout in contact with sand will be reduced and a stiff mortar will be obtained, which will not fill all the voids. Schlosser et al. (1991) recommended water cement ratio of 0.4 to 0.6 to obtain an economical and a good quality nail. 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.

Grout was injected using the tremie method by attaching a grout tube to the bottom of the nail. Grout tubes are typically attached to the central reinforcement and left in placed upon completion of grouting. The grout injection was done in one continuous operation to fill the annular space between the nail and soil without any voids or gaps. The pull-out capacity of the soil nail is heavily dependent on the soil-grout contact surface therefore care was taken in the selection of the grout mix for installation of nail.

4.5 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 acquisition card installed in a personal computer, and connected to the transducers through a NI SCB-68 interface box. Matric suction measurements were also taken during each pull-out test at various depths, relative to the location of the water table using 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. The HLP190 LVDT with a stroke length of

150 mm were used to measure the displacement. 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 matric suction. A list of the key instrumentation used for this research study is provided under table 4.2. Figure 4.10 illustrates some of the key instrumentation used for the test program.

Table 4.2 List of key instrumentation used for the pull-out test

Item	Capacity	No.	Measurement
ALCO Load cell	100 kN	1	Pull-out force
LDVT – HPL 190	200 mm	2	Nail displacement
Tensiometer (2100 F)	90 kPa	3	Suction measurement in the test box
NI PCI-6289	NA	1	Data logger
NI SCB-68	NA	1	Channel box

NA – Not Applicable

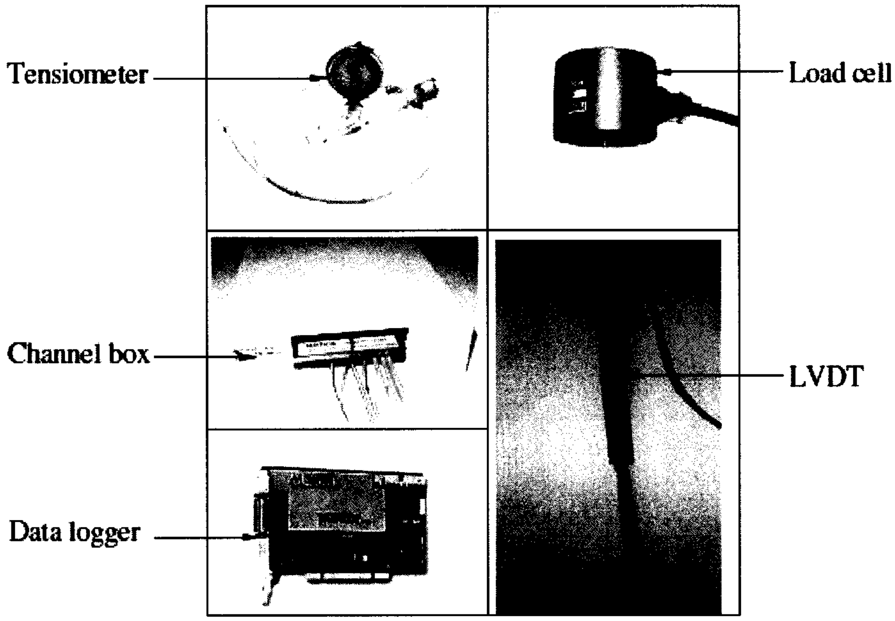

Figure 4.10 Key instrumentation used for the test program

4.5.1 Tempe cell apparatus for measuring the soil-water characteristic curve (SWCC)

The SWCC is commonly measured in a laboratory by using the Tempe cell apparatus and the axis-translation technique. The axis-translation technique facilitates an increase of air pressure in the tempe cell and prevents cavitation, especially for the measurement of the SWCC for suction greater than 100 kPa (Hilf, 1956). Axis-translation technique and the Tempe cell allows for direct measurement of the SWCC for matric suction range from 0 to 500 kPa. The Tempe cell apparatus is similar to the pressure plate apparatus. The pressure plate apparatus is commonly used for measuring the SWCC for a much larger suction range (0 to 1500 kPa). The Tempe cell is smaller in comparison to the pressure plate apparatus and facilitates measurement of the SWCC for individual specimens (ASTM D – 02 (2008)). The Tempe cell consists of a saturated high air entry disk (HAED), which separates air and water phases in a closed vessel. The difference between the applied air pressure, u_a and the pore water pressure, u_w at equilibrium conditions is the matric suction, $(u_a - u_w)$. The pore water pressure connection is typically open to atmosphere and hence the applied air pressure is the matric suction of the soil specimen.

In this research program, the Tempe cell apparatus was used for the measurement of the matric suction in the range of 0 to 20 kPa. The sandy soil used for this research program typically attains residual conditions (low degree of saturation) within about 10 – 15 kPa matric suction. The sand fully desaturates and attains low degrees of saturation (typically less than 5%) when the applied matric suction values are greater than 15 kPa.

A pressure gauge with a sensitivity of 0.2 kPa was connected to a pressure regulator. A sample of the soil having the same density as that used in the test box was placed in the Tempe cell, on the saturated ceramic disk. The soil sample was initially saturated by allowing access of water to the soil sample, by using a bottle of water placed at a higher elevation than the sample. The matric suction values were induced by increasing the applied air pressure. Typically, equilibrium condition with respect to water content was achieved for each applied pressure increment after a period of 24 hours. The mass of water lost due to pore-water drainage at each increment was measured by determining the mass of the Tempe cell. The SWCC relationship was obtained from the water content versus matric suction relationship. Figure 4.11 illustrates the Tempe cell apparatus.

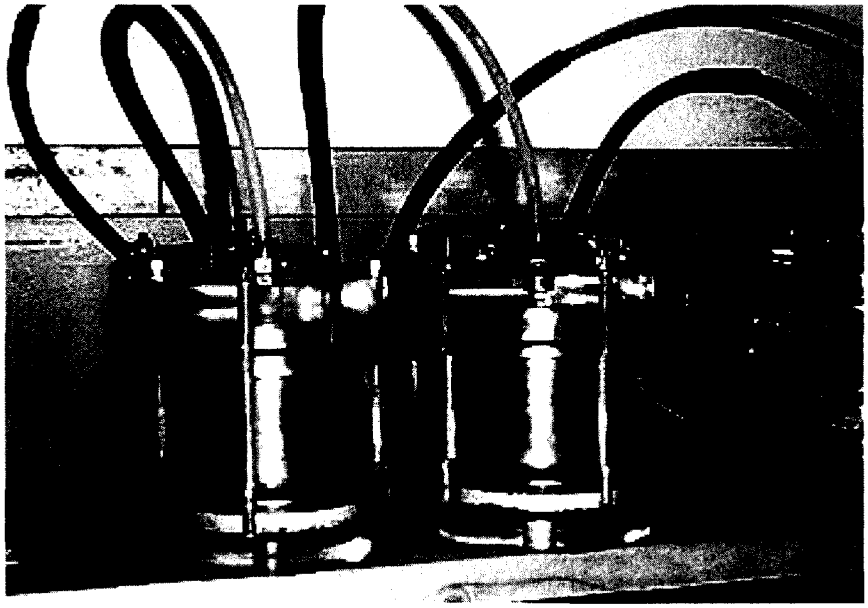

Figure 4.11 Tempe cell apparatus

4.5.2 Tensiometers

The tensiometers used for the test program were soil moisture probe 2100F, having an operating range from -100 to 100 kPa to measure soil suction. The vertical spacing of the tensiometers for each test was relative to the elevation of the water table in the test box. Three tensiometers were installed in the text box for each test.

Tensiometers are conventionally used for the direct measurement of suction in the range of 0 to 90 kPa. The ceramic tip of a tensiometer is typically an inverted cup or small probe that can be filled with water. The purpose of the ceramic tip is to create a saturated hydraulic connection between the unsaturated soil and the water in the tensiometer body, through the use of a pressure sensor. A set-up of a typical commercial tensiometer is shown in Figure 4.12.

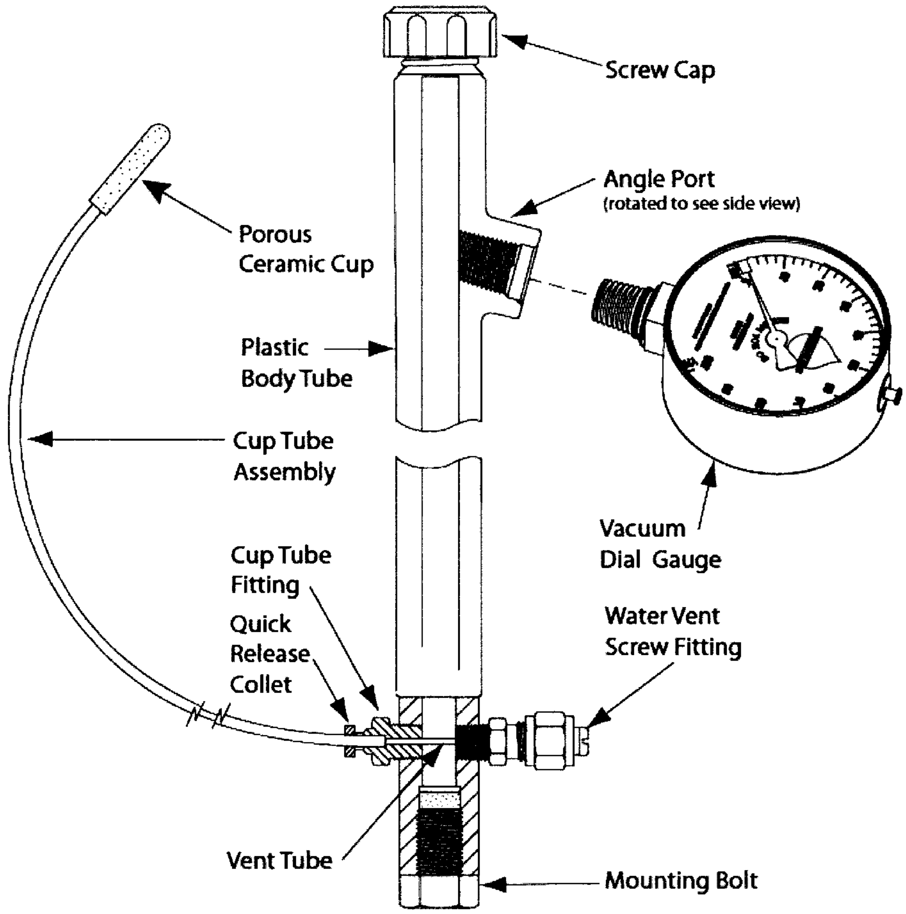

Figure 4.12 Schematic drawing of small-tip laboratory tensiometer (Soil Moisture Manual, 2009)

The main component used for measuring soil suction on the tensiometer is the high air entry (HAE) material. The HAE is made of ceramic materials such as kaolinite, which is characterized by microscopic pores of relatively uniform size and distribution. Surface tension forces maintain the gas-liquid interfaces formed in the ceramic material of the saturated HAE disk. The surface tension acts as a membrane for separating the air and water phases. Figure 4.13 shows a schematic cross-section of a typical saturated ceramic disk.

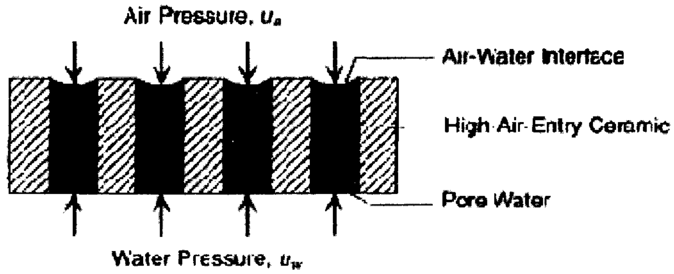

Figure 4.13 Operating principle of HAE ceramic cup (Lu and Likos, 2004)

4.5.2.1 Measurement of suction using tensiometers

The negative pore water pressure (matric suction) is transmitted through the saturated ceramic disk and facilitates the flow of water (drying process) to the soil. The tensiometer measures the matric suction at equilibrium condition or the time at which water stop flowing out of the unit. For measurement in a saturated soil, water will flow through the ceramic disk from the soil. Osmotic suction has no effect on the pressure measurements since the ceramic tip is permeable to dissolved solutes. The matric suction measurements should be corrected for the difference in elevation between the sensor and the pressure gauge. Measurements obtained from the tensiometer is the field, are generally limited to approximately 70 to 80 kPa. Figure 4.14 shows an enlarged schematic of the porous ceramic tip in contact with unsaturated soil grains.

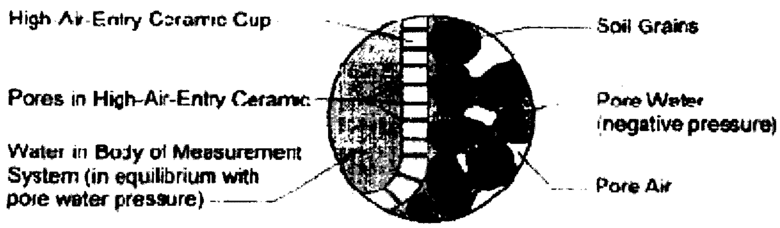

Figure 4.14 Enlarged schematic showing porous ceramic tip in contact with unsaturated soil grains (Fredlund and Rahardjo, 1993)

4.6 Summary

Equipment consisting of a soil nail pull-out box and other features was specially designed to study the influence of matric suction on the pull-out capacity of grouted soil nails at different inclinations under saturated and unsaturated conditions. In order to capture the pull-out test data on a real time basis with great accuracy, an elaborate instrumentation system was assembled. A comprehensive experimental program was undertaken using this equipment to determine the variation of soil nail capacity with respect to matric suction for compacted sand. The test program details along with the results are discussed in the next chapter.

CHAPTER 5

TESTING PROGRAM AND RESULTS

5.1 Introduction

The testing program of the research undertaken through this thesis is summarized in three sections within this chapter. The first section is Experimental program I, in which the soil properties are outlined and discussed. Experimental program II forms the second section in which the procedures used for the pull-out testing of soil nails performed under saturated and unsaturated conditions are presented along with the test results. The details of the procedure for sand compaction in the test box are also outlined in this section. In addition, the procedure for achieving different average matric suction values of the compacted sand in the test box is also summarized. Experimental program III comprises the third section in which test results related to the soil-water characteristic curve (SWCC) are presented. The SWCC was obtained by using three methods, namely, direct measurements, Tempe cell apparatus and one point technique.

5.2 Experimental program I

The soil used for this research program was commercial sand (Unimin 7030) supplied by Unimin Canada Ltd, St-Canut, Quebec. The sand was supplied in bulk bags with a total weight of 1385 kg per bag. Unimin 7030 sand is produced from high purity industrial quartz sands. The grain size distribution (GSD) with relatively uniform grain shapes offers excellent placement, repeatable compaction and mechanical properties.

Unimin 7030 sand was selected for the present research since it was used for several research programs previously conducted at the University of Ottawa. The physical properties, shear strength parameters and the soil water characteristic curve (SWCC) behavior are well known for this soil and published in the literature (Vanapalli and Mohamed, 2007; Oh and Vanapalli, 2008; Oh et al., 2008).

Figure 5.1 summarizes the various tests that were conducted as part of Experimental program I in the form of a flow chart.

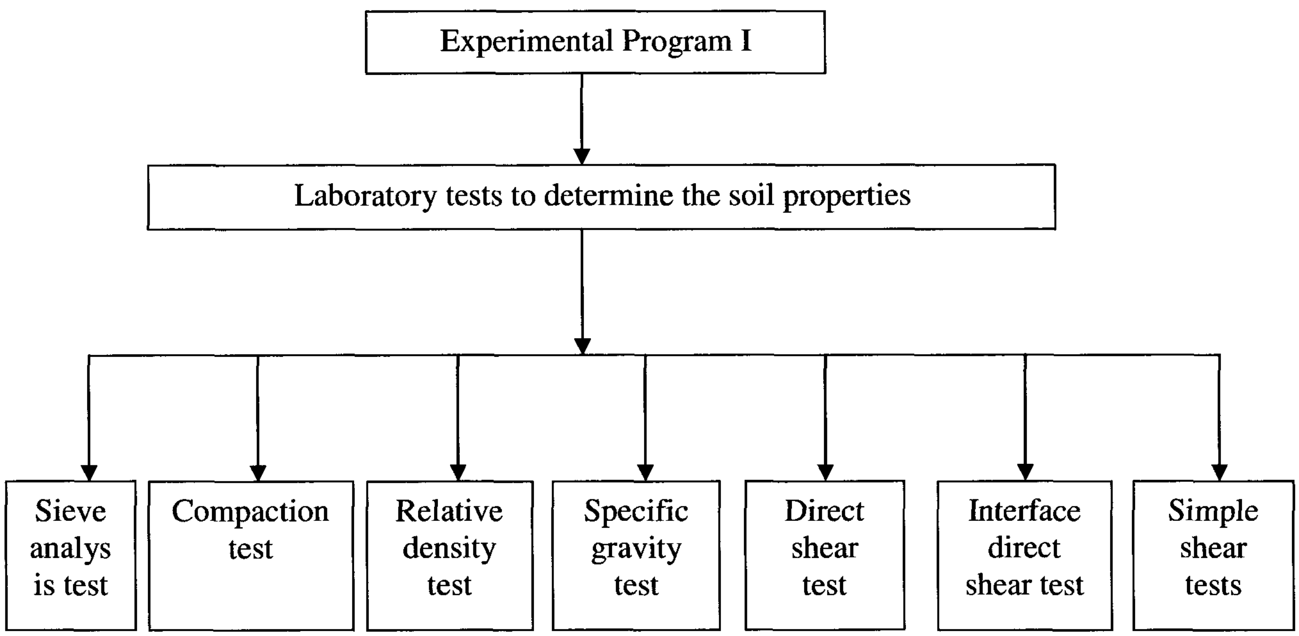

Figure 5.1 Experimental program I

5.2.1 Dry sieve analysis test

A representative sample (1.0 kg) of sand was used to determine the grain size distribution (GSD). The soil sample was air-dried for a period of one day prior to performing sieve analysis in accordance with ASTM D422 (2007). Figure 5.2 summarizes the GSD of the tested soil.

The soil was classified as poorly graded sand (SP) as per the Unified Soil Classification System (USCS). There was less than 1% of silt in the sand used for this research based on the grain size distribution.

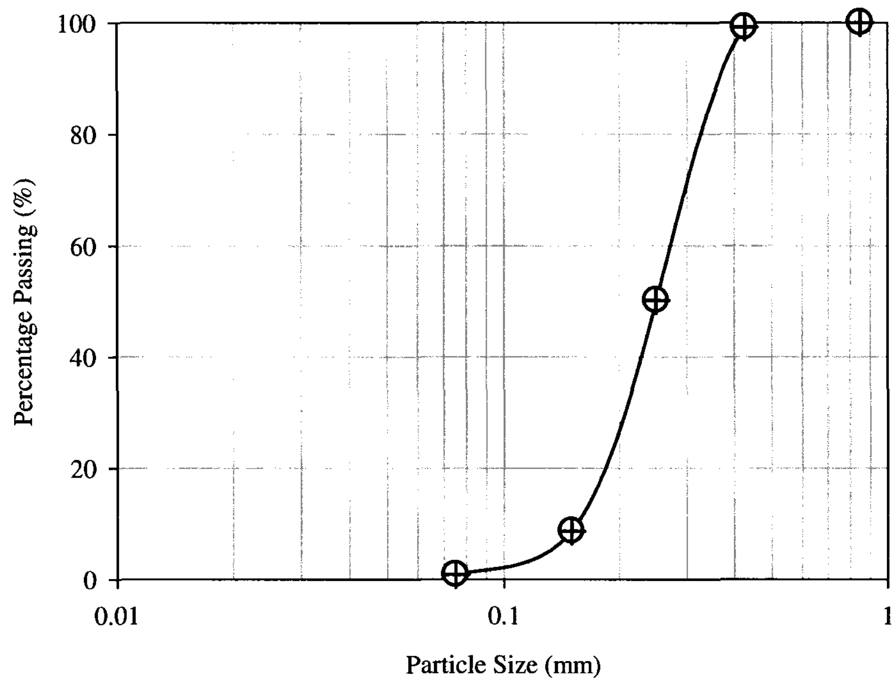

Figure 5.2 Grain size distribution of the soil used in the research program

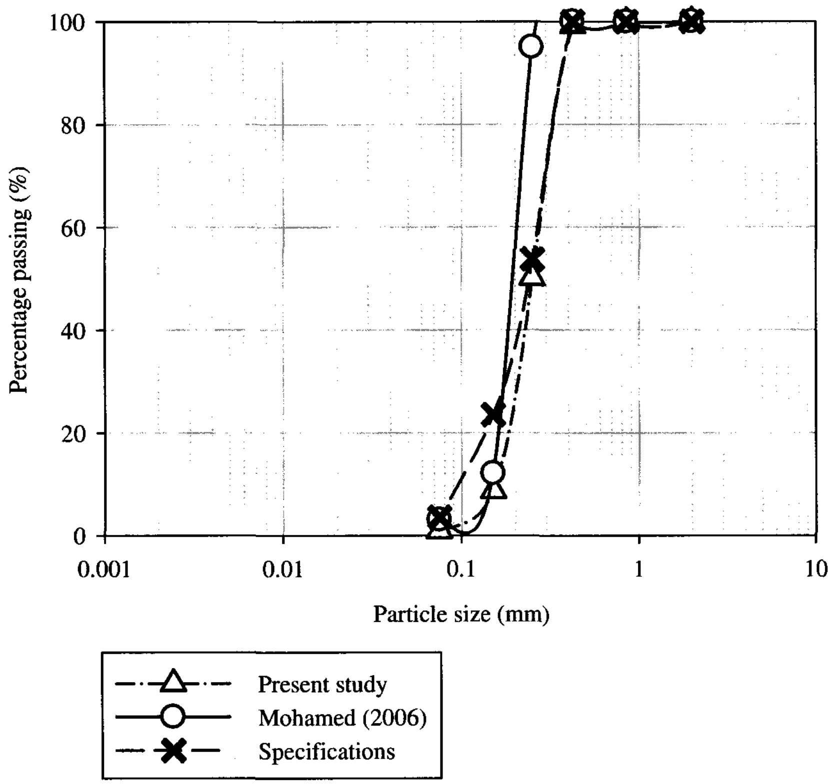

Figure 5.3 Comparison of grain size distribution curves from different studies

The GSD for the sand from the present study, Mohamed (2006) and the manufacturer's specifications is presented in Figure 5.3. There is a good comparison between the GSD curves from all these studies providing confidence that the soil is similar (i.e c_u = 1.83 for Mohamed (2006) and c_u = 1.75 for the present study/manufacturer's specification). The results also provided confidence for using the soil properties measured by Mohamed (2006) in the present study. While most of the soil properties are repeated in the present research program, the SWCC measured by Mohamed (2006) using the Tempe cell apparatus was adopted for the present research program.

5.2.2 Compaction test (Modified Proctor test)

The compaction test was conducted in accordance with ASTM 1557-09 on the sand used for this study. Figure 5.4 illustrates the relationship between the dry unit weight and water content. The optimum moisture content and the maximum dry unit weight from the compaction curve were 15.4% and 15.5 kN/m^3 respectively. The soil in the test box was compacted close to optimum moisture content by using a 6.8 kg manual compactor to achieve the highest value of density index.

5.2.3 Relative density and specific gravity tests

The relative density tests were conducted to determine the maximum and minimum densities for the sand following ASTM D4235 (1994). The sand was filled in a standard compaction mold in several layers. The mold with the soil was then vibrated by tapping it sharply on the sides with a rubber mallet. The maximum density of the sand was calculated from mass-density relationships. Tests were repeated three times in order to obtain an average value from three trials. The minimum density of the soil was obtained by filling the mold with the soil without any vibrations. The minimum and maximum void ratios are 0.88 and 0.64 respectively.

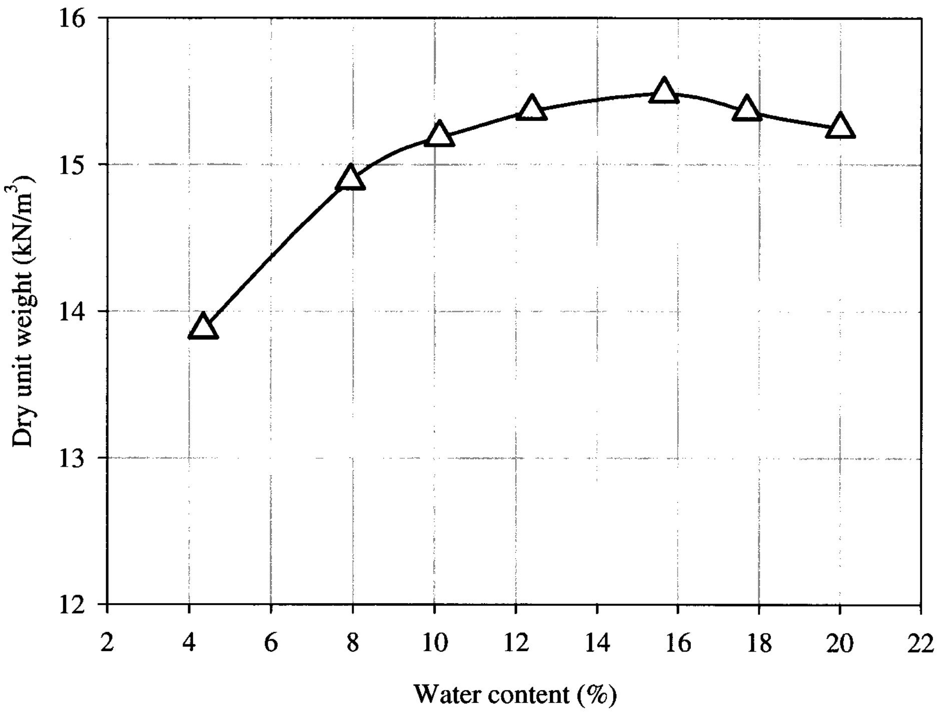

Figure 5.4 Compaction test results

The relative density can be expressed in terms of unit weight as given below:

$$D_r = \left(\frac{\gamma_f - \gamma_2}{\gamma_2 - \gamma_1}\right)\left(\frac{\gamma_2}{\gamma_1}\right) \tag{5.1}$$

where:

γ_1 = unit weight of the soil in the loosest state, 13.8 kN/m^3

γ_2 = unit weight of the soil in the densest state, 15.8 kN/m^3

γ_f = unit weight of the soil in the test box

5.2.4 Specific gravity test

The specific gravity tests were performed in the laboratory in accordance with ASTM D854 (2010). The average value of the specific gravity, G_s of the soil used in the study is equal to 2.65 from three tests.

Table 5.1 summarizes the properties of the tested soil.

Table 5.1 Soil properties

Property	Description or value
Specific gravity, G_s	2.65
D_{60} (mm)	0.28
D_{30} (mm)	0.2
D_{50} (mm)	0.25
Coefficient of uniformity, C_u	1.75
Coefficient of curvature, C_c	0.9
Unified soil classification system (USCS)	*SP*

5.2.5 Direct shear test

The effective shear strength parameters (i.e., c' and ϕ') of the compacted sand were measured using the direct shear test apparatus. The dry sand sample was tamped into the direct shear box to a dry density value equal to the soil compacted in the test box. The soil sample was saturated prior to loading and shearing in the direct shear box by allowing access of water slowly from the bottom of the soil sample into the shear box. The samples were then loaded under different normal stresses and sheared at a constant shearing rate of 1.0 mm/min. The rate used for pull-out testing of the soil nails was the same as the rate used for shearing the sand sample in the direct shear box.

The relationship between the shear stress and the normal stress at peak state for the tested soil is presented in Figure 5.5. The angle of internal friction ϕ' was found to be 30.1° degrees (tested under normal stresses of 23, 34 and 78 kPa).

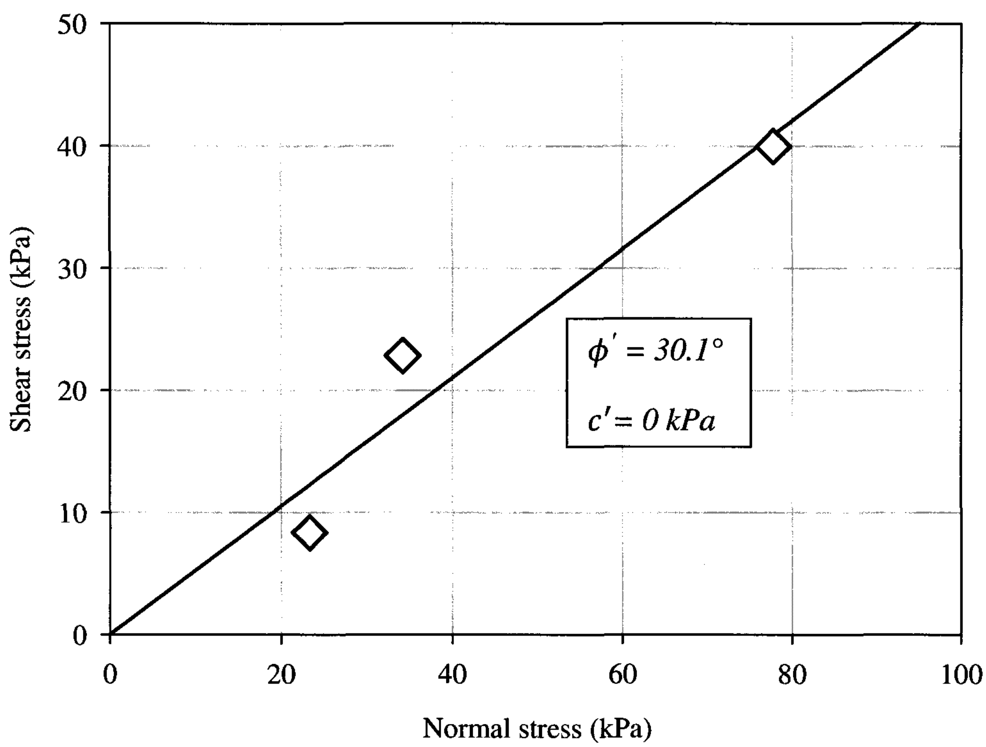

Figure 5.5 Direct shear test results

5.2.6 Simple shear test

Simple shear test was also performed on the sand used for this research program as a check to verify the results obtained from the direct shear test apparatus. The results obtained from the simple shear test for the sand under a dense state (e = 0.65) is presented below in Figures 5.6.

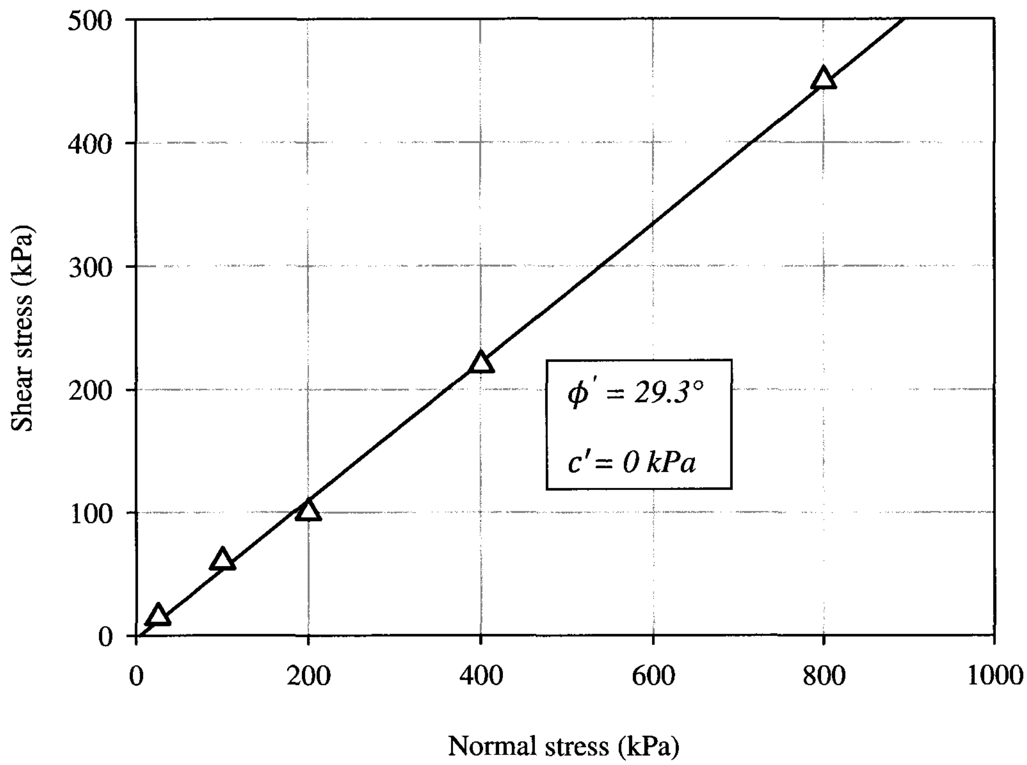

Figure 5.6 Simple shear test results

5.2.7 Interface (grout-soil) direct shear test

The interface friction angle *(δ)* between the compacted sand and grout was measured using the direct shear test apparatus. This parameter is required for the estimation of the pull-out capacity of the soil nails in both saturated and unsaturated conditions using the technique proposed in this research program.

The upper section of the direct shear box was placed upside-down with a temporary cover secured to the bottom. The dry sand sample was then tamped into the upper section to a dry density value similar to the compacted soil in the test box. The lower section of the box was attached to the upper section with the compacted sand, allowing for a 1 mm gap between the two sections. Grout was mixed at a water-cement ratio of 0.45 and poured into the other section of the direct shear box. The grout was allowed to cure in place for a time period of 7 days. During the direct shear test, the grout was in the lower section of the direct shear box and the sand in the upper section. The sand was saturated prior to testing by allowing access to water slowly from the bottom of the shear box.

A plot of the shear stress against the normal stress at the peak state is presented in Figure 5.7.

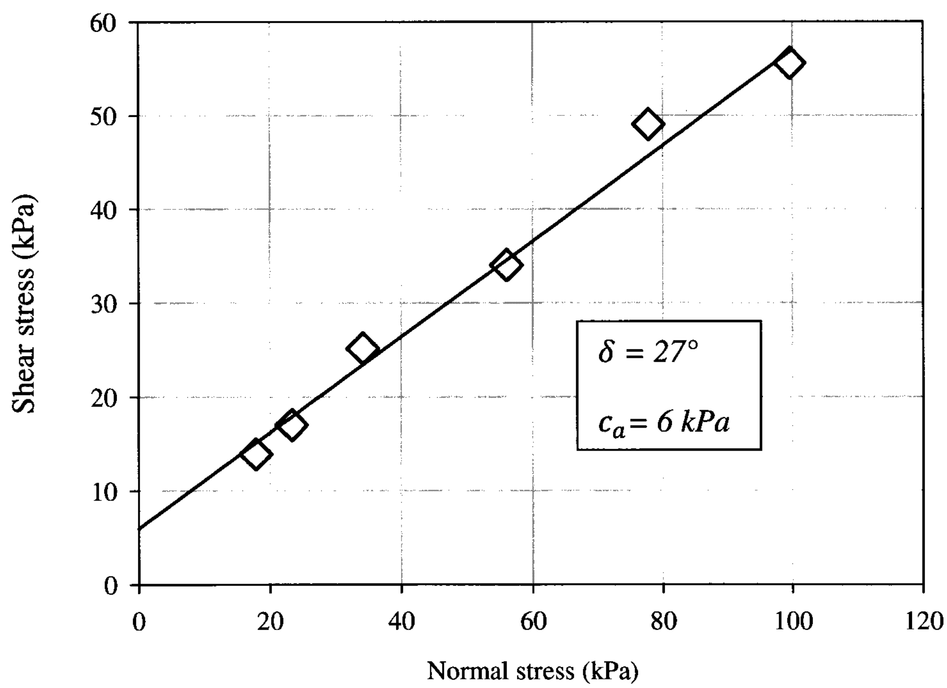

Figure 5.7 Interface (soil/grout) direct shear test results

The sample was then loaded under normal stresses of 18, 23, 34, 56, 78 and 100 kPa and sheared at a constant rate of 1.0 mm /min. The shearing rate used for pull-out testing of the soil nails was the same as the rate used for shearing the sand sample in the direct shear box.

5.3 Experimental program II

The pull-out testing was performed on nails installed in a test box under both saturated and unsaturated conditions. The testing was performed to understand the pull-out behaviour of soil nails installed vertically, horizontally and inclined at 15^0 to the vertical. The ground water table was elevated to the surface of the soil by using perforated pipes installed at the bottom of the test box. The water flow and level were controlled by using water supply/drainage valves installed on the test box. The water table was lowered by using the drainage valves to achieve desired matric suction values at which the soil nail pull-out tests were proposed to be conducted.

Upon achieving desired degree of saturation, the soil nails were loaded axially to establish the pull-out capacity. Figure 5.8 provide the details of different tests performed in Experimental program II in the form of a flow chart.

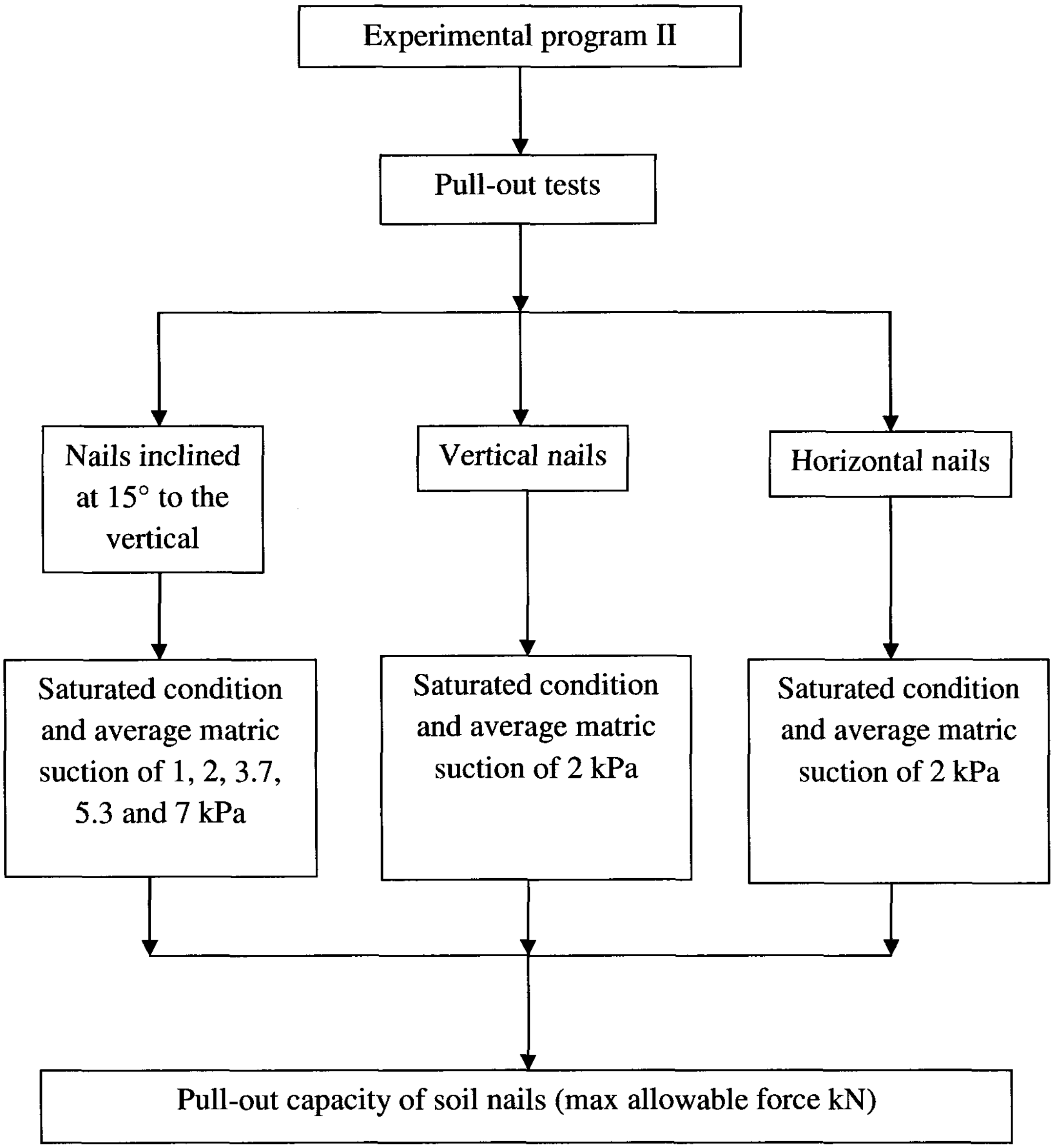

Figure 5.8 Details of the experimental program undertaken using the test box to determine the pull-out capacity of the tested soil nails in sand under saturated and unsaturated conditions

5.3.1 Preparation of soil in the test box for pull-out testing

The sand in the test box was compacted at a water content that was close to its optimum moisture content (i.e approximately 15.4 %). Sand was placed in the test box in a loose state (i.e approximate void ratio of 0.88) by using a shovel and leveled in layers of 200 mm before compaction. Prior to compaction of the loose sand, the water table was adjusted to approximately 200 mm below the underside of each new layer. The soil in each layer (i.e 150 mm after compaction), imbibed water by capillary stresses and achieved water content close to the optimum. The compaction process was done in a grid pattern by using a 6.5 kg manual compactor (250 mm x 250 mm). The sand was compacted to layers of 150 mm by dropping the compactor fifteen times from a height of 450 mm for each 250 x 250 mm section of each layer.This process allowed for uniformity in the density of the compacted sand and reproducible profiles for each pull-out test.

Franzen (1998) and Kim et al. (1995) prepared sand sample by pouring a predetermined quantity of sand inside a given volume and found that this method is effective in achieving homogeneous soil layers. Junaideen (2001) also adopted the same method to prepare loose sample of completely decomposed granite (CDG) and later verified that the prepared sample had reasonably uniform density.

The average density index value that was achieved in the test box was approximately 62%. The density index was carefully controlled for all tests to ensure identical conditions. The density of the tested soil was verified by collecting samples in aluminum cups and checking the in-situ density prior to the installation of each test nail. Additionally, three small cups with perforations were placed adjacent to the tensiometers to determine the variation of water content with depth. These cups were removed after the completion of the pull-out test. Figure 5.9 shows perforated cups used to measure the water content of soil samples within the test box.

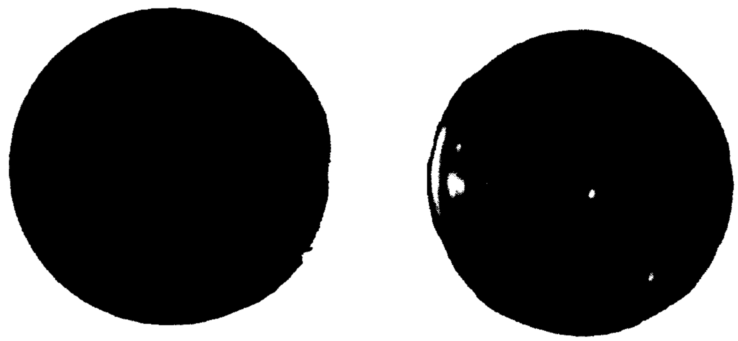

Figure 5.9 Perforated aluminum cups

5.3.2 Installation of soil nails for testing

The installation of the grouted soil nails were carried out in three main steps, namely; drilling of the hole, installation of the central reinforcement, and grouting. Details of the steps are outlined below.

5.3.2.1 Drilling of hole

An electric core drilling machine was used to drill 100 mm diameter hole. The soil was saturated prior to drilling and then subjected to desaturation to a level just below the proposed tip elevation of nail placement. The processes of saturation and desaturation of the soil provided adequate suction to temporarily maintain a stable open hole during the drilling process. The core barrel was advanced to the maximum achievable depth and then retracted to evacuate the cored material. This process was repeated until the drilled depth was achieved after which the core barrel was detached to facilitate installation and grouting of the test nail. The method of drilling was selected to provide a reproducible process for each test.

5.3.2.2 Installation of steel bar

The test nail was installed inside of the drilled hole soon after completion of drilling. Two centralizers and a tremie grout tube were attached to a # 7 Williams threadbar (yield stress = 517 MPa).

5.3.2.3 Grouting

The prototype soil nails used for pull-out testing were grouted using Type 10 Portland cement mixed a water/cement ratio of 0.45. The grout was mixed using a paddle mixer and batching was done by mass. A grout tube (25 mm diameter) was secured to the bottom of the nail during installation to discharge grout by the tremie method.

5.3.3 Testing procedure used for the grout

The following tests were performed on the grout mix used for this experimental program.

5.3.3.1 Consistency test

The consistency of the grout refers to the degree at which the grout can flow. The flow cone method as per ASTM C939-02 was used to measure the consistency by monitoring the time for a specific amount of grout (1 litre) to run out of the cone (Figure 5.10).

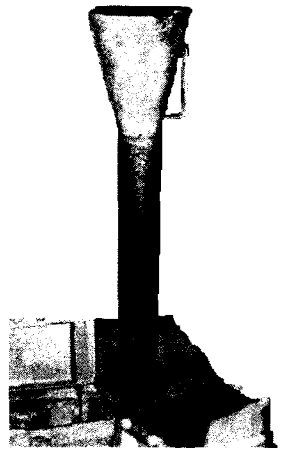

Figure 5.10 Set-up for flow cone test

The time period is called the efflux time. The grout used for this experimental program was mixed at a water cement ratio 0.45 and tested three times using the flow cone. The average efflux time for the mix used in this study was 34 seconds.

5.3.3.2 Grout cube compressive strength

Grout cubes (50 x 50 x 50 mm) were prepared and compressive strength test was determined as per ASTM C109-08 for hydraulic cement mortars. The average compressive strength of three grout cubes was measured after 7, 14 and 28 days and produced results of 28.2, 31.5 and 34.5 MPa respectively. The nominal strength required for soil nails in the practice is 30 MPa after 28 days. Figure 5.11 shows the development of the grout strength with time.

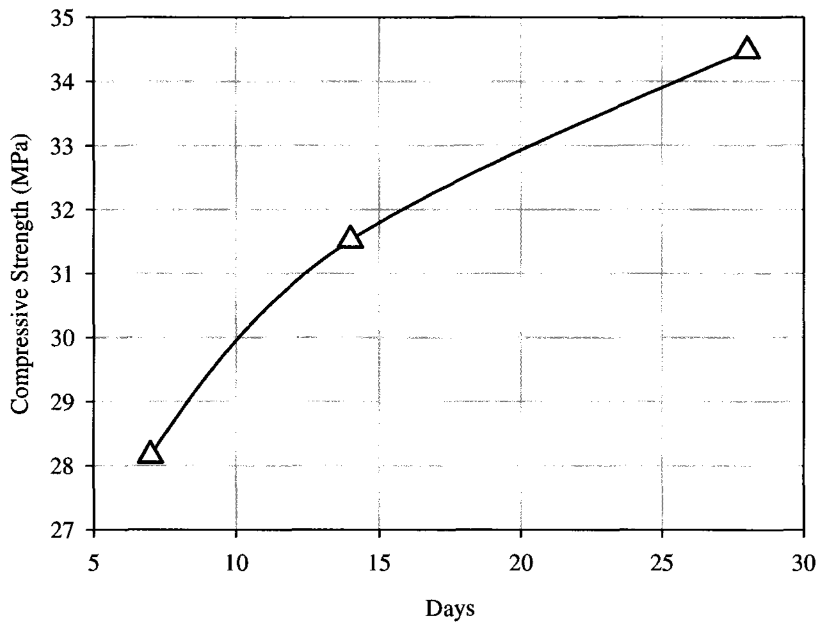

Figure 5.11 Grout cube compressive strength development with time

5.3.3.3 Bleeding and settlement test

Grout mixes are subjected to bleeding or the development of layer of water at the top of freshly placed grout, which is a result of sedimentation of solid particles (Warner, 2004). The water that bleeds is absorbed by the soil quickly causing settlement shrinkage. A grout mix comprising of a water/ cement ratio of 0.45 was prepared and placed in a graduated cylinder to observe the changes in total volume and accumulation of bleed water on the surface of the grout over a period of time as per ASTM C940. The average bleed recorded for the grout mix used for this study was 2%. An amount of 5% bleed is a reasonable amount and grouts with a higher amount of bleeding is considered to be unstable (Warner, 2004)

5.3.3.4 Specific gravity test for the grout

A Baroid mud balance was used to perform measurements of the specific gravity of the grout on a real time basis. This method was used to verify the water content used in the grout mixture. The specific gravity of the grout was measured in accordance with the method prescribed under API Recommended Practice 13B-1 for a Baroid mud balance. The Baroid mud balance is a calibrated scale that is used to measure the specific gravity. The mud balance was calibrated prior to testing of the grout sample by checking the specific gravity of water. Figure 5.12 shows the Baroid mud balance.

Figure 5.12 Baroid mud balance

5.3.4 Pull-out test

Pull-out testing was performed approximately 7 days after installation of the test nails. There are two general methods to perform pull-out tests, namely; displacement-rate controlled test and force controlled test. Displacement-rate controlled tests are used to establish the ultimate pull-out capacity. The residual pull-out capacity can also be obtained easily from the displacement-rate controlled test. Force controlled pull-out tests provides a rough estimation of the peak capacity of the nails and commonly used in the field because it is easier to conduct (Barley et al, 1997; Junaideen et al., 2004). The pull-out rate for this study was 1 mm/min as per the recommendations of FHWA (1993). Table 5.2 outlines the series of tests performed for this research study.

5.3.4.1 Pull-out testing sequence

The pull-out testing sequence consisted of the following main steps:

- Filling and compacting the soil in the test box and setting up of instrumentation
- Installation of nails and allowing for a curing period of 7 days
- Conducting the pull-out test using the displacement-rate method in controlled manner

5.3.5 Procedure to estimate the average matric suction value in the test box

The relationship between matric suction with respect to depth is non-linear as indicated from the results obtained from tensiometers embedded in the test box. However, matric suction variation was considered to be linear with respect to depth for this research. The suction was taken as the average value of three readings obtained by tensiometers placed in the unsaturated zone. In addition to the tesnsiometers, the gravimetric water contents were determined approximately at the same levels by collecting soil specimens in small aluminum cups. These cups with perforations were embedded in soil and placed close to the ceramic tip of the tensiometers. Figure 5.13

shows a typical cross section of the test box in a schematic form and provides the details of the placement of the tensiometers and the perforated cups at different elevations.

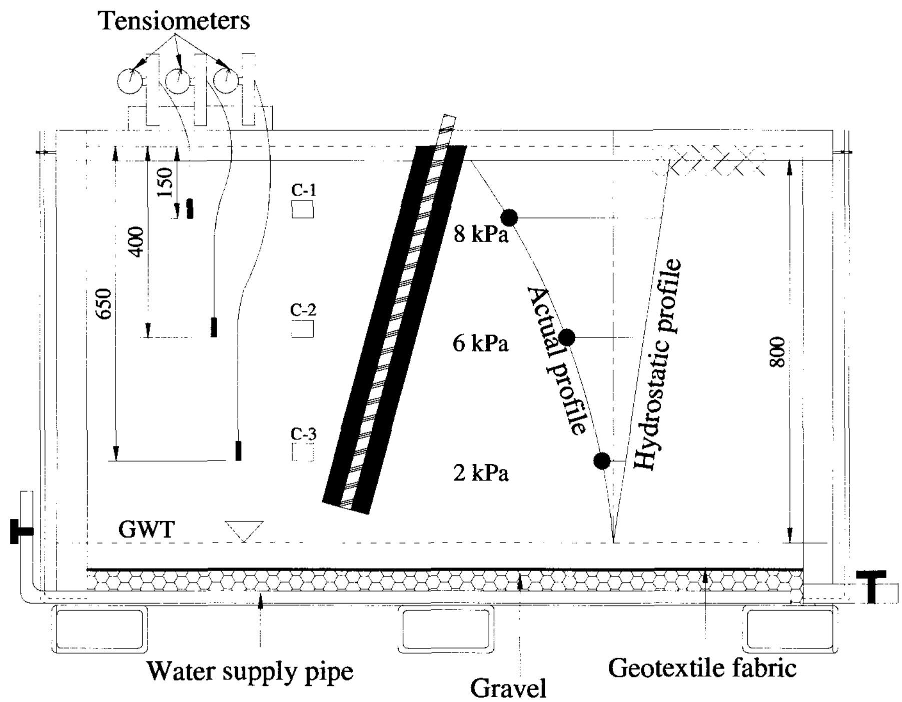

Figure 5.13 A schematic illustrating the procedure used for determining the average matric suction in the test box

5.3.5.1 Effects of hydration on the average matric suction value

A test was performed to evaluate the effects of hydration on the average matric suction value within the test box. The compaction and drilling process used for the test nails were repeated for the installation of a 400 mm deep grouted hole (i.e. without the central reinforcement) to check the effects of hydration. Perforated cups were installed during the compaction stage of the soil and located at the interface (i.e. grout/soil), 150 mm and 300 mm away from the interface. A total of nine cups were embedded in the same plane at similar offsets from the interface as shown in Figure 5.14 below. Readings were taken after seven, fourteen and twenty eight days from the same test set-up by removing three cups at a time to check the variation in water content with time. The level of the water table in the test box was maintained at the same elevation for the entire test period.

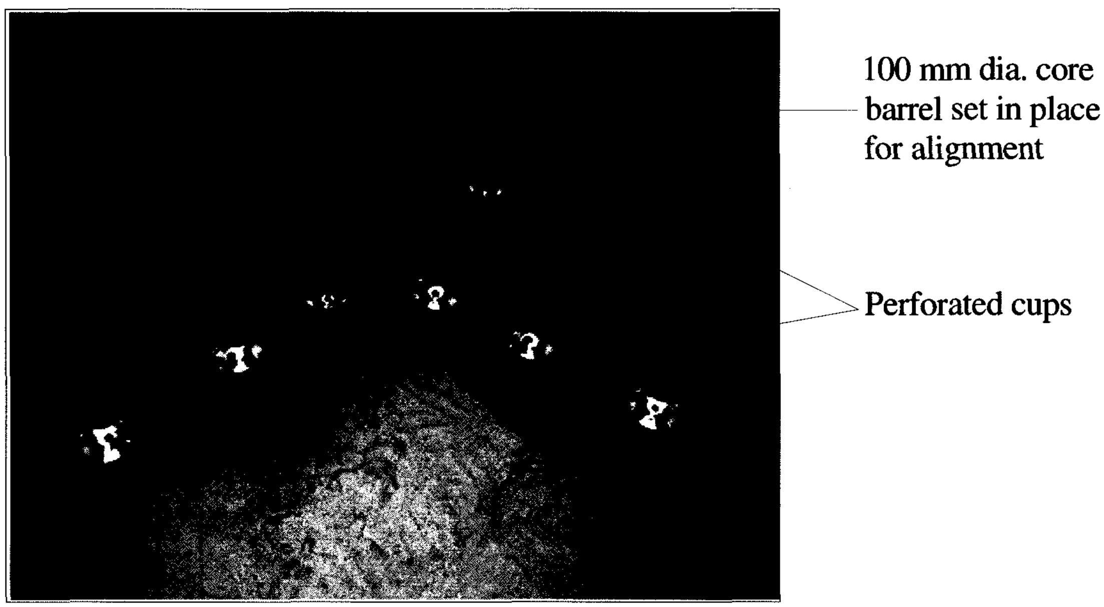

Figure 5.14 Arrangement for hydration test

Table 5.2 Pull-out test performed during the present study

Test number	Description	Inclination	Average Suction (kPa)
1	Saturated condition	15° to vertical	0
2	Water table at 0.15 m below surface	15° to vertical	1
3	Water table at 0.275m below surface	15° to vertical	2
4	Water table at 0.55 m below surface	15° to vertical	3.7
5	Water table at 0.8 m below surface	15° to vertical	5.3
6	Dry condition	15° to vertical	7
7	Saturated condition	Vertical	0
8	Water table at 0.275 m from surface	Vertical	2
9	Saturated condition	Horizontal	0
10	Water table at 0.275 m from centre of the nail	Horizontal	2

5.3.4.2 Test nail failure criteria

Pull-out failure occurs when the following condition is reached (FHWA, 1993): There is no further increase in the applied load as displacement of the nail continues during the load test.

5.3.5 Pull-out testing of nails inclined at 15° to the vertical

The first series of pull-out tests were performed on prototype soil nails installed at an inclination of 15° to the vertical. The key objective of this test series was to evaluate the pull-out capacity from saturated condition to dry condition (residual suction values) or across the entire range of the SWCC.

5.3.5.1 Pull-out test under saturated condition for a nail inclined at 15° (no suction)

The first test was performed with the soil in the test box under saturated condition. The soil was gradually saturated from the bottom by using the perforated pipes embedded in the test box. The water level was confirmed by checking the stabilized level on the piezometers attached to the test box. A tensiometer was also placed at 150 mm from the surface of the soil to confirm saturated condition (i.e. no suction). Perforated cups were placed at depths of 150, 400 and 650 mm from the surface during compaction of the sand. These cups were used to extract samples of the soil after the testing to verify the water content (and the degree of saturation) within the test box. Figure 5.15 shows a schematic of the nail inclined at 15° under saturated conditions (no suction). Table 5.3 presents a summary of data obtained from the perforated cups.

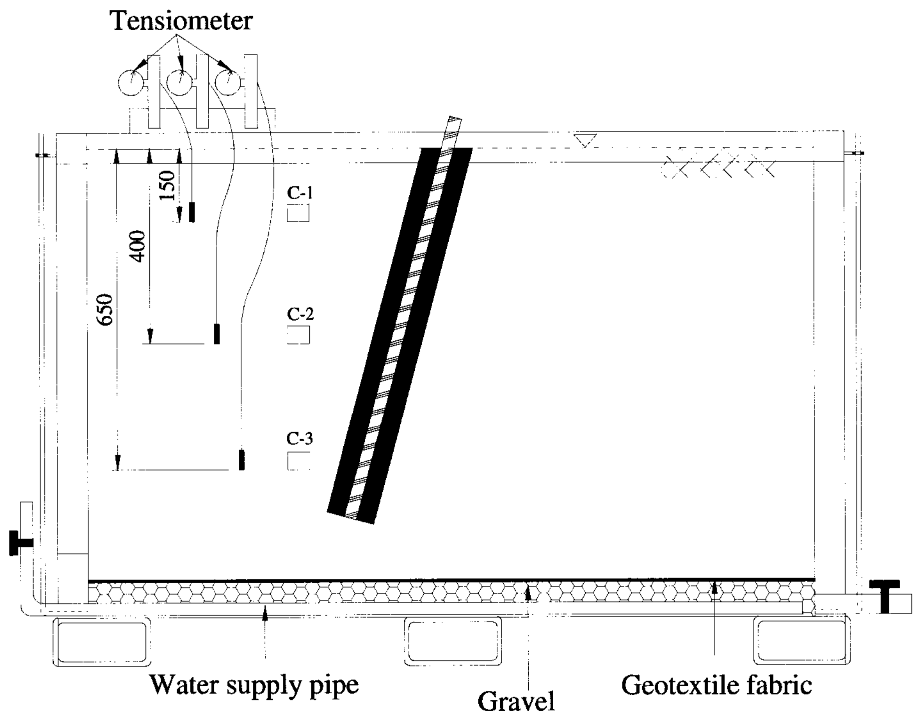

Figure 5.15 Schematic of the nail inclined at 15° under saturated conditions

After completion of the pull-out test, the soil nail was carefully extracted from the test box and the failure surface was examined. The soil within the zone of influence of the soil nail was excavated and re-compacted to meet the relative density previously achieved. A 400 mm wide by 800 mm deep trench was made with the centre line of excavation being along the axis of the previously installed nail. The excavated material was recompacted to an average dry density of 95% of the optimum dry density.

Figure 5.16 presents the load-displacement plot for the nail inclined at 15° tested under saturated condition.

Table 5.3 Data obtained from perforated cups embedded in the test box for the nail inclined at 15° under saturated condition

D (mm)	γ_t (kN/m^3)	γ_d (kN/m^3)	e	w (%)	S (%)	$(u_a - u_w)$ (kPa)
150	19.09	15.01	0.73	27.2	98.60	0.0
400	19.21	15.13	0.72	27.0	99.67	0.0
650	19.03	14.89	0.74	27.8	98.96	0.0

where:

D = depth from the surface of the soil in the test box, mm

γ_t = total unit weight, kN/m^3

γ_d = dry unit weight, kN/m^3

e = void ratio

w = water content, %

S = degree of saturation, %

$(u_a - u_w)$ = matric suction, kPa

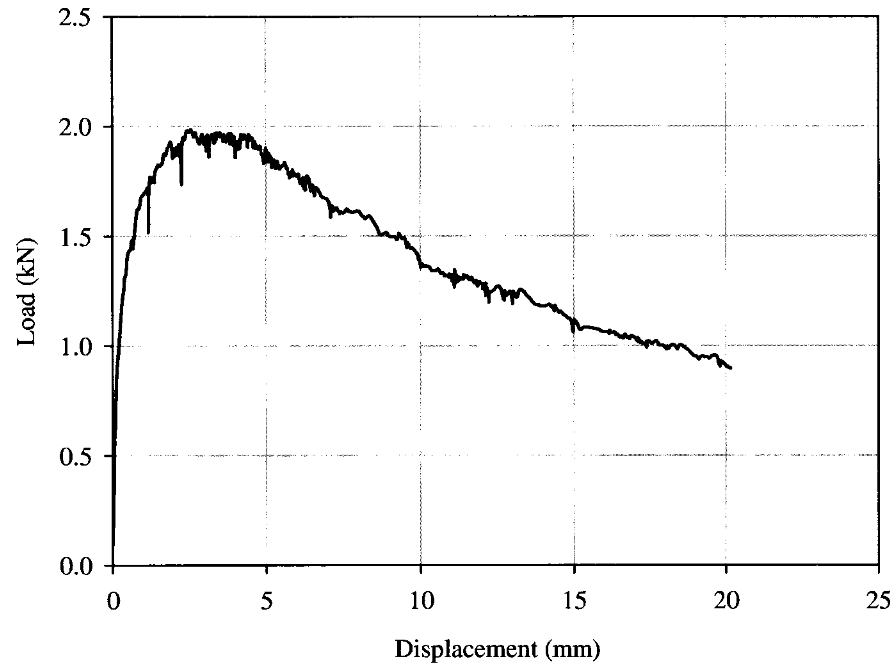

Figure 5.16 Load-displacement plot for the test nail inclined at 15° under saturated condition

5.3.5.2 Pull-out test under unsaturated condition for nail inclined at 15° (average suction = 2 kPa)

The soil was saturated from the bottom-up using the procedure described in Section 5.3.5.1 to a level of 0.275 m below the soil surface. Equilibrium conditions with respect to matric suction value within the unsaturated zone (i.e. from surface to a depth of 0.275 m) were achieved over a time period of 24 hours. Three tensiometers were placed at depths of 64, 125 and 200 mm from the soil surface to measure the matric suction within the unsaturated zone. Additionally, perforated cups were also embedded in the soil at depths adjacent to the ceramic tip of the tensiometers. These cups were placed in the soil during the recompaction process. Figure 5.17 shows a cross section of the test box in schematic form and provide the details of the location of the tensiometers and perforated cups (labeled as C-1, C-2 and C-3) at different elevations. Table 5.4 presents a summary of data obtained from the perforated cups for the test nail inclined at 15° at an average suction of 2 kPa. Figure 5.18 presents the load-displacement plot for the nail inclined at 15° under an average suction of 2 kPa (i.e. average of three readings – 1, 2 and 3 kPa). Figure 5.19 presents a comparison of the pull-out test results for the entire series of nails inclined at 15°.

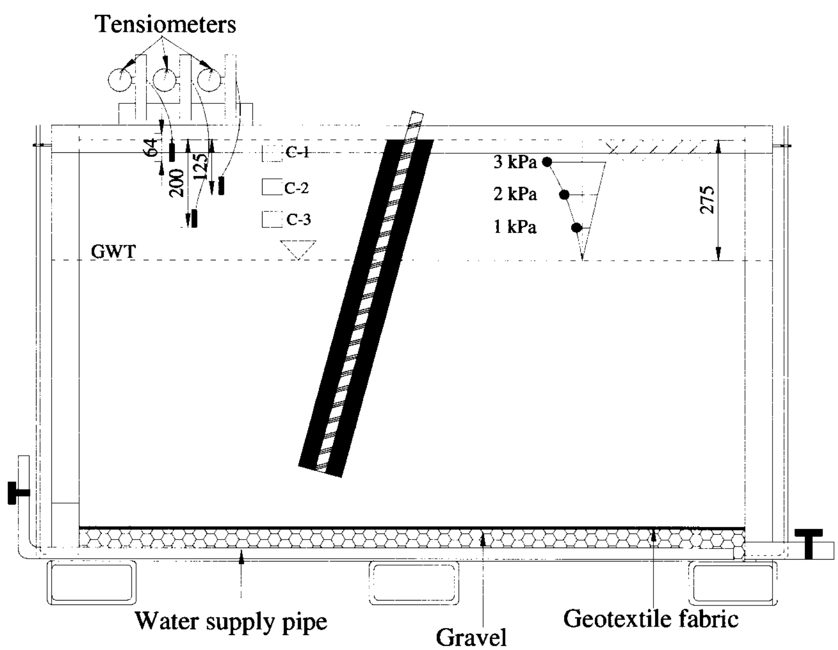

Figure 5.17 Schematic of nail inclined at 15° with matric suction profile (average suction = 2 kPa)

Table 5.4 Data obtained from perforated cups embedded in the test box for the nail inclined at 15° under an average suction of 2 kPa

D (mm)	γ_t (kN/m^3)	γ_d (kN/m^3)	e	w (%)	S (%)	(u_a-u_w) (kPa)
50	18.56	15.13	0.72	22.7	83.58	3.0
125	18.85	15.01	0.73	25.6	92.66	2.0
200	19.03	15.01	0.73	26.8	96.93	1.0

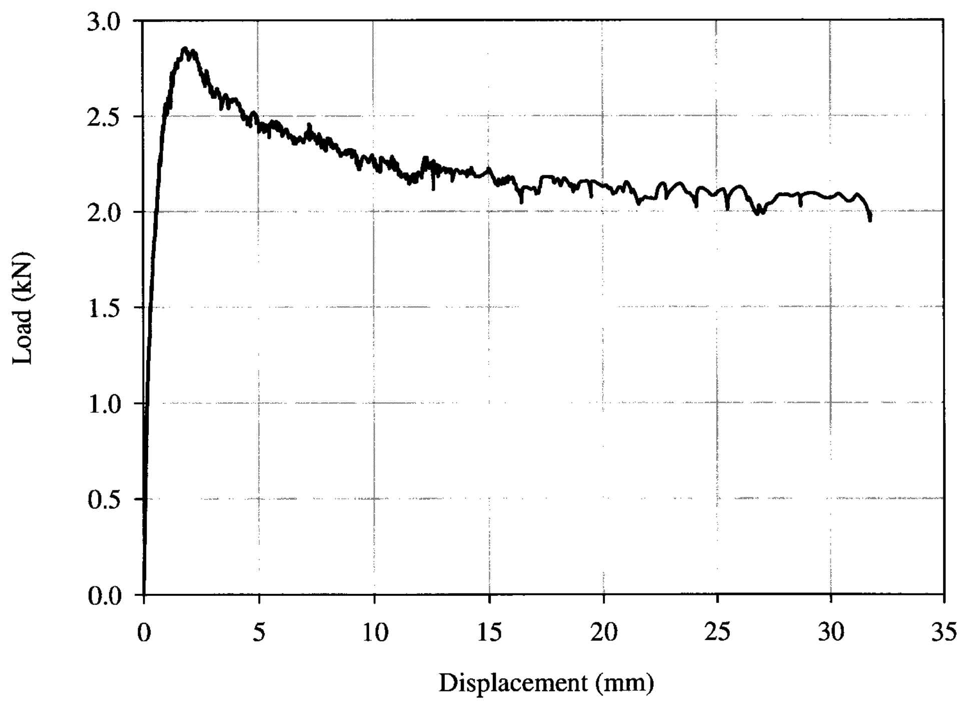

Figure 5.18 Load-displacement plot for the test nail inclined at 15° under an average suction of 2 kPa

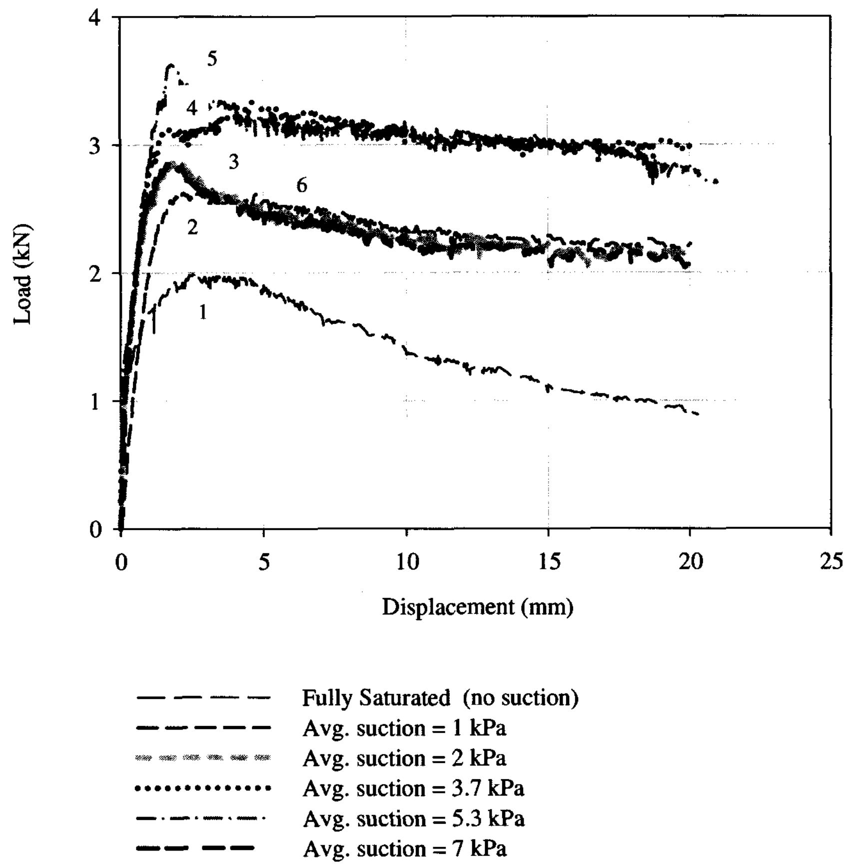

Figure 5.19 Comparison of the pull-out test results for the entire series of nails inclined at 15°

5.3.6 Pull-out testing of vertical nails

The prototype soil nails were also installed vertically to evaluate its pull-out capacity under saturated condition and unsaturated condition (average suction of 2 kPa).

5.3.6.1 Pull-out test under saturated condition for vertical nail (no suction)

Figure 5.20 shows a schematic of the vertical nail under saturated condition. The load-displacement relationship for the vertical nail under saturated condition is presented in Figure 5.21.

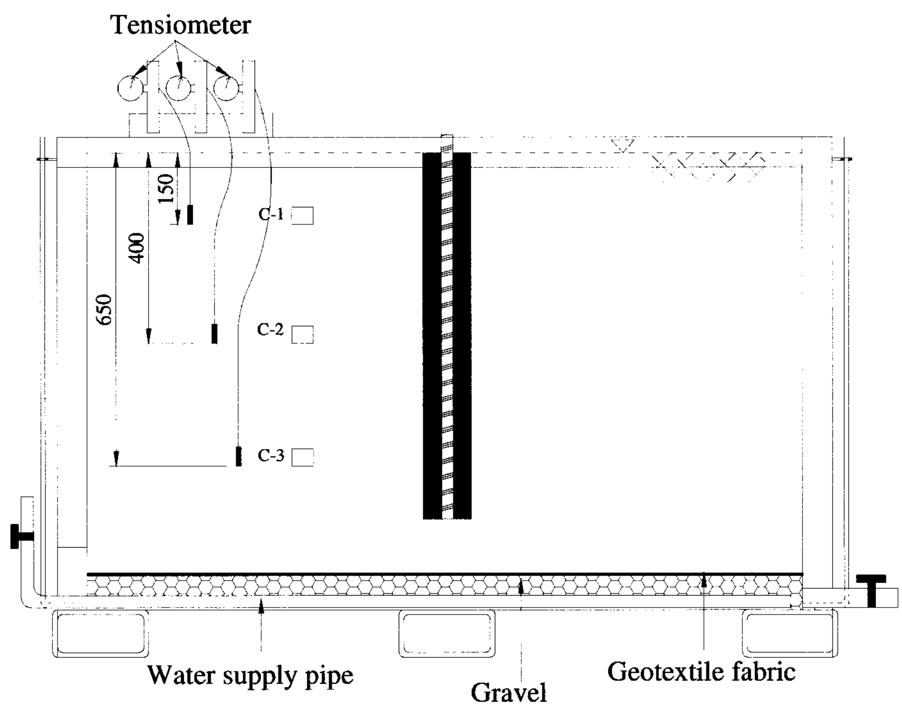

Figure 5.20 Schematic of vertical nail under saturated condition (no suction)

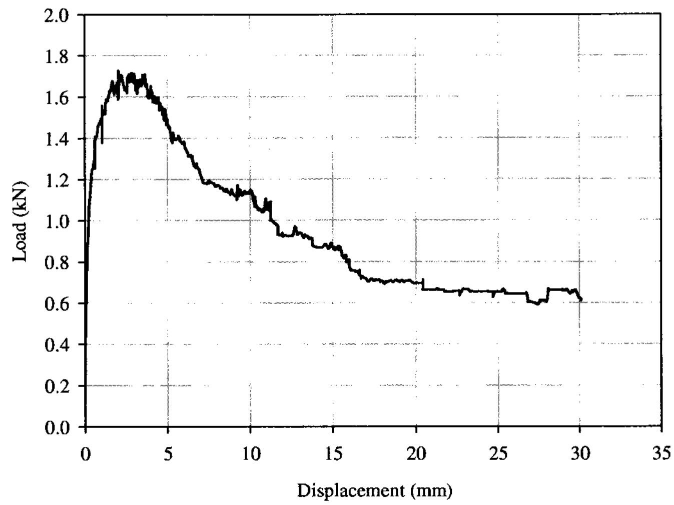

Figure 5.21 Load-displacement plot vertical nail under saturated condition

5.3.6.2 Pull-out test under unsaturated condition for vertical nail (average suction = 2 kPa)

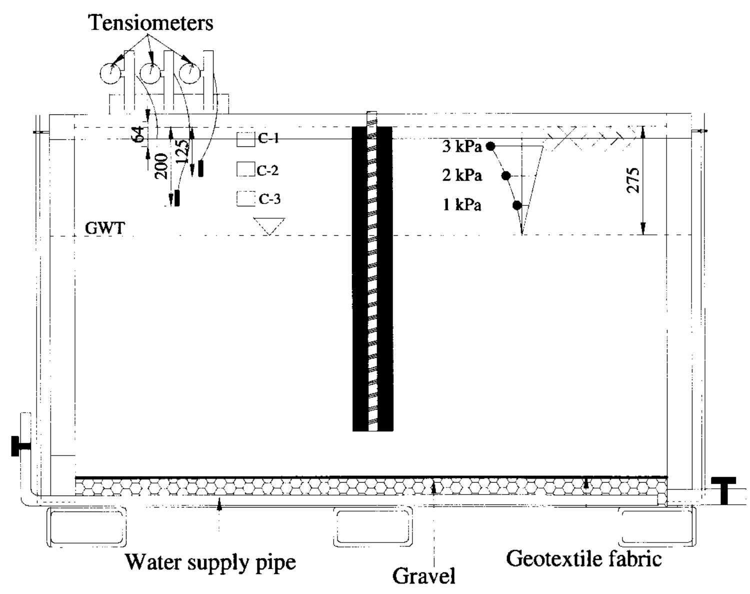

Figure 5.22 Schematic of vertical nail with matric suction profile (average suction = 2 kPa)

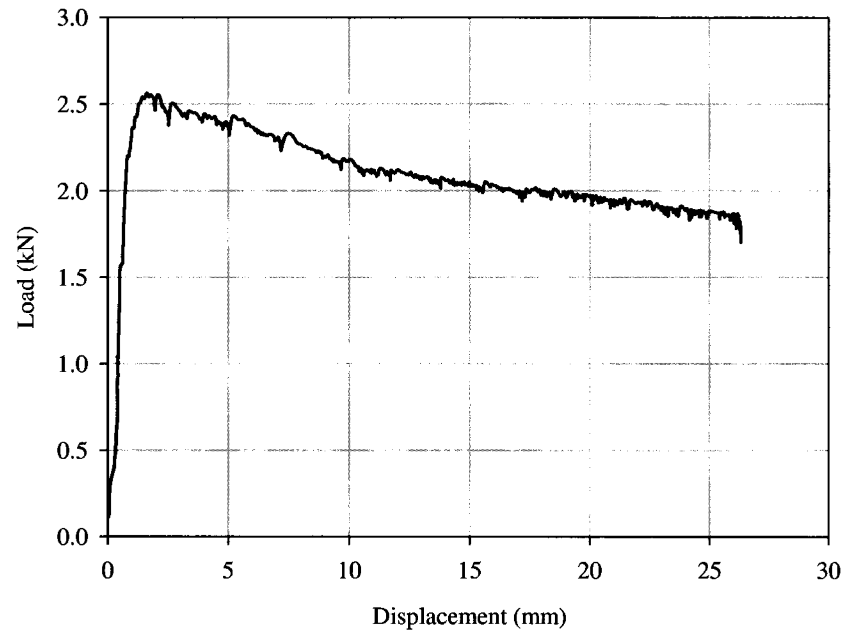

Figure 5.23 Load-displacement plot for vertical nail (average suction = 2 kPa)

5.3.7 Pull-out testing of horizontal nails

In order to examine the influence of inclination and check the validity of the proposed technique for estimating the soil-nail pull out capacity, two soil nails were installed horizontally and tested. The horizontal nails were tested under saturated condition and also under unsaturated conditions with average matric suction value of 2 kPa. The embedment depth of the horizontal nail was similar to that of the vertical nail (780 mm).

5.3.7.1 Pull-out test under saturated condition for horizontal nail (no suction)

The layout of the horizontal soil nail under saturated condition is shown in Figure 5.24. The load-displacement plot for the horizontal nail under saturated condition is presented as Figure 5.25.

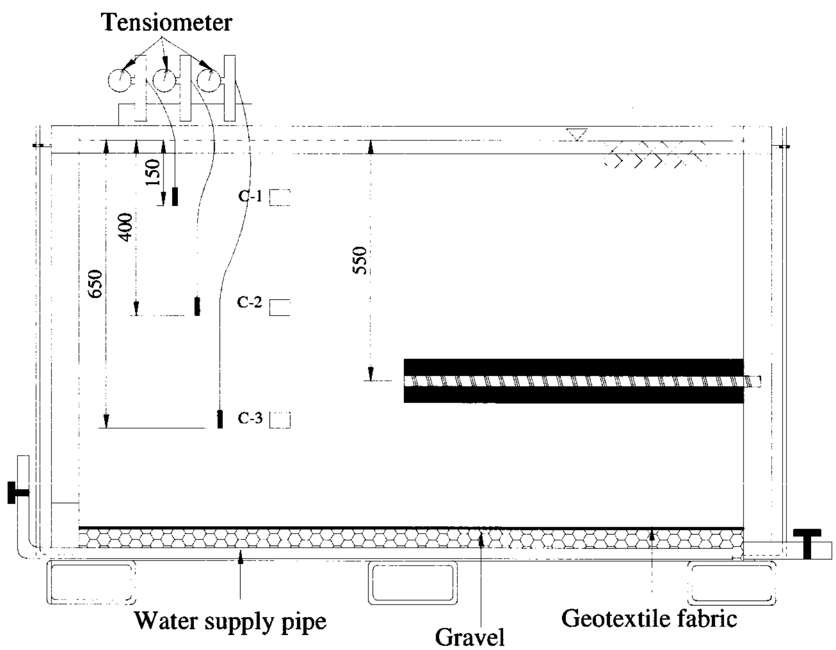

Figure 5.24 Schematic of horizontal nail under saturated condition (no suction)

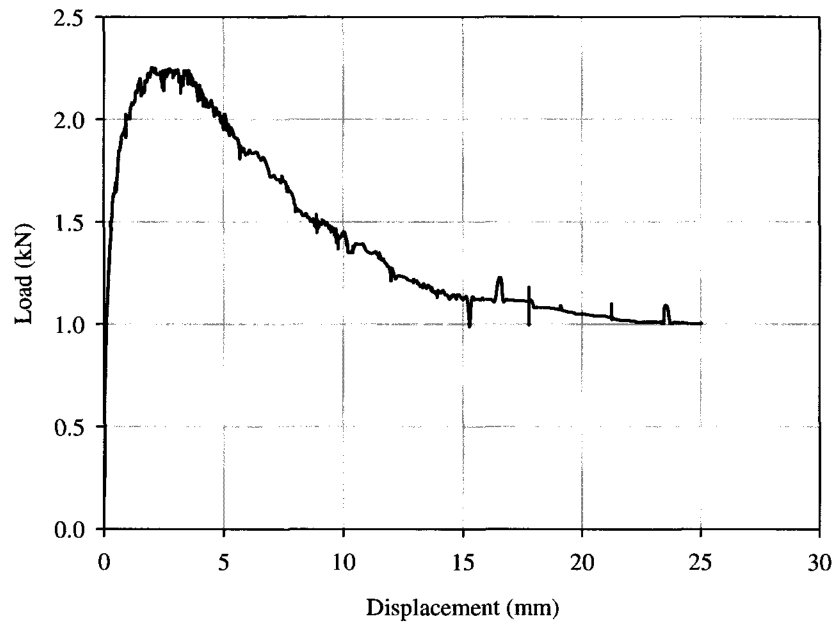

Figure 5.25 Load-displacement plot for the horizontal nail under saturated condition (no suction)

5.3.7.2 Pull-out test under unsaturated condition for the horizontal nail (average suction= 2 kPa)

A schematic of the horizontal nail under an average suction of 2 kPa is illustrated under Figure 5.26. The load-displacement plot for the horizontal nail with an average suction of 2 kPa is shown in Figure 5.27.

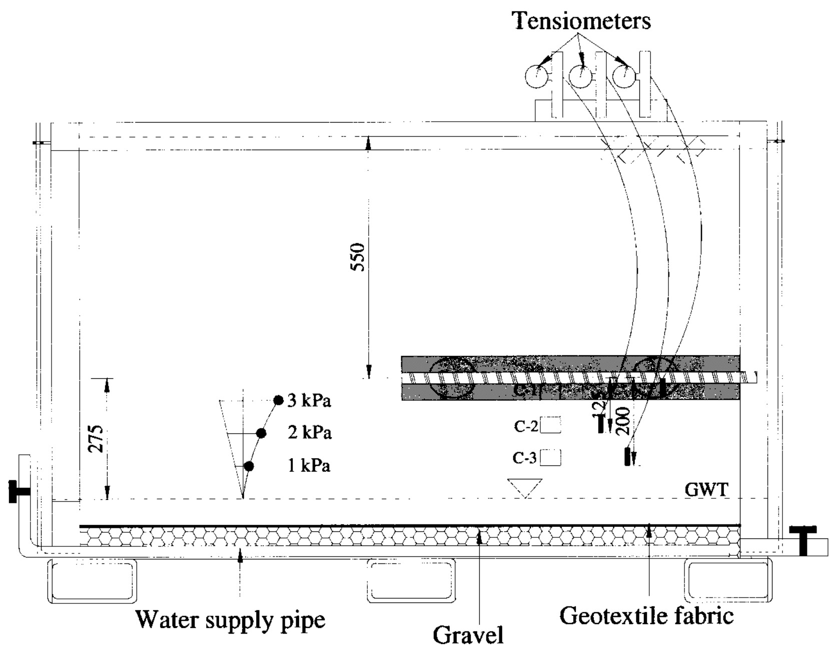

Figure 5.26 Schematic of horizontal nail with matric suction profile (average suction = 2 kPa)

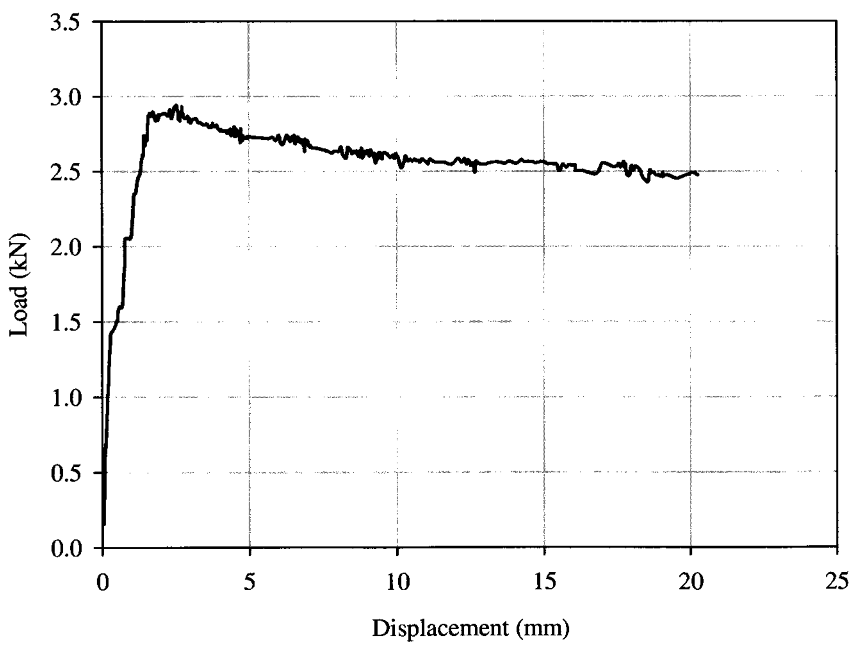

Figure 5.27 Load-displacement plot for horizontal nail (average suction = 2 kPa)

5.4 Experimental program III

The SWCC was measured as it is required for the prediction of the pull-out capacity of soil nails. The SWCC was determined using three different methods. Figure 5.28 shows the details of the three different procedures used for the determination of the SWCC.

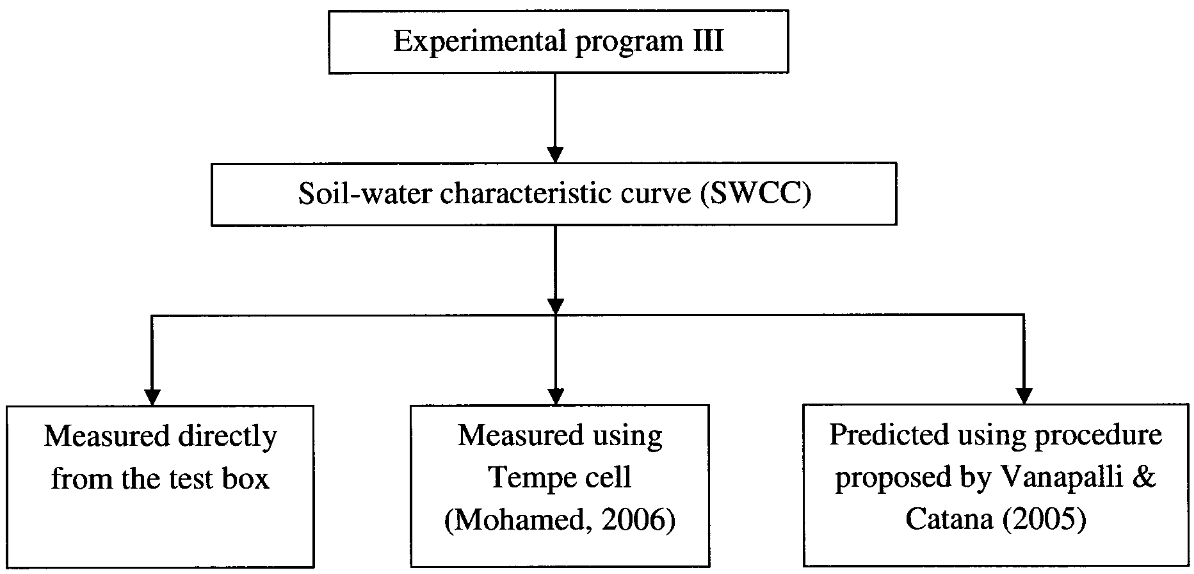

Figure 5.28 Experimental program III

5.4.1 Measuring the SWCC from the test box

The SWCC was also measured directly from the test box. The water content measurements were determined from the test box by using small aluminum cups with perforations (see section 5.3.1 for more details). The cups were embedded within the soil at different elevations in the test box during the compaction process. Tensiometers were placed adjacent to the cups to measure the matric suction in the region where the water content was measured. Figure 5.29 presents the SWCC that was measured from the test box.

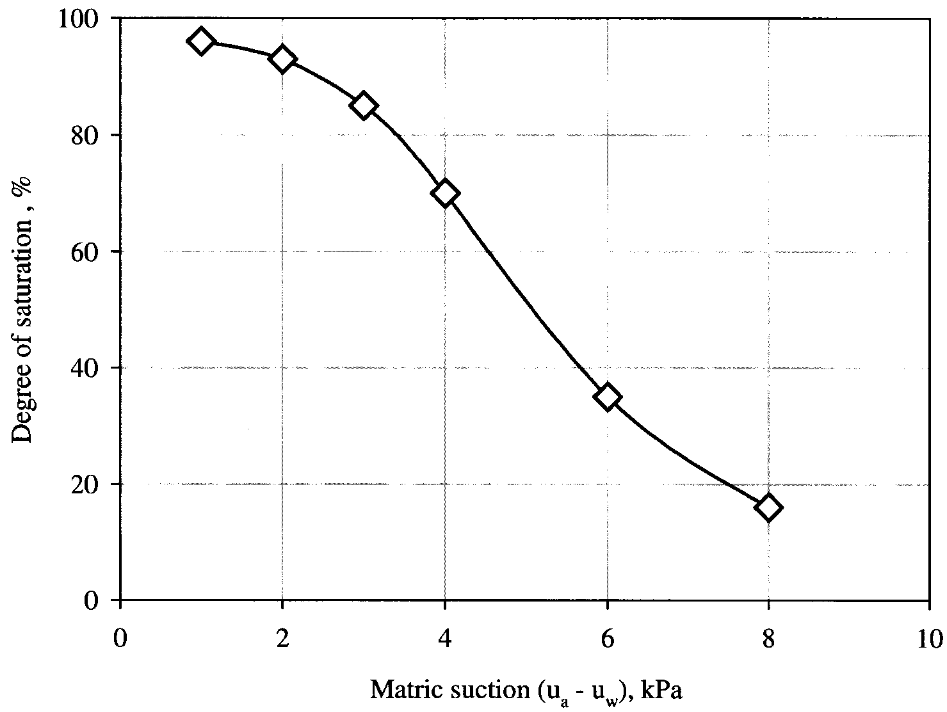

Figure 5.29 SWCC measured from the test box

5.4.2 Measuring the SWCC using the Tempe cell apparatus

The key objective of this test was to desaturate a saturated specimen by applying different values of matric suction. The variation of water content of the sample with respect to different values of matric suction is measured following the ASTM D – 02 (2008)) to establish the SWCC relationship. The tempe cell apparatus used for measuring the SWCC in the laboratory is shown in Figure 5.30.

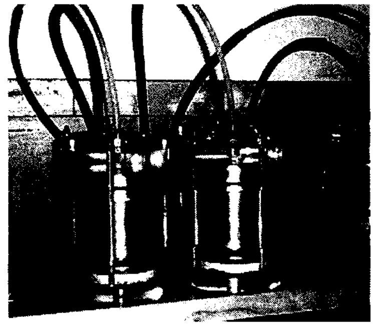

Figure 5.30 Tempe cell apparatus

The measured SWCC using the Tempe cell is plotted in Figure 5.31.

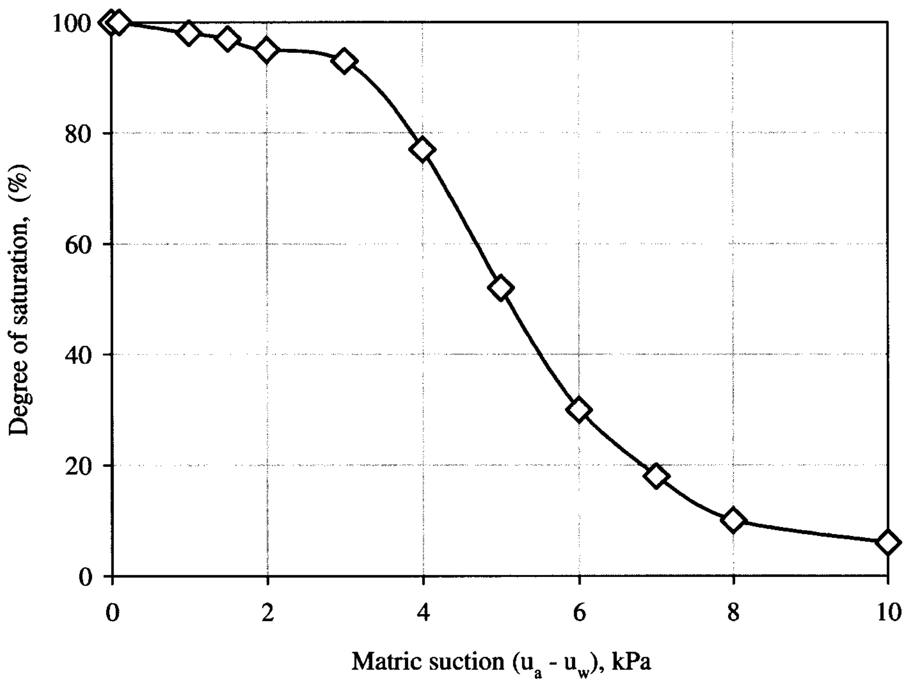

Figure 5.31 The measured SWCC using the Tempe cell apparatus (Mohamed, 2006)

5.4.3 Prediction of the SWCC

The third method that was used to obtain the SWCC was a prediction method proposed by Vanapalli and Catana (2005) for coarse-grained soils. The method requires one measured data point comprising of matric suction (u_a - u_w) and water content, w. One point data of the SWCC and some parameters derived from the GSD curve along with the volume-mass properties are used in this method. The correlations required for the estimation of the SWCC are based on relationships between the fitting parameters, a and n, which are functions of the coefficient of uniformity, C_u, the dominant particle size, d_e and void ratio e.

The procedure used to establish the SWCC by using this method is summarized below:

- The measured data of one point of the SWCC which comprises matric suction and the corresponding water content was required for estimating the SWCC. The data point of water content value, w and matric suction, (u_a - u_w) of 12.4 % and 6 kPa respectively were used in the estimation of the SWCC.

- The fitting parameters a and n were estimated using equation 5.2 and 5.3 respectively as presented below.

$$a = \frac{1.33}{(d_e)^{.86}} \quad [5.2]$$

$$n = \frac{7.78}{(C_u \times e)^{1.14}} \quad [5.3]$$

- Using one measured data point and the developed relationships to obtain the parameters, a and n, for estimating the SWCC as given below:

$$w_w = w_r + (w_s - w_r)(1/\ln(f)) \quad [5.4]$$

where:

$$f = \left(e + \left(\frac{\psi}{1.33/d_e^{0.86}}\right)^{7.78/(C_u \times e)^{1.14}}\right)^{mf} \qquad [5.5]$$

where:

a = first fitting parameter

n = second fitting parameter

e = void ratio

d_e = dominant diameter, *mm*

C_u = coefficient of uniformity

ψ = soil suction, *kPa*

The predicted SWCC using the method proposed by Vanapalli and Catana (2005) is presented in Figure 5.32.

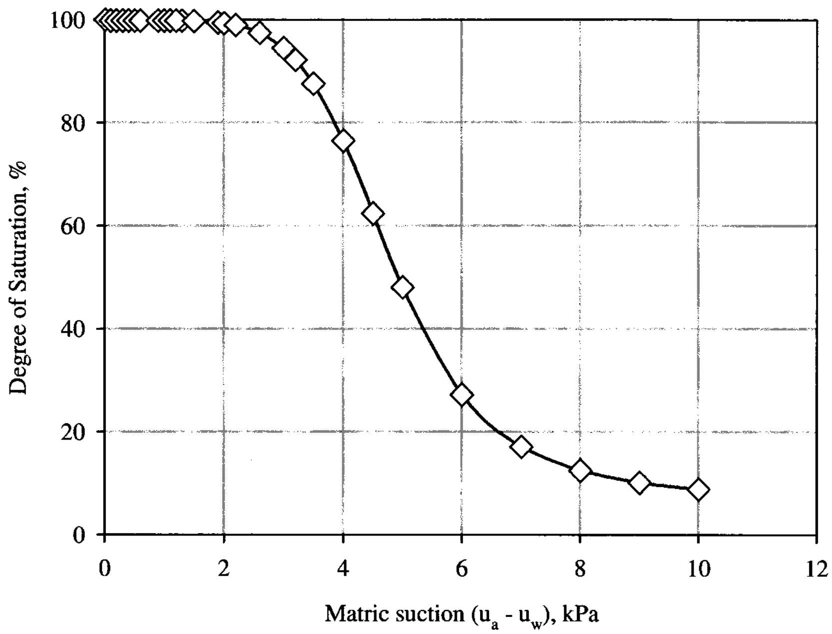

Figure 5.32 SWCC predicted using the one point technique as proposed by Vanapalli and Catana (2005)

There is a good comparison between the SWCCs using all the three different methods as illustrated under Figure 5.33.

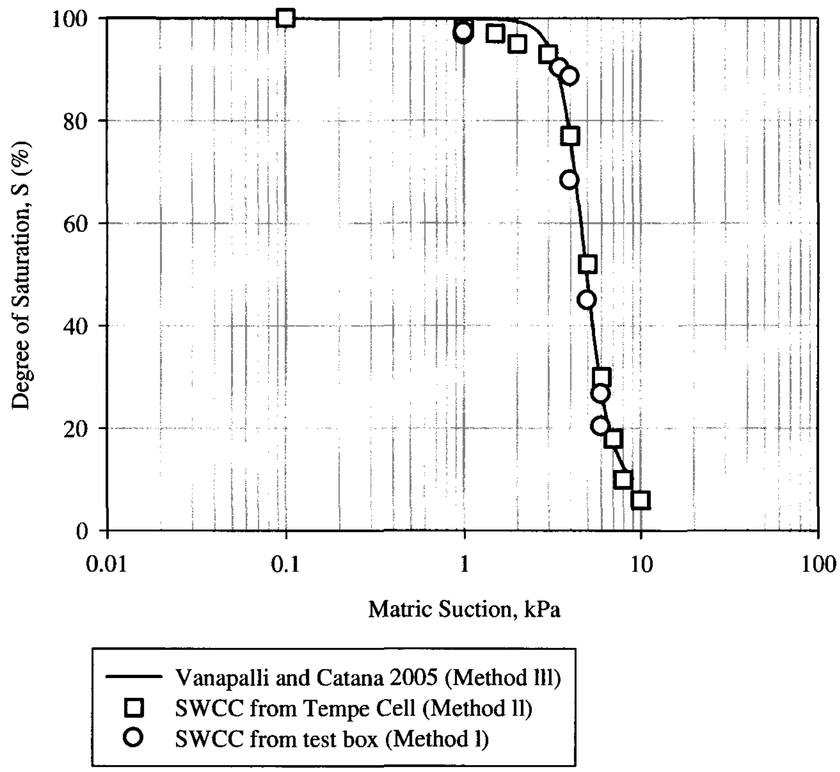

Figure 5.33 Measured and predicted SWCCs for the tested sand

5.5 Summary

The key data with respect to the determination of the pull-out capacity of soil nails, under both saturated and unsaturated conditions on compacted coarse-grained soil along with the soil properties are summarized in this chapter. All the experimental procedures for determining the soil properties are also briefly summarized.

The pull-out capacity was measured in a controlled laboratory environment using prototype soil nail comprising of a Williams Form Hardware #7 (22 mm) diameter threadbar as the central reinforcement, installed and grouted in a 100 mm diameter drilled hole. The nails were installed vertically, horizontally and at 15^0 to the vertical. The experimental pull-out capacity of the nails installed in the coarse grained-soil under unsaturated conditions was found to be approximately 1.3 to 1.7 times higher than the pull-out capacity under saturated conditions. The results obtained from the present comprehensive experimental program suggest that the conventional approach based on the mechanics of saturated soils and empirical procedures is conservative when it is applied for unsaturated soils.

The pull-out behaviour of soil nails in unsaturated coarse grained soil showed similarities to the shear strength of unsaturated soils. A trend was observed in the variation of the pull-out capacity with the contribution of matric suction and the SWCC. Therefore, SWCC can be a useful tool to provide a preliminary assessment of the measured pull-out capacity with the variation of matric suction. The pull-out behaviour of the nails and comparison with the SWCC is discussed further in the following chapter.

CHAPTER 6

DISCUSSION OF THE TEST RESULTS

6.1 Introduction

A technique is proposed for the interpretation and prediction of the pull-out capacity of soil nails placed both in saturated and unsaturated coarse-grained soils such as sands. The proposed technique was developed by extending the concepts for predicting the shear strength of unsaturated soils and the conventional β method used for estimating the shaft capacity of piles in sandy soils. The saturated shear strength parameters, c' and ϕ' and the soil-water characteristic curve (SWCC) are the key parameters required in this equation to predict the variation of the pull-out capacity with respect to matric suction.

A comprehensive experimental program was undertaken using compacted sand in specially designed equipment. The details of the equipment design are presented in Chapter 4. The results obtained from the test program are presented in Chapter 5. The test results are analyzed and interpreted in this chapter. The test results from the present study are also analyzed using other equations available in the literature to estimate the pull-out capacity of soil nails. Additionally, two sets of results of soil nail pull-out test data published in the literature (Prahdan, 2003 and Su et al., 2008) are also interpreted and analyzed by using the proposed technique. Comparisons are provided between the measured and predicted pull-out capacity using the proposed technique. The study shows that there is a reasonably good comparison between the measured and the predicted pull-out capacity of soil nails using the proposed technique for both saturated and unsaturated conditions for coarse-grained soils.

6.2 Pull-out capacity of soil nails of sands in saturated condition

The pull-out capacity of the prototype soil nails were measured in the present study under both saturated and unsaturated conditions. There were significant differences in the pull-out behaviour of soil nails in saturated and unsaturated conditions. The pull-out capacity of soil nails placed in unsaturated conditions is 1.3 to 1.7 times higher in comparison to soil nails capacity in saturated conditions.

The peak load for the nails inclined at 15° to the vertical under saturated condition was achieved at a displacement of 2.4 mm. The value of the peak load was 1.98 kN. The load-displacement results of the present study are consistent with the trends of results obtained by Prahdan (2003) and Su et al. (2008) for completely decomposed granite (CDG) under saturated condition

The vertical soil nail pull out strength under saturated condition was equal to 1.69 kN at a displacement of 2.0 mm. The horizontal soil nail pulled out under saturated condition achieved its peak load at a displacement of 2.2 mm. The peak pull-out load for the soil nail tested was 2.25 kN. The highest pull-out capacity was obtained for horizontal nails which can be attributed to the contribution of uniform overburden pressure and matric suction.

6.3 Pull-out capacity of soil nails in sand under unsaturated conditions

Pull-out testing of soil nails inclined at 15°, horizontal and vertical nails was performed under unsaturated condition at an average matric suction value of 2 kPa. This value of matric suction was chosen as it is close to air-entry value and is within the boundary effect zone. Theoretically, maximum contribution of matric suction towards the pull out capacity of soil nails is possible when it is less than the air-entry value. Such a behavior can be supported based on the studies reported in the literature with respect to the shear strength behavior of unsaturated soils in general and sands in particular (for example, Donald, 1956; Fredlund and Rahardjo, 1993; Vanapalli and Lacasse, 2009)

In addition to these tests, an entire series of tests were performed on the nails installed at 15° with matric suction values ranging from 1 to 7 kPa, covering the different zones of the SWCC (i.e. the boundary effect zone, transition zone and residual zone) to understand the influence of the non-linear contribution of matric suction on the pull-out capacity of soils. These test results were also useful to evaluate the relationship between the SWCC and the pull-out capacity of soil nails. The relationship between the SWCC and the pull-out capacity of soil nails was observed to be similar to that of the relationship between the shear strength and the SWCC for unsaturated soils as discussed in later sections of this Chapter.

6.3.1 Nails inclined at 15° to the vertical with average suction values of 1, 2, 3.7, 5.3 and 7 kPa

The soil nails tested under unsaturated condition produced typically higher pull-out capacities in comparison to soil nails tested under saturated condition. Significant increase in the peak load of the nails during pull-out was observed even for low matric suction values of 1 or 2 kPa. However, a gradual reduction in the peak load was observed when the average matric suction fell within the residual zone of the SWCC. In other words, the contribution towards the pull out capacity gradually decreased with an increase in the matric suction in the residual zone. The pull-out capacity is similar to that of the non-linear behaviour of the shear strength of different sands with respect to matric suction as illustrated in Figure 6.1 by Vanapalli and Lacasse (2009) using Donald (1957) results over a suction range of 0 to 30 kPa.

A summary of the pull-out test results for inclined nails is provided in Table 6.1

Table 6.1 Summary of pull-out test results for the inclined nail under unsaturated condition

Average matric suction (kPa)	Length of proto-type nail (m)	Pull-out capacity (peak load) (kN)	Displacement at peak (mm)
0	0.8	1.98	2.40
1	0.8	2.62	2.20
2	0.8	2.85	1.80
3.7	0.8	3.10	1.60
5.3	0.8	3.42	1.55
7	0.8	2.72	1.90

As observed from Table 6.1 above, the displacement at peak load reduces with an increase in the average matric suction value. However, the displacement increases again as pull out capacity start decreasing in the residual zone (i.e. for an average suction of 7 kPa). Pull-out test results reported by FHWA (1993) indicated that the maximum pull-out force was reduced by more than half when the soil condition changed from optimum to saturation moisture content. A similar trend is indicated for the sand used for the present research as indicated for average suction values of 0 and 5.3 kPa which indicates saturation and close to optimum moisture contents respectively.

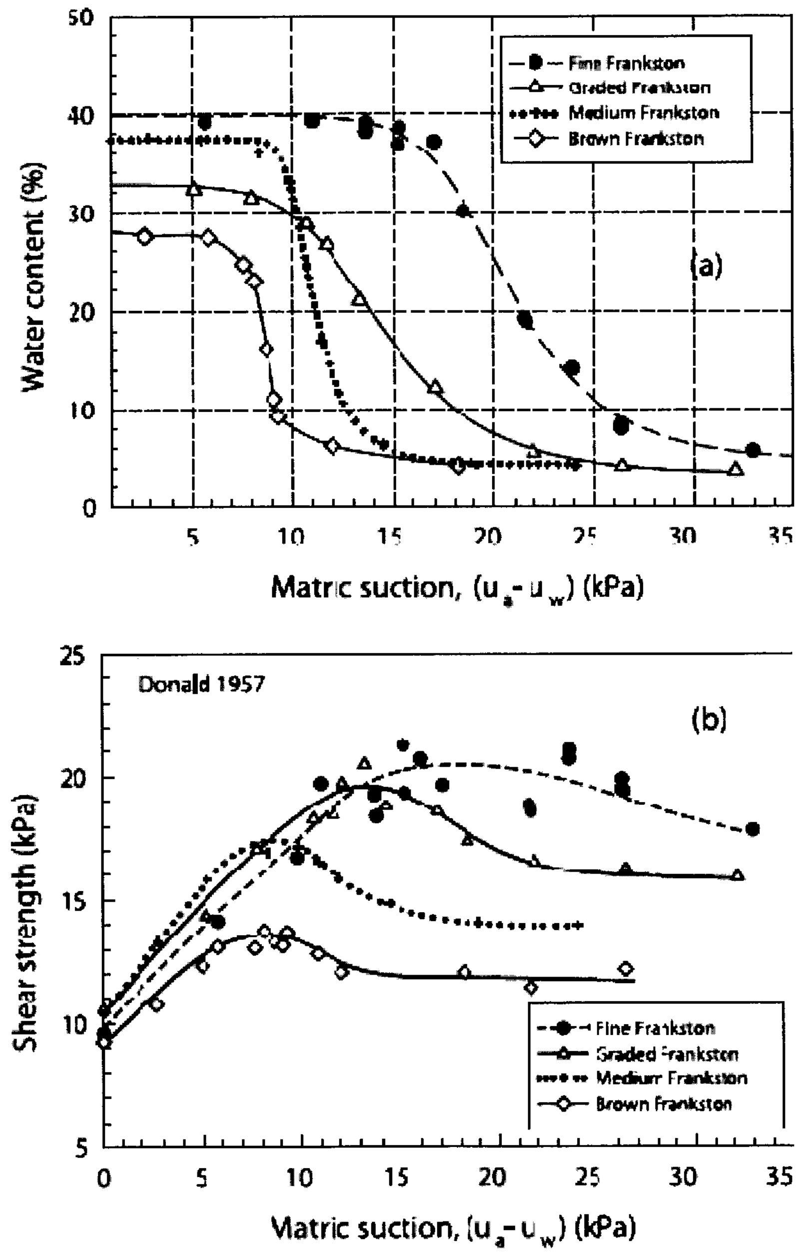

Figure 6.1 (a) SWCCs and (b) variation of shear strength with respect to matric suction for four sands (modified after Donald, 1957)

There are limited studies reported in the literature on the influence of degree of saturation (i.e. a direct change in matric suction values) of soil on the pull-out capacity of soil nails (Su et al., 2008). Most pull-out test data reported in the literature were done in soil with moisture contents ranging between optimum and saturation moisture contents. It is very likely that the pullout capacity will be close to 1.98 kN when the matric suction increases further and the degree of saturation decreases. In other words, soil nails behavior is similar both under saturated and dry conditions.

6.3.2 Vertical and horizontal nail at an average suction of 2 kPa

The pull out capacity (i.e., peak load) for the vertical nail under unsaturated condition at an average matric suction value of 2 kPa was 1.3 times higher than the nail capacity tested under saturated condition. A peak load of 2.56 kN was achieved at a displacement of 1.65 mm. The development of the pull-out resistance under unsaturated conditions occurs at lower displacements when compared with saturated conditions. The lower displacement to achieve the peak load can be attributed to the increase in soil adhesion (i.e. increased adhesion due to the contribution of matric suction).

A horizontal nail was also pulled out under unsaturated condition with an average suction of 2 kPa. The peak load of 2.93 kN occurred at a displacement of 2.5 mm, and was 1.3 times higher than the horizontal nail pulled out under saturated condition.

6.4 Analysis of test results using the proposed equation

The equation [3.18] as proposed in Chapter 3 was used to estimate the pull-out capacity of the nails as provided below.

6.4.1 Analysis of test results for saturated conditions

The pull-out capacity of the nails under saturated condition was estimated by using the modified β method to incorporate the effects of dilatancy eq. [3.17]. The same philosophy used by Vanapalli et al., (2010) for the estimation of the shaft capacity of piles has been extended for soil nails. A soil adhesion value of 6 kPa and interface friction angle of 27° measured from the interface (i.e. grout/soil) direct shear test were used in the analysis. The SWCC is not required since there is no suction component for the saturated case.

The β value used in the analysis was obtained as outlined under section 3.5.2. The influence of the angle of inclination of the soil nail on the coefficient of earth pressure (K_s) was taken into account. An equation was proposed to estimate a value for K_θ, where θ ranges from 0 to 90° (i.e. 90° for nails vertical nails). The variation in inclination on the pull-out capacity of the nails was obtained by using the following equations [6.1] to [6.5].

$$\beta = K_\theta \tan\delta \qquad [6.1]$$

For the vertical case,

$$K_\theta = K_0 \qquad [6.2]$$

where,

$$K_0 = 1 - \sin\phi = 0.5 \qquad [6.3]$$

For nails inclined at 15° to the vertical,

$$K_\theta = 1.06\, K_0 = 0.53 \qquad [6.4]$$

For the horizontal case,

$$K_\theta = 2.0\,K_0 = 1.0 \qquad [6.5]$$

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 (Figure 6.2). The dilation angle was estimated based on the average values for normal stress of 18, 23 and 34 kPa in order to capture the effects of low stress levels. 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, 2008). 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.

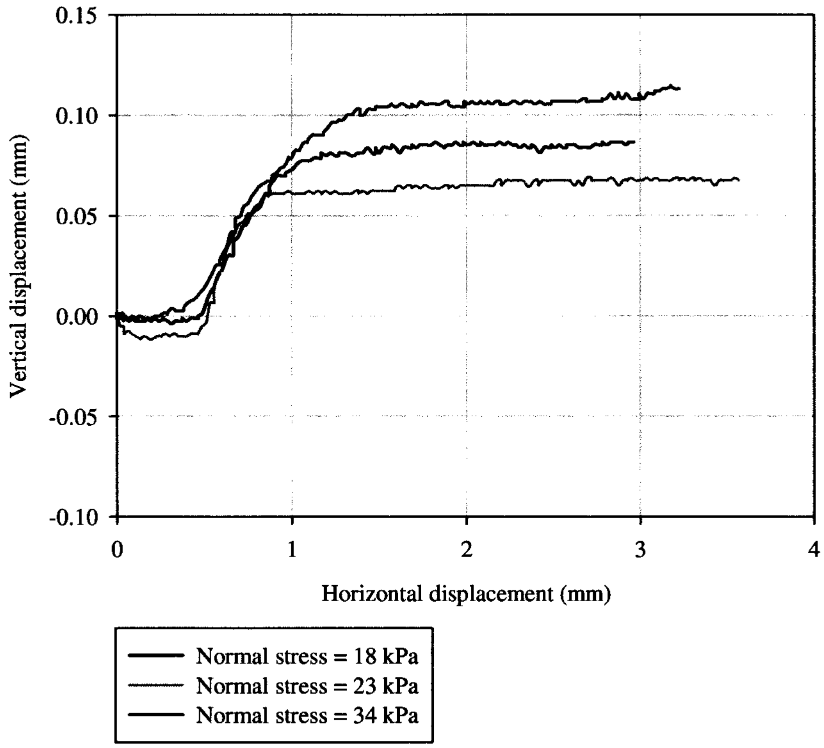

Figure 6.2 Vertical displacements vs. horizontal displacement for normal stresses of 18, 23 and 34 kPa

6.4.2 Analysis of tests results for unsaturated conditions

Pull-out tests were performed on prototype nails under unsaturated conditions with nails installed vertically, inclined at 15° and horizontally. The pull-out capacity of the nails installed under a state of unsaturated condition was estimated using the saturated shear strength parameters (c' and δ) and the average suction value.

The parameters used for the estimation of the pull-out capacity for soil nails tested in the present study is provided in Table 6.2. A summary of the estimated pull-out capacity for the nails installed in soil under both saturated and unsaturated conditions and a comparison with the measured values are presented in Table 6.3 and represented graphically under Figure 6.3

Table 6.2 Parameters used to estimate the pull-out capacity of soil nails used for the present study by using eq. 3.18 and β as a function of nail inclination

Nail orientation	*Avg. matric suction* U_a-U_w *(kPa)*	c_a *(kPa)*	β	σ_z' *(kPa)*	S	κ	*Saturated length* $L_s(m)$	*Unsaturated length* $L_{us}(m)$
Vertical	0	6	0.31	3.35	1.00	1.0	0.800	0.000
Vertical	2	6	0.31	5.27	0.85	1.0	0.525	0.275
15 deg.	0	6	0.32	3.72	1.00	1.0	0.800	0.000
15 deg.	1	6	0.32	4.88	0.95	1.0	0.650	0.150
15 deg.	2	6	0.32	5.65	0.85	1.0	0.520	0.280
15 deg.	3.7	6	0.32	6.80	0.62	1.0	0.230	0.570
15 deg.	5.3	6	0.32	6.80	0.52	1.0	0.000	0.800
15 deg.	7	6	0.32	6.80	0.13	1.0	0.000	0.800
Horizontal	0	6	0.61	4.65	1.00	1.0	0.800	0.000
Horizontal	2	6	0.61	8.50	0.85	1.0	0.000	0.800

The average suction value for each case was applied to the unsaturated section of the nail only. The β values shown in Table 6.2 were obtained by using eq. [6.1] to eq. [6.5].

Table 6.3 Estimated vs. measured pull-out capacity for nails tested under saturated and unsaturated conditions by using parameters provided in Table 6.2

Nail orientation	Average suction (kPa)	Measured $Q_{f(us)}$ (kN)	Estimated $Q_{f(us)}$ (kN)
Vertical	0	1.69	1.7
Vertical	2	2.56	1.93
15°	0	1.98	1.81
15°	1	2.62	1.93
15°	2	2.85	2.05
15°	3.7	3.10	2.31
15°	5.3	3.42	2.51
15°	7	2.72	2.20
Horizontal	0	2.25	2.22
Horizontal	2	2.93	3.09

The lower pull-out capacity at an average suction of 7 kPa 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.

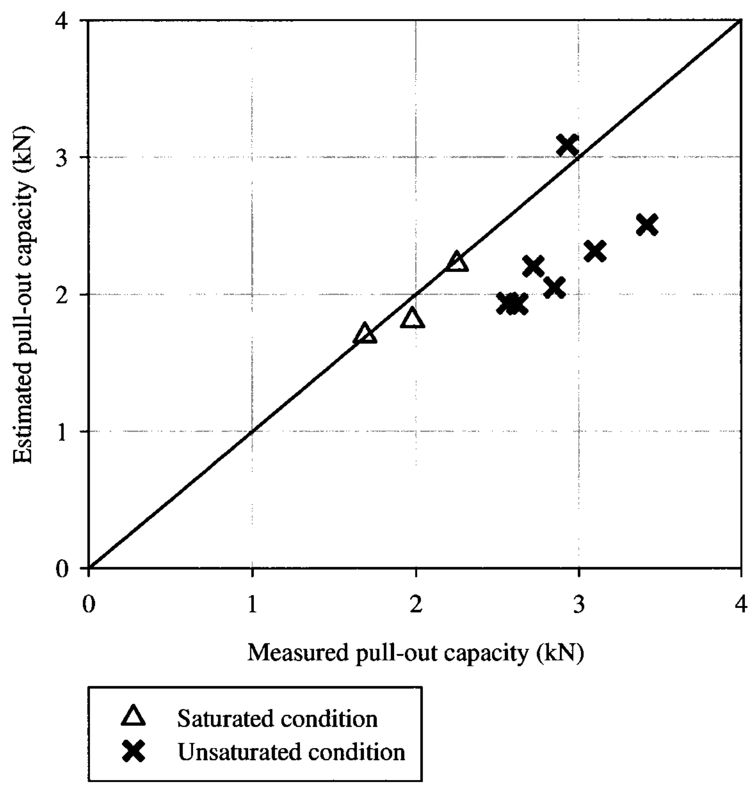

Figure 6.3 Estimated values vs. measured pull-out capacity for nails tested under saturated and unsaturated conditions based on β values obtained from eq. [6.1] to [6.5]

6.5 Review of the β values used in the proposed method

The estimated values using the proposed equation are not close to the measured values as indicated under section 6.4.2. The main variable is the estimation of the β value by using the previously described analytical method. 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. [6.9] and eq. [6.10].

$$\beta_{sat} = K_o \tan(\delta + \psi) \qquad [6.9]$$

$$\beta_{us} = 2 \times \beta_{sat} \qquad [6.10]$$

The β values estimated from using the equations [6.1] to [6.5] and the proposed empirical technique eq. [6.9] and [6.10] are illustrated in Figure 6.4.

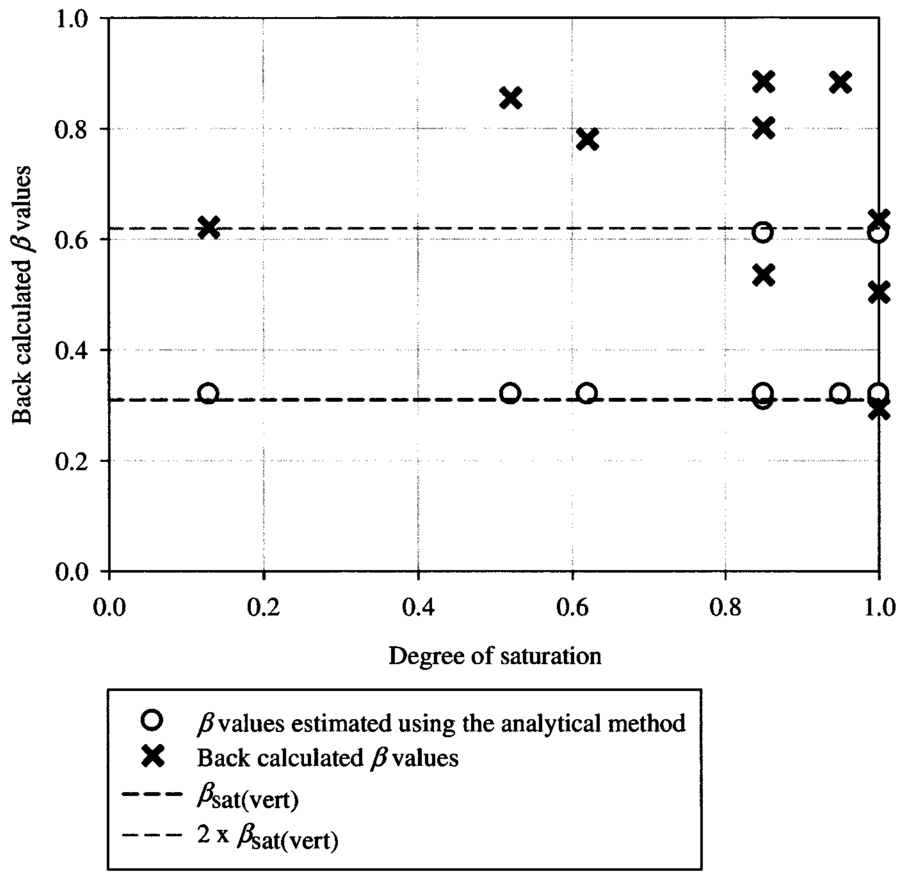

Figure 6.4 Comparisons of estimated β values and proposed values using an empirical technique

The re-evaluated β values as proposed in eq. [6.9] and eq. [6.10] are presented in Table 6.4a along with the estimated pull-out capacities. A comparison between the measured and estimated results is presented under Figure 6.5

Table 6.4 Comparison of estimated vs. measured pull-out capacity for nails tested under saturated and unsaturated conditions based on β values obtained from eq. [6.9] and [6.10]

Nail orientation	Average suction (kPa)	β	Measured $Q_{f(us)}$ (kN)	Estimated $Q_{f(us)}$ (kN)
Vertical	0	0.31	1.69	1.70
Vertical	2	0.62	2.56	2.32
15°	0	0.31	1.98	1.80
15°	1	0.62	2.62	2.30
15°	2	0.62	2.85	2.47
15°	3.7	0.62	3.10	2.81
15°	5.3	0.62	3.42	2.99
15°	7	0.62	2.72	2.71
Horizontal	0	0.31	2.25	1.87
Horizontal	2	0.62	2.93	3.09

Table 6.4 and Figure 6.5 indicates a better comparison between the measured and estimated pull-out capacity for the prototype soil nails used for the present study. The empirical technique was used to estimate the β values as proposed under section 6.5. A

more consistent trend can be observed from Figure 6.5 when compared with Figure 6.3 for both saturated and unsaturated conditions. As a result of this analysis, β values in the proposed technique will be obtained by using eq. [6.9] and [6.10].

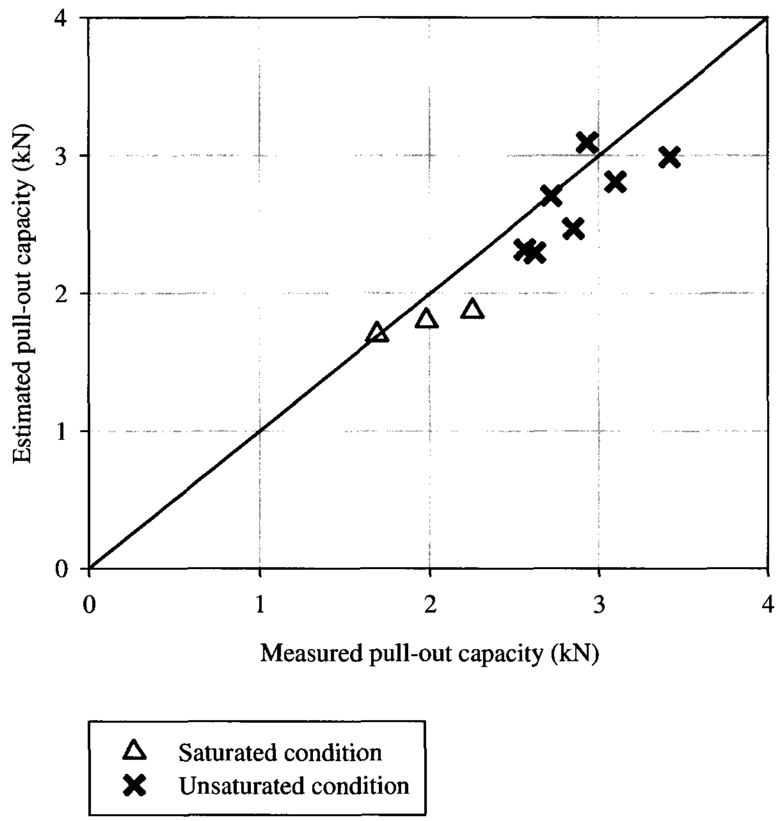

Figure 6.5 Estimated values vs. measured pull-out capacity for nails tested under saturated and unsaturated conditions based on β values obtained from eq. [6.10]

6.6 Influence of matric suction on the pull-out capacity of soil nails from the present study

The test results indicated that the post-peak pull-out capacity declines at a much faster rate as the degree of saturation of the soil increases. The decrease in the pull-out capacity is a direct result of the reduction in matric suction. The peak pull-out capacity in tests at average suction of 5.3 kPa was approximately 1.7 times that higher than that of the saturated case. The pull-out capacity increased with the increase in matric suction of the soil. The displacement at the peak pull-out capacity in tests at average suction of 5.3 kPa was about 40% less than the saturated case. These results showed similar trends to results presented in FHWA (1993) which showed that the maximum pull-out force was increased by two times when the moisture content was decreased from saturation to the optimum water content and the displacement corresponding to this maximum force was increased by three times. The decrease in pull-out capacity with the degree of saturation 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 behavior 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.

6.7 Relationship between the pull-out capacity of soil nails and the SWCC

The pull-out capacity of soil nails in a state of unsaturated condition is higher than the pull-out capacity of the same nail in a state of saturated condition. The SWCC (plotted on an arithmetic scale) and variation of the pull-out capacity with respect to matric suction is shown in Figure 6.6. 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 matric 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. 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). 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 suction of 7 kPa). The behaviour of the pull-out capacity of soil nails with 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) as illustrated in Figure 6.7 (Vanapalli, 2009).

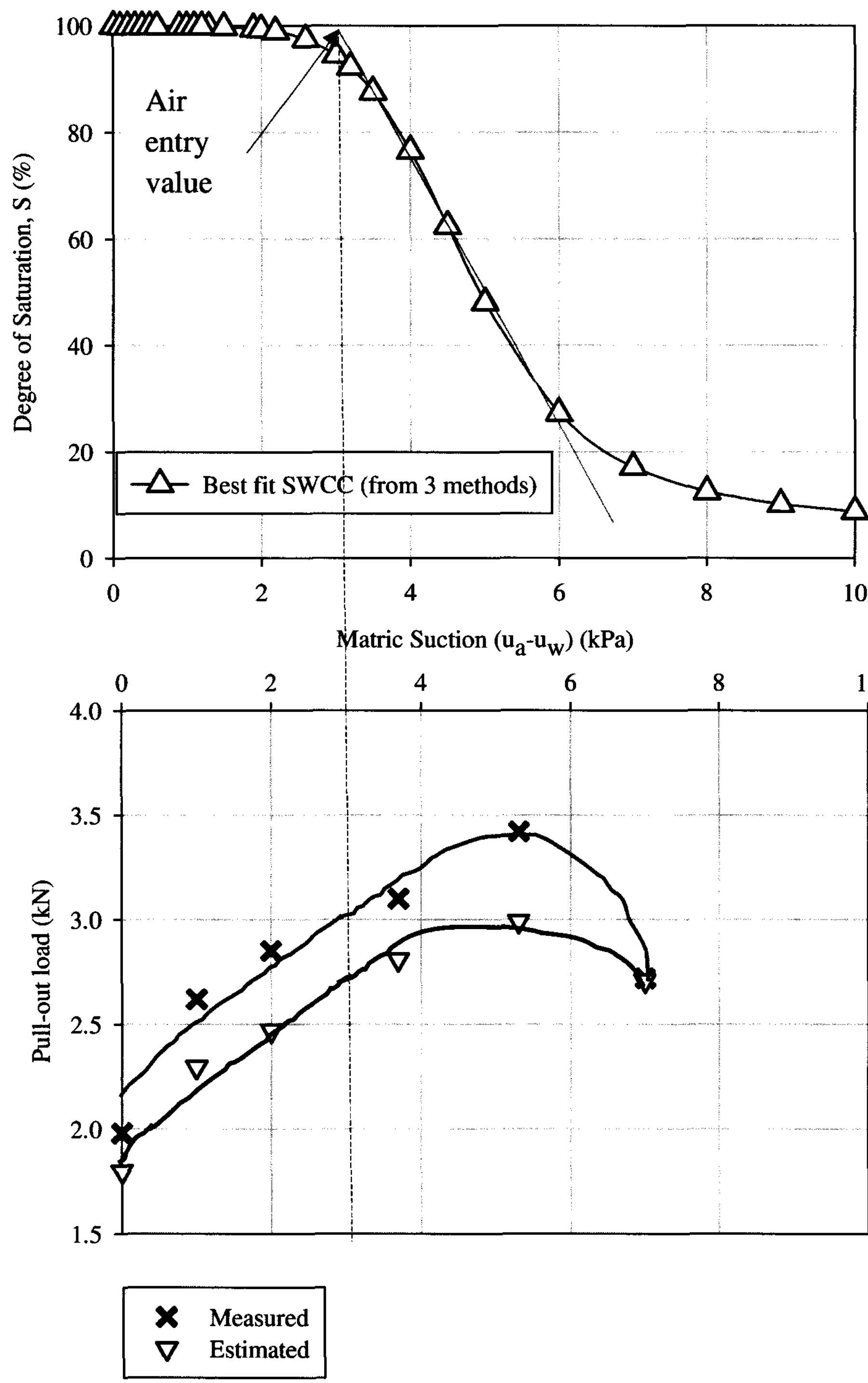

Figure 6.6 Variation of the pull-out capacity with matric suction by using the proposed technique and β values obtained from equations [6.9] and [6.10]

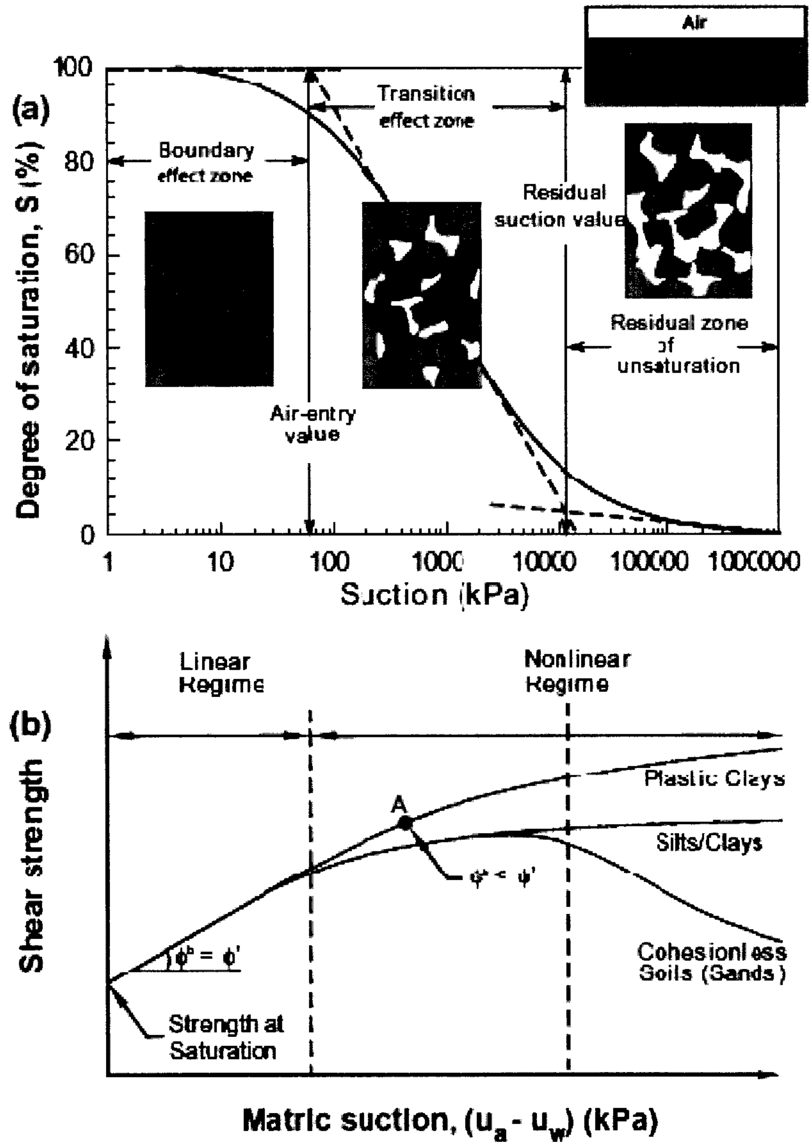

Figure 6.7 (a) SWCC showing different zones and (b) the variation of shear strength of unsaturated soils in various zones of desaturation for different soils (Vanapalli, 2009)

6.8 Difference between the proposed technique and other equations in the literature

The proposed technique to estimate the pull-out capacity of soil nails was compared with other equations available in the literature. A comparison between the proposed technique and some of the commonly used equations in the literature is provided below:

6.8.1 Equation proposed by Schlosser and Guilloux (1981)

The following equation was proposed by Schlosser and Guilloux (1981) has been adopted in Hong Kong to estimate the ultimate pull-out resistance of grouted soil nails (Watkins and Powell, 1992).

$$P_{ult} = \pi D c' + 2D\sigma_v' \mu^* \qquad [6.11]$$

where:

P_{ult} = ultimate pull-out resistance (kN/m)

c' = effective cohesion of the soil

σ_v' = effective vertical stress calculated at the mid-point of the nail in the resistance zone

μ^* = coefficient of apparent friction of the soil (for granular soils, μ^* is usually taken to be equal to $\tan\phi'$

The coefficient μ^* takes the effects of dilation into account.

This equation does not take the effects of matric suction into account for the evaluation of the pull-out capacity of soil nails.

6.8.2 Equation proposed by Chu and Yin (2005)

The following equation was proposed by Chu (2003) to estimate the pull-out capacity of soil nails:

$$T = \left(\pi D c_a' + 2D\sigma_v' \tan \delta''\right) \qquad [6.12]$$

where:

c_a' = soil adhesion at the interface

δ'' = interface friction angle for the normal stress on a strip

Th equation [6.12] do not account for the effects of matric suction on the pull-out capacity of soil nails. The eq. [6.12] proposed by Chu and Yin (2005) is an extension of eq. [6.11] as proposed by Schlosser and Guilloux (1981).

6.8.3 Equation proposed by Zhang et al. (2009)

The equation proposed by Schlosser and Guilloux (1981) was also extended by Zhang et al. (2009) to incorporate the effects of soil suction and soil dilatancy. The following equation [6.13] was proposed by Zhang et al. (2009) to estimate the ultimate pull-out resistance of soil nails by incorporating the effects of soil suction and soil dilatancy.

$$P_{ult} = \pi D\,[c' + (u_a - u_w)\tan\phi^b] + \frac{2D\,\sigma_v'\tan\phi'}{1-\left[\frac{2(1+v)}{(1-2v)\,(1+2K_0)}\right]\tan\phi'\tan\psi} \qquad [6.13]$$

where:

D = diameter of grouted nail

$(u_a - u_w)$ = matric suction

ϕ^b = internal friction angle with respect to soil suction

v = Poisson's ratio

ψ = dilation angle

K_0 = coefficient of earth pressure at rest

The contribution due to matric suction in eq. [6.13] is taken into account by considering an increase of soil shear strength as part of the apparent soil cohesion as shown below:

$$c = c' + (u_a - u_w)\tan\phi^b \qquad [6.14]$$

where:

c = apparent cohesion

In equation [6.14], the angle of shearing resistance with respect to suction, ϕ^b is required to estimate the contribution due to matric suction. However, ϕ^b, is a variable for soils with non-linear shear behaviour (Vanapalli et al., 1996).

6.8.4 Estimated pull-out capacity using other equations available in the literature

The equations described above under sections 6.8.1 to 6.8.3 were used to estimate the pull-out capacity of the prototype soil nails used for the test program. A comparison was made between the measured values and the estimated values by using the proposed technique. Table 6.5 presents a summary of the results by using the different equations. A comparison of the estimated and measured results for the vertical, inclined and horizontal nails are presented graphically in Figures 6.8.

Table 6.5 Comparison between the estimated and measured pull-out capacity by using the proposed technique and other equations available in the literature

Orientation	Average matric suction (u_a-u_w) kPa	Measured pull-out capacity (kN)	Estimated pull-out capacity (kN)			
			Present study (kN)	Schlosser and Guilloux (1981)	Chu and Yin (2005)	Zhang et al. (2009)
Vertical	0	1.69	1.70	1.75	1.71	2.35
Vertical	2	2.56	2.32	2.00	1.94	2.75
15°	0	1.98	1.80	1.85	1.81	2.40
15°	1	2.62	2.30	1.96	1.91	2.73
15°	2	2.85	2.47	2.03	1.97	2.80
15°	3.7	3.10	2.81	2.14	2.06	2.90
15°	5.3	3.42	2.99	2.14	2.06	2.88
15°	7	2.72	2.71	2.14	2.06	2.83
Horizontal	0	2.25	1.87	1.87	1.82	2.53
Horizontal	2	2.93	3.09	2.21	2.12	3.20

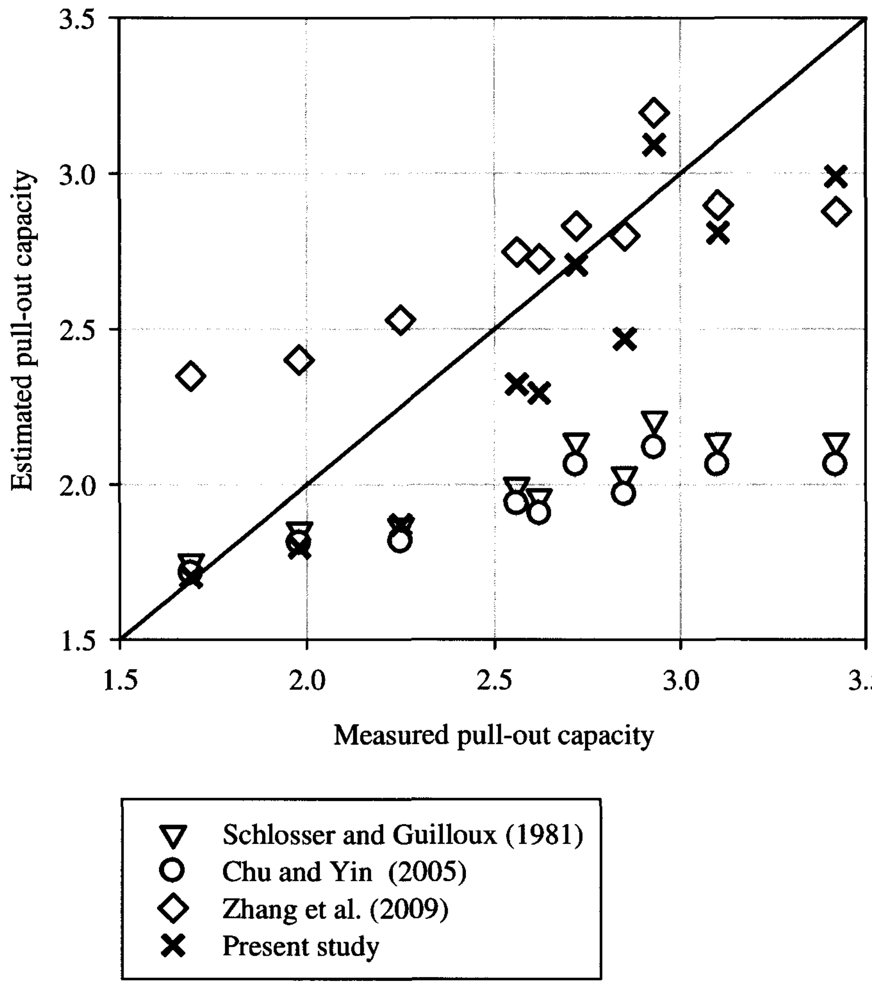

Figure 6.8 Comparison between the estimated and measured values for the test nails by using the proposed technique (present study) and other methods available in the literature

As illustrated in Figure 6.8, there a reasonable good match between the estimated and measured values for the pull-out capacity of soil nails under both saturated and unsaturated conditions by using the proposed technique. The estimated values provided a better match than other equations available in the literature.

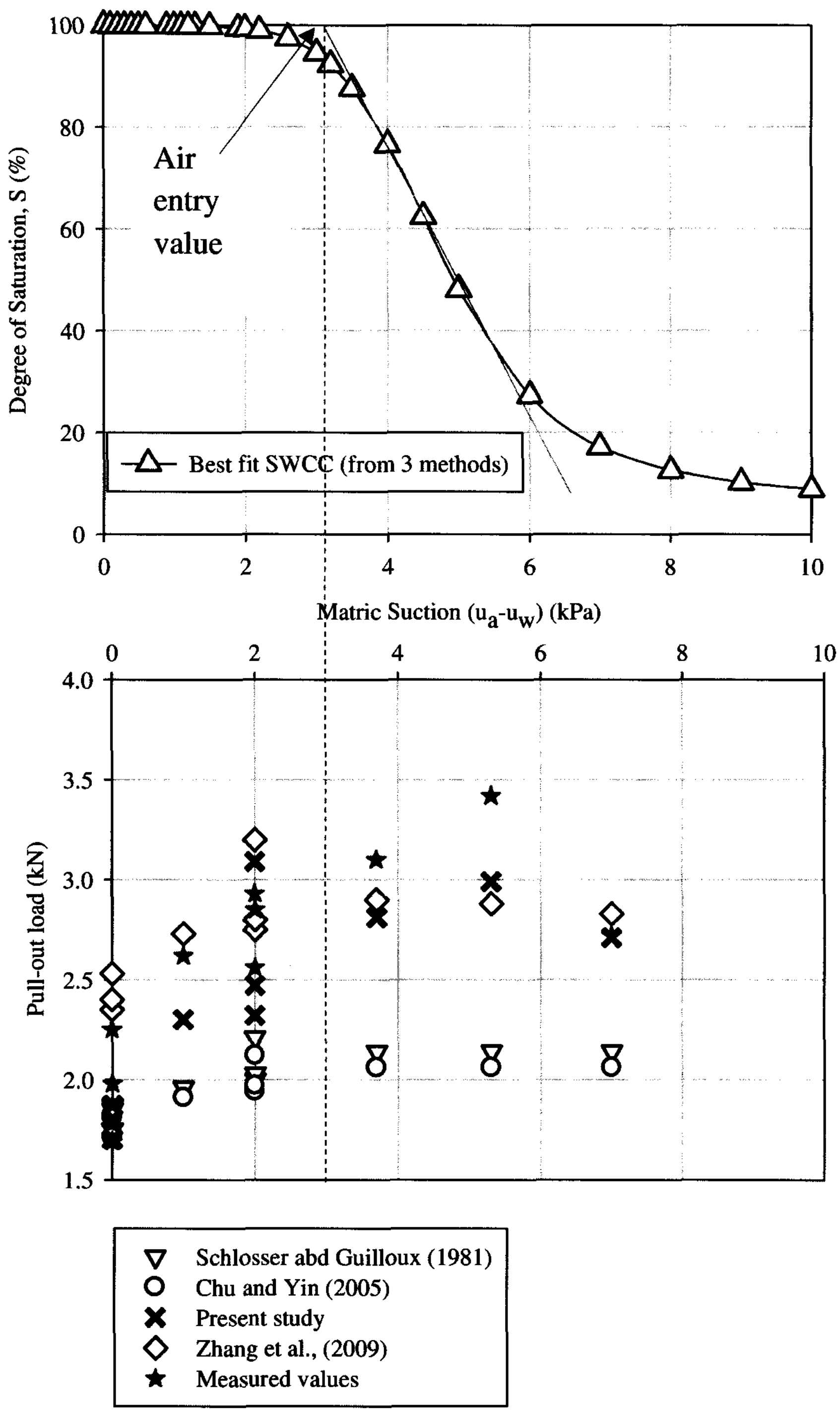

Figure 6.9 Variation of estimated pull-out capacity using the proposed technique and other equations available in the literature vs. measured values with the variation in matric suction

The figure above (6.9) shows the comparison between the estimated and measured values for the test nails by using the proposed technique (present study) and other methods available in the literature along with the variation of matric suction (SWCC). A relationship is observed with a linear trend up to the air entry value (AEV) followed by a non-linear pattern in the pull-out capacity. The test results obtained and presented in Figure 6.9 supplement the relationship of the pull-out capacity with the shear strength of unsaturated soils.

6.9 Effect of hydration on the measured suction values

The effect of hydration of the grout was examined as outlined in the previous Chapter. The test results indicated that there is some amount of influence of hydration on the variation of water content, especially within a span of 300 mm. A difference existed after 7 days between the cups located at the interface, at 150 and 300 mm away from the interface at the same elevation. However, the results obtained after 14 days shows similar values and then the differences reoccur after 28 days. The effects of hydration on suction values for grouted soil nails requires further investigation since one data set was used for this examination. The effect of hydration on matric suction was investigated since the tensiometers were located approximately 300 mm away from the soil/grout interface during pull-out. The impact is not significant for the tested soil but highlights an area which should be addressed during large scale testing. Figure 6.10 shows the effects of hydration on water content of the soil from the soil/nail interface.

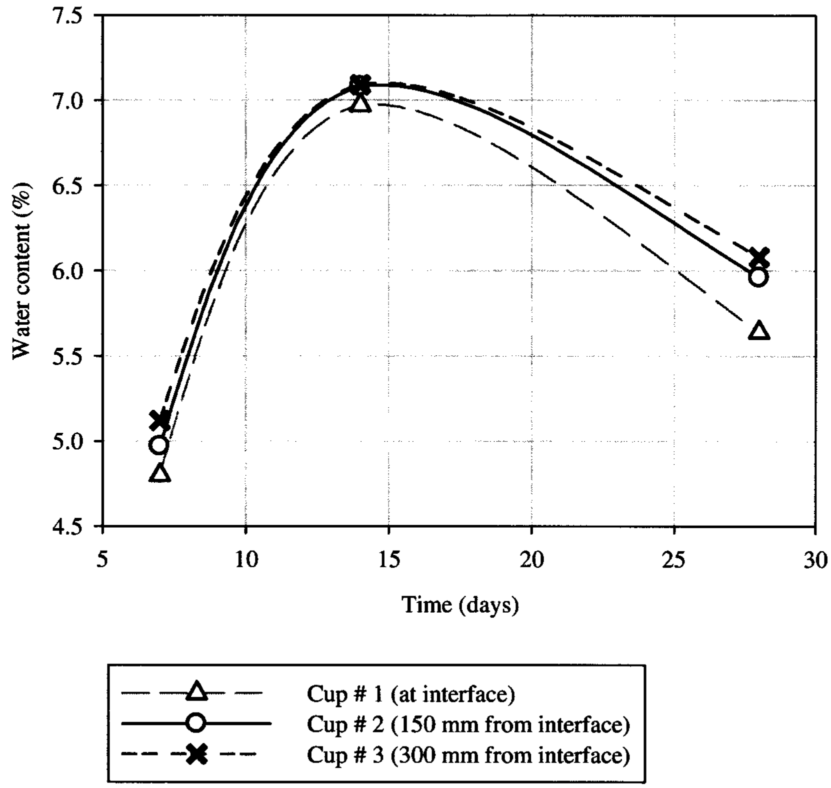

Figure 6.10 Effects of hydration on water content adjacent next to the soil/grout interface

6.10 Analysis of data available in the literature by using the proposed technique

There are limited soil nail pull-out test data available in the literature where the variation in the degree of saturation (i.e. variation in matric) was measured, especially for grouted nails. Laboratory test results obtained by Pradhan (2003) and Su (2006) to evaluate the pull-out behaviour of soil nails installed in completely decomposed granite (CDG) under saturated unsaturated conditions were analyzed. No pull-out test results were found in the literature for sand to the author's best knowledge where the variation in matric suction was taken into account.

6.10.1 Data from Pradhan (2003)

Pull-out tests were performed by Pradhan (2003) by using a test box (2 x 1.6 m in plan and 1.4 m high) and grouted soil nails installed in completely decomposed granite (CDG) fill. The tests were performed under different conditions by varying the degree of compaction and degree of saturation, along with the application of overburden pressure by using hydraulic jacks. The development of the pull-out resistance and the soil-nail interface characteristics were examined, especially for loose fill at natural moisture content (average suction = 87 kPa).

Results from the study produced distinct peaks on the load-displacement plots, followed by a reduction in the post-peak stage for both dense and loose fills. The apparent interface adhesion was found to be dependent on the degree of saturation and the degree of compaction of the soil.

6.10.1.1 Analysis of data obtained by Pradhan (2003) by using the proposed technique

The pull-out test results obtained by Pradhan (2003) for soil nails installed at an inclination of 10° to the horizontal, along with the application of overburden pressure is presented below. Figure 6.11 shows some details of the nail used for laboratory testing performed by Pradhan (2003).

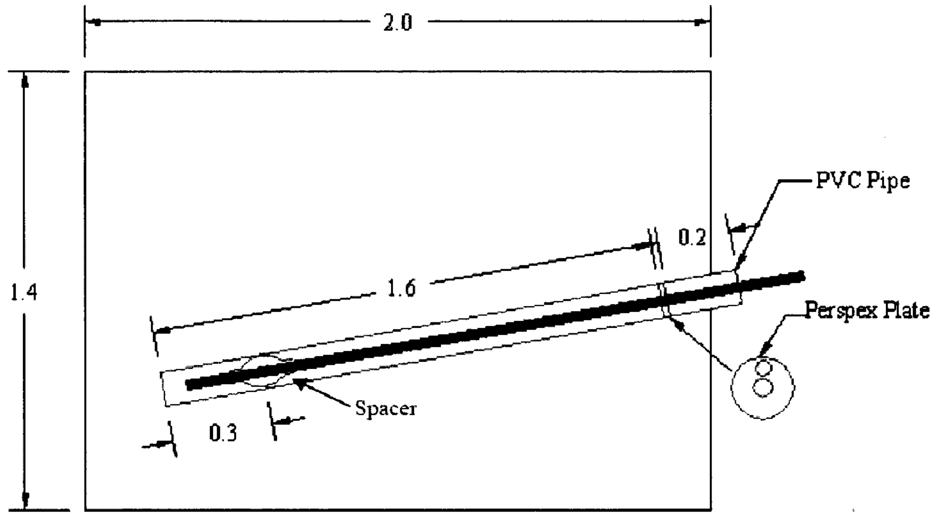

Figure 6.11 Details of soil nail (Pradhan, 2003)

The soil parameters used for the estimation of the pull-out capacity of the soil nails is shown in Table 6.6 (Pradhan, 2003).

Table 6.6 Soil parameters (Pradhan, 2003) used for the estimation of the pull-out capacity of the soil nails

Parameter	Saturated condition	Natural moisture content (S = 38%)
ϕ'	39	38.5
c_a	0	4.2
δ	37	37

A comparison of the measured and estimated pull-out capacity of the soil nails installed in CDG under saturated and unsaturated conditions is presented below in Table

6.7. The pull-out capacity was estimated based on the technique proposed in the present study and the β values were obtained by using eq. [6.9] and [6.10].

Table 6.7 Measured and estimated pull-out capacity for nails installed in CDG fill under saturated and unsaturated conditions

Test	Average matric suction $(u_a - u_w)$ kPa	Effective overburden pressure (kPa)	Measured peak pull-out force (kN)	Estimated pull-out capacity (kN)
1	0	31.53	6.88	7.53
2	0	39.5	11.01	8.81
3	0	53.76	14.5	10.94
4	0	19.8	5.44	5.64
5	0	35.6	8.3	8.18
6	0	38.4	12	8.63
7	0	51.9	13.9	10.81
8	87	17.05	12.60	9.65
9	87	17.05	13.10	9.65
10	87	16.25	16.52	9.40
11	87	34.43	15.27	15.25
12	87	57.5	20.82	22.67
13	87	66.15	25.46	25.45
14	87	77.16	24.47	28.99
15	87	94.26	29.03	34.50
16	87	107.03	37.80	38.60

A comparison of the measured and estimated pull-out capacity of soil nails tested under saturated and unsaturated conditions in CDG is presented in Figure 6.12.

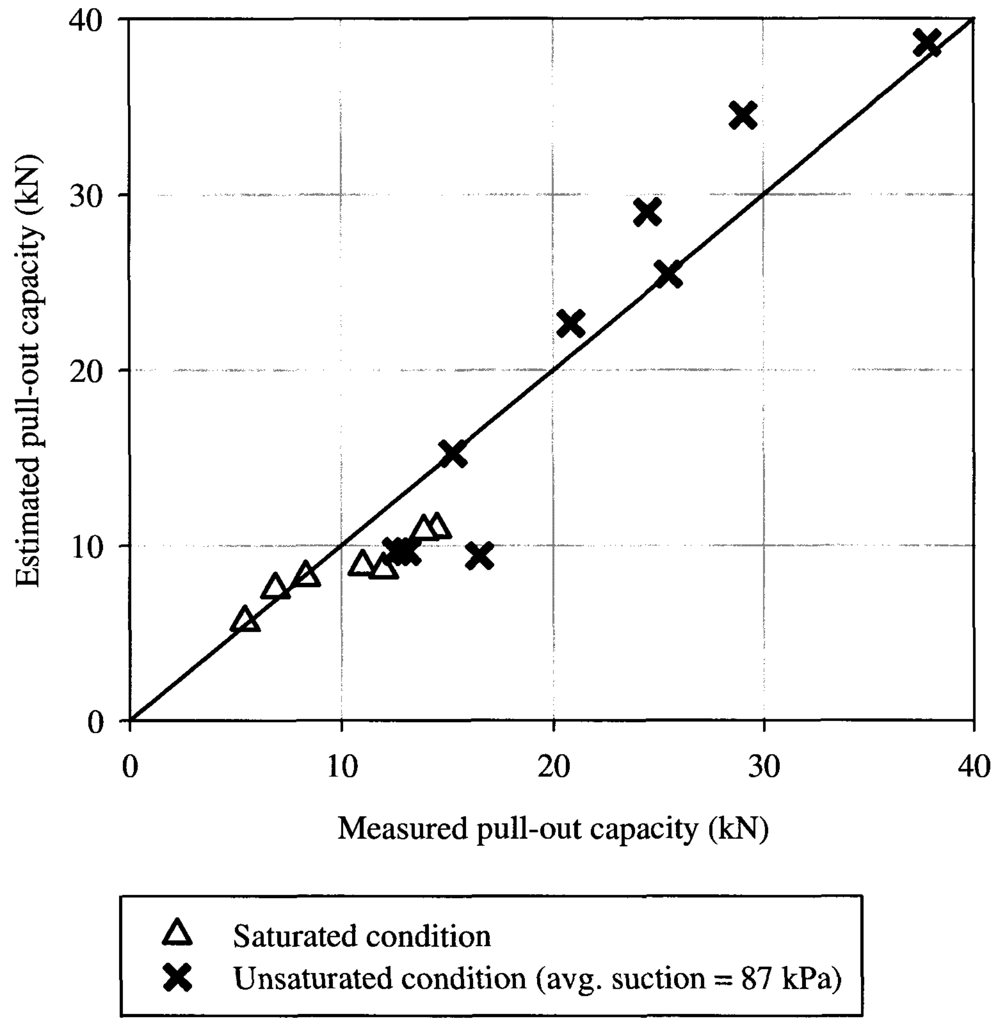

Figure 6.12 Comparison between estimated and measured pull-out capacity (Pradhan, 2003) for nails installed in CDG fill under saturated and unsaturated conditions

6.10.2 Data from Su (2006)

A laboratory study on the pull-out resistance of grouted soil nails was performed on completely decomposed granite (CDG) fill in a test box (1.0 m x 0.6 m in plan and 0.83 m high). A series of pull-out tests were conducted at various degrees of saturation, overburden pressures and grouting pressures. Pull-out tests in soil at different degrees of saturation indicated that the peak shear resistance varies with the degree of saturation and hence variation in matric suction. At degree of saturation of 50% and 75%, much higher pull-out resistance was achieved since the soil is considered to be within the transition zone of the SWCC as illustrated above.

6.10.2.1 Analysis of data obtained by Su (2006) by using the proposed technique

The pull-out test results obtained by Su (2006) for soil nails installed in completely decomposed granite (CDG), under different degrees of saturation and varying overburden pressures were analyzed using the proposed technique. A set-up of the test box and instrumentation used by Su (2006) is illustrated in Figure 6.13. The soil parameters used for the analysis is presented in Table 6.8

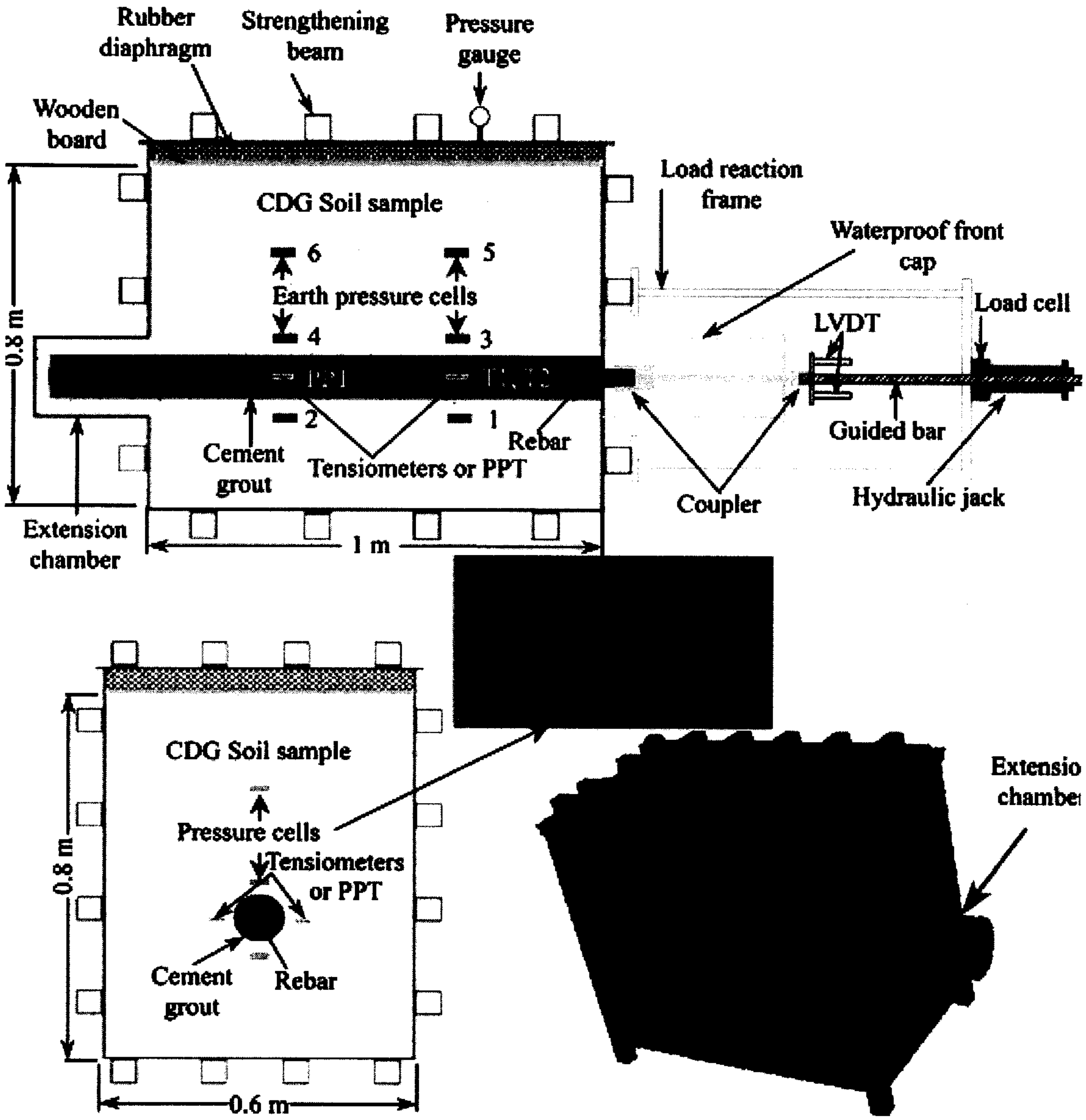

Figure 6.13 Set-up of the test box and instrumentation (Su et al., 2008)

Table 6.8 Soil parameters used for the estimation of the pull-out capacity of the soil nails used by Su (2006)

Degree of saturation (%)	Cohesion (c')	Internal friction angle (ϕ')	Interface friction angle (δ)
38	36.6	33	22
50	59.5	33	22
75	26.8	33	22
98	9.4	33	22

A comparison between the measured and estimated pull-out capacity of the soil nails installed in compacted CDG is presented in Table 6.9 (Su, 2006) and graphically illustrated under Figure 6.14.

Table 6.9 Measured and estimated pull-out capacity for nails pulled out from compacted CDG under saturated and unsaturated conditions

Test	Average matric suction $(u_a - u_w)$ kPa	Effective overburden pressure (kPa)	Degree of saturation (%)	Measured peak pull-out force (kN)	Estimated pull-out capacity (kN)
1	87	40	38	26.39	18.40
2	6	40	75	32.05	13.92
3	0	40	98	16.97	3.68
4	87	120	38	27.52	28.45
5	68	120	50	32.80	36.24
6	6	120	75	26.39	23.97
7	0	120	98	22.62	8.70
8	87	200	38	26.39	38.51
9	68	200	50	26.39	46.29
10	6	200	75	35.06	34.03
11	0	200	98	15.08	13.73
12	87	300	38	26.39	51.07
13	68	300	50	41.47	58.86
14	6	300	75	33.93	46.59
15	0	300	98	15.84	20.01

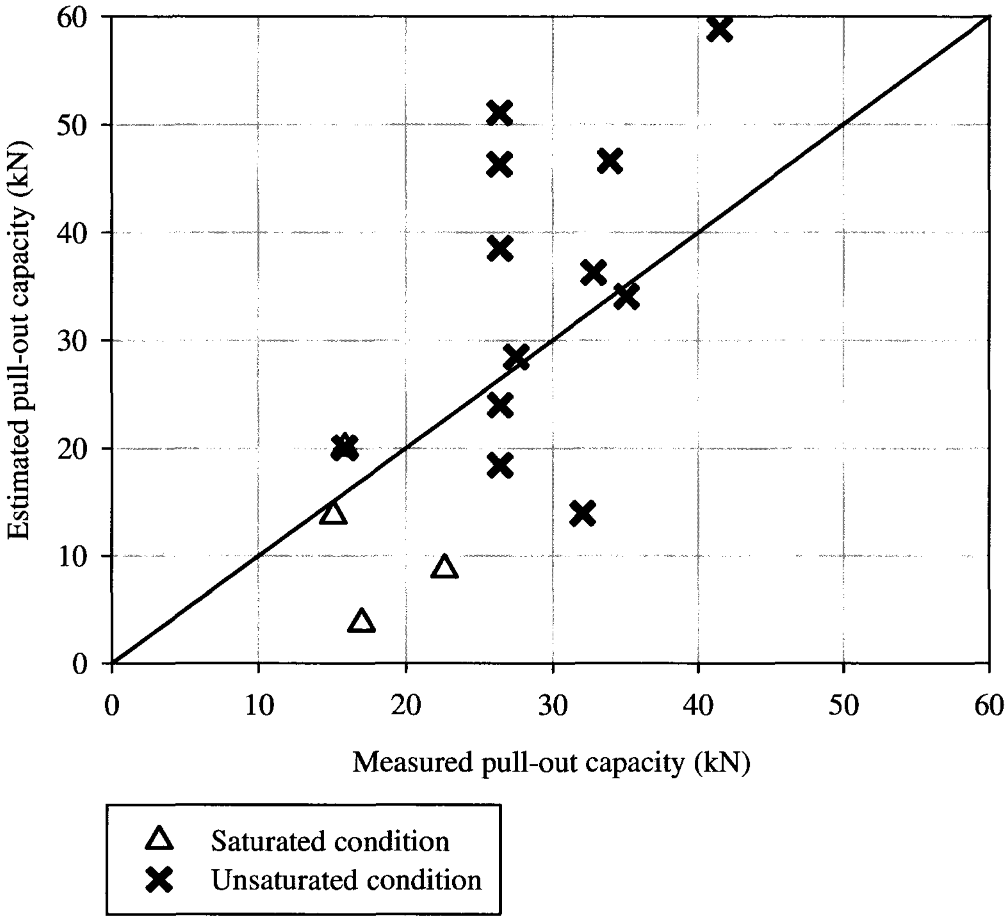

Figure 6.14 Comparison between estimated and measured pull-out capacity for nails installed in compacted CDG (Su, 2006)

The measured results obtained by Su et al. (2008) shows a large scatter in the results, which may be a direct result of variation in the procedure used for the installation and grouting of the nails.

6. 11 Summary

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.

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.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

A comprehensive experimental program was undertaken to determine the pull-out capacity of soil nails installed in a compacted coarse grained soil. The pull-out capacity of prototype soil nails was evaluated under both saturated and unsaturated conditions in a laboratory environment. The data related to the soil properties, shear strength parameters, soil-water characteristic curve (SWCC) and suction measurements were collected. The conventional β method used to estimate the shaft capacity of piles was extended to estimate the pull-out capacity of soil nails in both saturated and unsaturated coarse grained soil. A simple technique was proposed to predict the variation of pull-out capacity with respect to suction by using the SWCC and the saturated shear strength parameters (c' and ϕ'). However, the pull-out capacity can be estimated by using the saturated shear strength parameters and the average suction value.

In order to achieve the objectives of the research as outlined in Chapter 1, several pull-out tests were performed under saturated and unsaturated conditions in specially designed equipment. The prototype soil nails were installed and tested at various orientations – vertically, inclined at 15° to the vertical and horizontally. Additionally, several laboratory experiments were performed such as direct shear test, compaction test, grout testing, simple shear tests, sieve analysis and interface direct shear tests.

7.2 Conclusions

The following conclusions can be drawn from the studies undertaken through this research program:

- The specially designed test box for this research satisfied all of the testing objectives.
- The pull-out capacity of soil nails in unsaturated coarse grained soil was found to be 1.3 to 1.7 times higher than saturated conditions.
- The conventional β method used to estimate the shaft capacity of piles was extended for interpreting the pull-out capacity of soil nails by taking the influence of suction into account.
- The study shows that there is a strong relationship between the pull-out capacity of unsaturated soils and the soil water characteristic curve (SWCC).
- The proposed technique can be used for prediction of the pull-out capacity of soil nails installed in unsaturated soils by using the saturated shear strength parameters (c' and ϕ') and the SWCC.
- The predicted pull-out capacity values have shown a good agreement with the measured pull-out capacity for the soil tested in this research program as well as two other sets of data collected from the literature.
- The pull-out capacity can be estimated by using the saturated shear strength parameters (c' and ϕ') and the average suction value.
- The influence of dilatancy was taken into account in the proposed technique to predict/estimate the pull-out capacity of soil nails.

- The present understanding of the shear strength of unsaturated soils was extended for the interpretation and prediction of the pull-out capacity of soil nails.
- A simple technique was proposed for the estimation of the pull-out capacity of soil nails in unsaturated soils.

7.3 Recommendations

The following recommendations are offered for further research work:

- To study the influence of matric suction on β values.
- Instrumented field testing of the pull-out capacity of soil nails in order to compare with the proposed technique.
- Influence of other inclinations on the pull-out capacity of soil nails.
- To encourage practicing engineers to apply the simple technique proposed in this thesis towards estimating the pull-out capacity of soil nails.
- Pull-out testing over a larger range of matric suction values.
- Investigate the pull-out capacity of grouted soil nails for other soil types.
- Additional pull-out tests and modeling of the results to establish the relationship between the SWCC and β values.

REFERENCES

ASTM, D422. (2007). "Standard test method for particle size analysis of soils." In annual Book of ASTM Standards, American Society of Testing Material, Philadelphia, PA.

ASTM, D1557. (2009). "Test method for laboratory compaction characteristics of soils using modified effort." In annual Book of ASTM Standards, American Society of Testing Material, Philadelphia, PA.

ASTM, D854.(2006). "Standard test method for specific gravity of soils." In annual Book of ASTM Standards, American Society of Testing Material, Philadelphia, PA.

ASTM, D 2325-68. (2000). "Standard test method for capillary-moisture relationship for coarse and medium testure soils by porous plate apparatus." In annual Book of ASTM Standards, American Society of Testing Material, Philadelphia, PA.

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

Banyai, M. (1984). "Stabilization of earth walls by soil nailing." Proceedings of 6th International Conference on Soil Mechanics and Foundation Engineering, Budapest, 459-466.

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

Barley, A.D. (1992). “Soil nailing case histories and developments.” Conference on retaining structures, Robinson College, Cambridge, England, 559-573.

Barley, A.D., Davies, M.C.R. and Jones, A.M. (1997). “Review of current methods for soil nailing.” Ground improvement geosystems densification and reinforcement, London, 477-486.

Barr, B.I.G., Davies, M.C.R. and Jacobs, C.D.(1991). “A large direct shear box – some initial test results of tests on nails.” Ground Engineering, 24(3), 44-50.

Bishop, A.W. (1959). “The principle of effective stress.” Lecture delivered in Oslo, Norway, 1955; Technisk Ukeblad, 106(39): 859–863.

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.

Bruce, D.A. and Jewell, R.A. (1986). “Soil Nailing Application and Practice – Part 1.” Ground Engineering, vol 19, No.8, Nov, 10-15.

Bryne, R.J., Cotton, D., Porterfield, J., Wolschlag, C., and Ueblacker, G. (1998). “Manual for design and construction monitoring of soil nail walls.” Report No. FHWA-SA-96-069, Federal Highway Administration, Washington, D.C.

Budhu, M. (2007). “Soil mechanics and foundations.” John Wiley and Sons, Hoboken, NJ.

Burland, J.B. (1964). “Effective stresses in partly saturated soils.” Géotechnique. 14: 65–68.

California Transportation Department Caltrans. (1997). "Foundation manual." Sacramento, California.

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.

Chai, X.J. and Hayashi, S. and Du, Y.J. (2004). "Contribution of dilatancy to pullout capacity of nails in sandy clay." In soil nailing and stability of soil and rock engineering, Nanjing, China, 73-80.

Chu, L.M. (2003). "Study on the influence of shear strength of soil nailing in completely decomposed granite (CDG) soil." M.Phil thesis, The Hong Kong Polytechnic University.

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.

Davies, M.C.R. & Jewell, R.A. (1992). "Earth reinforcement practice." Proceedings of the International Symposium on Earth Reinforcement. Kyushu, Japan, Vol. 2.

Donald, I.B. (1957). "Effective stresses in unsaturated non-cohesive soils with controlled negative pore pressure." M.Eng. Sc. Thesis, University of Melbourne, Melbourne, Australia.

Dregne, H.E. 1976. "Soils of arid regions." Elsevier Scientific Pub. Co., Amsterdam, New York.

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., Morgenstern, N.R. and Widger, R.A. (1978). "The shear strength of unsaturated soils." Canadian Geotechnical Journal 15: 313–321.

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

Fredlund, D.G., and Xing, A. (1994). "Equations for the soil-water characteristic curve." Canadian Geotechnical Journal, 31: 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, 31: 533-546.

Fredlund, D.G., Vanapalli, S.K., Xing, A., and Pufahl, D.E. (1995). "Predicting the shear strength functions for unsaturated soils using the soil-water characteristic curve." Proceedings of the 1st International Conference on Unsaturated Soils, ed. Alonso, E.E., and Delage, P., Paris September 6-8, 1995, A. A. Balkema, pp. 63-69.

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

Fredlund, D.G. (1996). "The relationship of the unsaturated soil shear strength to the soil-water characteristic curve." Canadian Geotechnical Journal, 33(3): 440.

Gassler, G. and Gudehus, G. (1981). "Soil nailing - some aspects of a new technique." Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, 3: 665-670.

Gassler, G. (1990). "State of the art report-insitu techniques of reinforced soil". Proceeding of the International Reinforced Soil Conference, Glasgow, 185- 196.

Gardner, W.R., (1958). "Some steady state solutions of the unsaturated moisture flow equation with application to evaporation with application to evaporation from a water table." Soil Science, 85: 228-232

Garven, E.A. and Vanapalli, S.K. (2006). "Evaluation of empirical procedures for predicting the shear strength of unsaturated soils." Proceedings of 4th International Conference on Unsaturated Soils, April 2 – 6, 2006, Arizona, USA, 2570-2581.

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.

Heymann, G. (1993). "Soil nailing systems as lateral support for surface excavations." Master Thesis, Faculty of Engineering, University of Pretoria, South Africa.

Jewell, R.A. and Wroth, C.P. (1987). "Direct shear tests on reinforced sand." Geotechnique, No 37, 53-68.

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

Junaideen, S.M. (2001). "The design and performance of a pressure chamber for testing soil nails in loose fill." MPhil Thesis, The University of Hong Kong, Hong Kong.

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.

Kimmerling, R.E. and Chassie, R.G. (1993). “Performance monitoring of a soil nail wall used in a bridge abutment application.” Proceedings of Soil Reinforcement Full Scale Experiments of the 80’s, Paris, 63-92.

Lazarte, C.A., Elias, V., Espinoza, D., Sabatini, P.J. (2003). “Soil nail walls.” Report No. FHWA 0-IF-03-017, Federal Highway Administration, Washington, D.C.

Lu, N. and Likos, W. (2004). “Unsaturated soil mechanics.” John Wiley and Sons, Hoboken, N.J.

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 Enineering Division ASCE 102(GT3):195-228.

Milligan, G.W.E, Chang, K.T. and Morris, J.D. (1997). “Pullout resistance of soil nails in sand and clay.” Proceedings of the Third International Conference of Ground Improvement Geosystems, London, 415-422.

Mohamed, F.M.O. (2006). "A semi-empirical approach for interpretation of the bearing capacity of unsaturated soils." Masters thesis, The University of Ottawa, Ottawa, Ontario.

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.

Mualem, Y. (1986). "Hydraulic conductivity of unsaturated soils: prediction and formulas." In methods of soil analysis. Part 1 Physical and mineralogical methods. 2nd Edition. Agronomy. Edited by A. Klute, American Society of Agronomy, Inc. and Soil Society of America, Inc., Madison, Wisconsin, U.S.A., 799-823.

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., Garga, V.K. and Vanapalli, S.K. (2008). "Shear strength characteristics of statically compacted unsaturated kaolin." Canadian Geotechnical Journal 45(7): 910–922.

Oh, W.T. and Vanapalli, S.K. (2008). "Modeling the bearing capacity and settlement behavior of unsaturated soils." Proceedings of the 12th IACMAG Conference, October 1 – 6, 2008, Goa, India.

Oh, W.T. & Vanapalli, S.K. (2009). "A simple method to estimate the bearing capacity of unsaturated fine-grained soils." Proceedings of the 62nd Canadian Geotechnical Conference, September 20 - 24, 2009, Halifax, Nova Scotia.

Oh, W.T., Vanapalli, S.K. and Puppala, A.J. (2009). "Semi-empirical model for the prediction of modulus of elasticity for unsaturated soils." Canadian Geotechnical Journal, 46: 903- 914.

Ortigao, J.A.R. Palmeira, E.M. & Zirlis, A.C. (1995). "Experience with soil nailing in Brazil: 1970 – 1994." Procdeedings of the Institution of Civil Engineers, Geotechnical Engineering, Vol. 113, 93-106

Ortigao, J.A.R. and Palmeira, E.M. (1997). "Optimised design for soil nailed walls." Proceedings of the Third International Conference on Ground Improvement Geosystems, 369-374.

Plumelle, C., Schlosser, F., Delage, P., and and Knochenmus, G. (1990). "French national research project on soil nailing: CLOUTERRE." In the Design and performance of earth retaining structures, 660-675.

Porterfield, J.A., Cotton, D.M., and Bryne, R.J. (1994). "Soil nailing field inspectors manual." Project Demonstration 103, Publication no. FHWA-SA-93-068, Federal Highway Administration, Washington, D.C.

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

Powell, G.E. and Watkins, A.T. (1990). "Improvement of marginally stable existing slopes by soil nailing in Hong Kong." Proceedings of the International Reinforced Soil Conference, Glasgow, U.K., 241-247.

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.

Rabcewicz, L. V. (1964, 1965). "The New Austrian Tunneling Method." Parts I to III, Water Power, London.

Schlosser, F. and Guilloux, A. (1981). "Le frottement dens les sols. Revue Francaise de." Geotechnique. No. 16, 65-77 (1981).

Schlosser, F. (1982). "Behaviour and design of soil nailing." Proceeding of International Symposium on Recent Development in Ground Improvement Technique, Bangkok, 399-413.

Schlosser, F., Jacobsen, H.M., and Juran, I. (1983). "Soil reinforcement, General Report-Specialty Session 5." Proceedings of the 8th International Conference Soil Mechanics and Foundations Engineering, Helsinki, 1159-1180.

Schlosser, F., Plummelle, C., Unterreiner, P. Salencon, J. and Magnan, J.P. (1991). "Recommendations Clouterre-1991." French National Research Project Clouterre, FHWA-AB-93-026.

Shen, C.K., Bang, S. and Herrman, L.R. (1981). "Ground movement analysis of earth support system." Journal of Geotechnical Engineering Division, ASCE 107 (GT12): 1609-1624.

Singala, S. (1999). "Demonstration project 103: Design and construction monitoring of soil nail walls." Report No. FHWA-IF-99-026, Federal Highway Administration, Washington, D.C.

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.

Soilmoisture Equipment Corporation. (2009). "Soilmoisture product catalog." Soilmoisture Equipment Corporation, Santa Barbara, CA.

Steensen-Bach, J.O., Foged, N. and Steenfelt. J.S. (1987). "Capillary Induced Stresses – Fact or Fiction?" Proceedings of the 9th European conference on soil mechanics and foundation engineering, Budapest (Hungary), 83-89.

Stocker, M.F., Korber, G.W., Gassler, G. and Gudehus, G. (1979). "Soil nailing." Proceedings of the International Conference on Soil Reinforcement, Paris, Vol. 2, 469-474.

Su, L.J. (2006). "Laboratory pull-out testing study on soil nails in compacted completely decomposed granite fill." PhD thesis, The Hong Kong Polytechnic University.

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.

Sweeney, D.J. (1982). "Some in-situ soil suction measurements in Hong Kong's residual soil slopes." Proceedings of the 7th Southeast Asian Regional Conference, Hong Kong, November 22 - 26, 1982, Southeast Asian Geotechnical Society, Hong Kong, Vol. 1: 91-106.

Vanapalli, S.K.(1994). "Simple test procedures and their interpretation in evaluating the shear strength of unsaturated soils." Ph.D. Thesis, University of Saskatchewan, Saskatoon.

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

Vanapalli, S.K., Fredlund, D.G. & Pufahl, D.E. (1996b). "The relationship between the soil-water characteristic curve and unsaturated shear strength of a compacted glacial till." American Society of Testing Materials, Geotechnical Testing Journal 19(3): 259–268.

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, October 4 – 8, 1998, Edmonton, 101-108.

Vanapalli, S.K., Pufahl, D.E. & Fredlund, D.G. (1999a). "Interpretation of the shear strength of unsaturated soils in undrained loading conditions." Proceedings of the 52nd Canadian Geotechnical Conference, October 25–27, 1999, Regina, Saskatchewan, 643–650.

Vanapalli, S.K., Fredlund, D.G. & Pufahl, D.E. (1999b). "The influence of soil structure and stress history on the soil-water characteristics of a compacted till." Géotechnique 49(2): 143–159.

Vanapalli, S.K. & Fredlund, D.G. (2000). "Comparison of empirical procedures to predict the shear strength of unsaturated soils uses the soil-water characteristic curve." Geo-Denver 2000, American Society of Civil Engineers, Special Publication, 99: 195–209.

Vanapalli, S.K., Salinas, L.M., Avila, D. and Karube. D. (2004). "Suction and storage characteristics of unsaturated soils." Presented the State-of-the-art report, Proceedings of the 3rd International conference on Unsaturated Soils, March 10 – 12, 2002, Brazil, 3: 1045–1069.

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. and Lacasse, F. (2009). "Comparison between the measured and predicted shear strength behaviour of four unsaturated sands." Proc. 4th Asia-Pacific Conference on Unsaturated Soils. New Castle, Australia. (Accepted for publication).

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., 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.

Vanapalli, S.K. and Oh, W.T. (2010). "Bearing capacity of unsaturated fine-grained soils." Journal of Geotechnical and Geoenvironmental Engineering. Paper accepted for publication.

Van Genuchten, M.T. (1980). "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." Soil Science Society of America Journal, 44: 892-898.

Vukovic, M. and Soro A. (1992). "Determination of hydraulic conductivity of porous media from grain size composition." Water Resources Publications, Littleton, Colorado, USA.

Wang, Z. and Richwein, W. (2002). "A Study of Soil-Reinforcement Friction." Journal of Geotechnical and Geo-environmental Engineering, January, 92-94.

Warner, J. (2004). “Practical handbook of grouting: soil, rock, and structures.” John Wiley and Sons, Hoboken, N.J.

Watkins, A.T. and Powell, G.E. (1992). “Soil nailing to existing slopes as landslip preventive works.” Hong Kong Engineers, March, 20-77.

Winterkorn, H.F., Nat., P., and Pamukcu, S. (1991). “Soil Stabilization and Grouting. Foundation Engineering Handbook.” 2nd Edition, VanNostrand Reinhold, N.Y., NY.

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

Yin, J. H., Su, L. J., Cheung, R. W. M., Shiu, Y. K., and Tang, C. (2008). “The influence of grouting pressure on the pullout resistance of soil nail in compacted completely decomposed granite fill.” Geotechnique, Vol. 59-2, 103–113.

Yin, J. and Zhou, W. (2009). “Influence of grouting pressure and overburden stress on the interface resistance of a soil nail.” Journal of Geotechnical and Geoenvironmental Engineering, 135(9): 1198-1208.

Zhang, L.L. (2004). “Numerical study of soil conditions under which matric suction can be maintained.” Canadian Geotechnical Journal, 41(4): 569.

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(7)-973.

Zhou, L.L., Zhang, L.M., and Tang, W.H. (2007). "Study of the effects of grouting pressure and overburden pressure on the pullout resistance of soil nail." Proceedings of the 60th Canadian Geotechnical Conference, October 24 – 27, 1007, Ottawa, ON.

APPENDIX

(Paper published from this research)

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

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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).

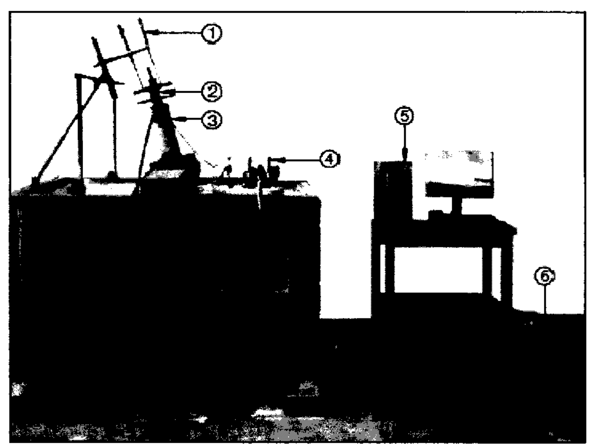
3 EQUIPMENT AND METHODOLOGY

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:

iv) To evaluate the contribution of suction towards the pull-out capacity of soil nails in compacted coarse-grained soil, under saturated and unsaturated conditions.
v) 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.

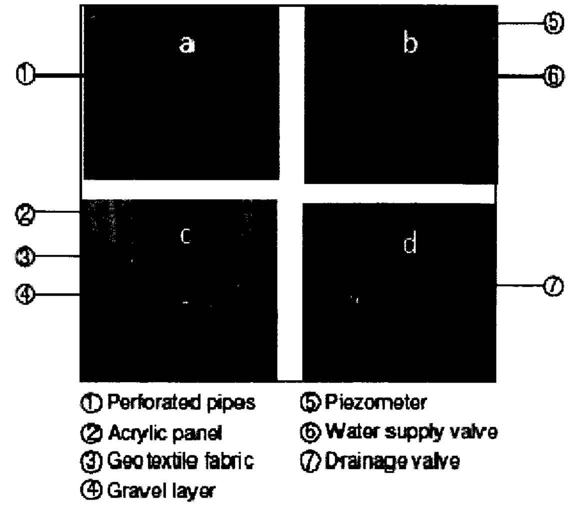


Figure 2. Key features of the test box

3.3 Drilling and installation of the test nails

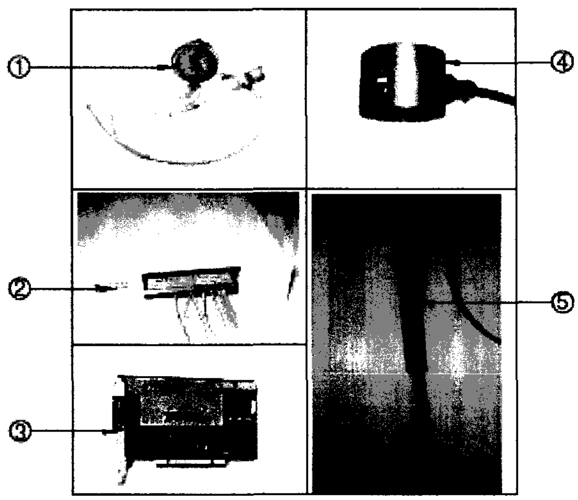
The influence of inclined soil nails were studied in this paper as they are conventionally done in the field. An electric core drilling machine was used to drill the holes at a diameter of 100 mm. The steel tendon was installed and then grouted in the drilled hole. Prior to drilling, the water table 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.



① Tensiometer ④ Load cell
② Channel box ⑤ LVDT
③ Data logger

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°
Grout–soil Interface friction angle (δ)	28.8°
Dilation angle (ψ)	4.3°

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, (ua – uw), 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

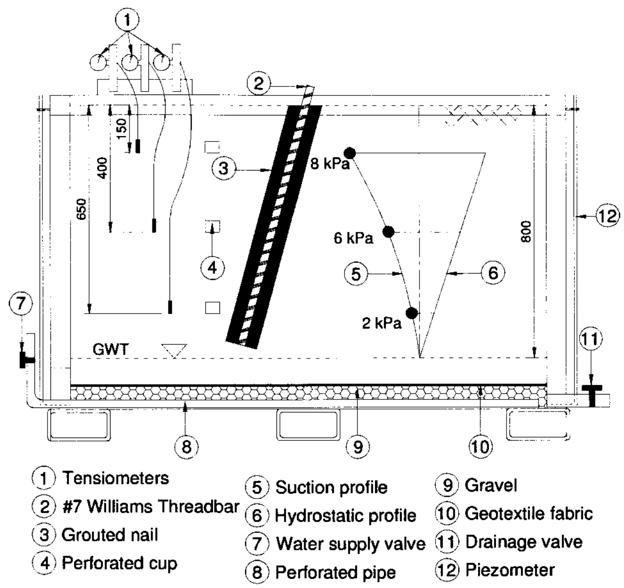


Figure 4. Section through the text box along with the suction profile

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.

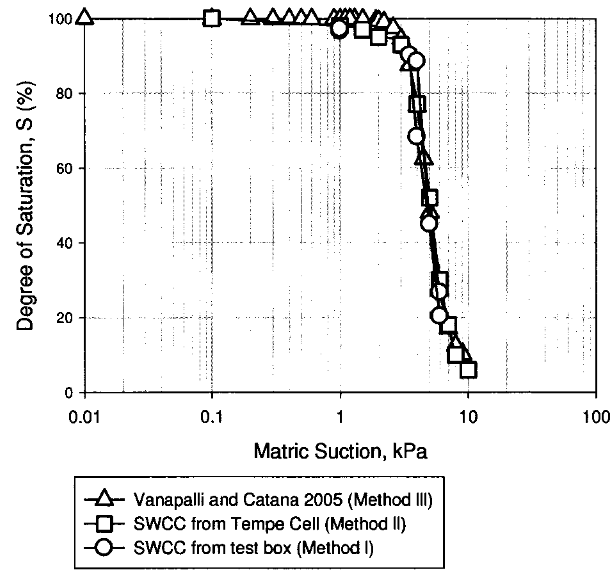


Figure 5. Measured and predicted SWCCs for the tested sand

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.

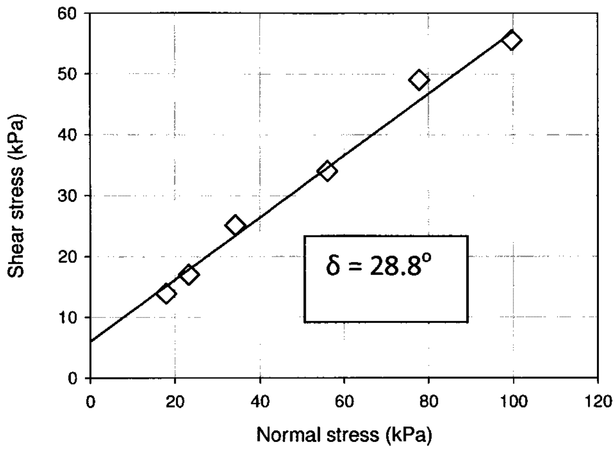


Figure 6. Interface direct shear test results

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.

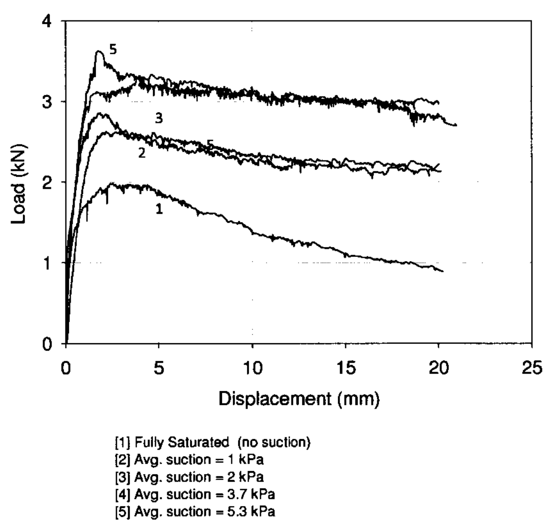


Figure 7. Load - displacement relationship under different average suction values

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:

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

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).

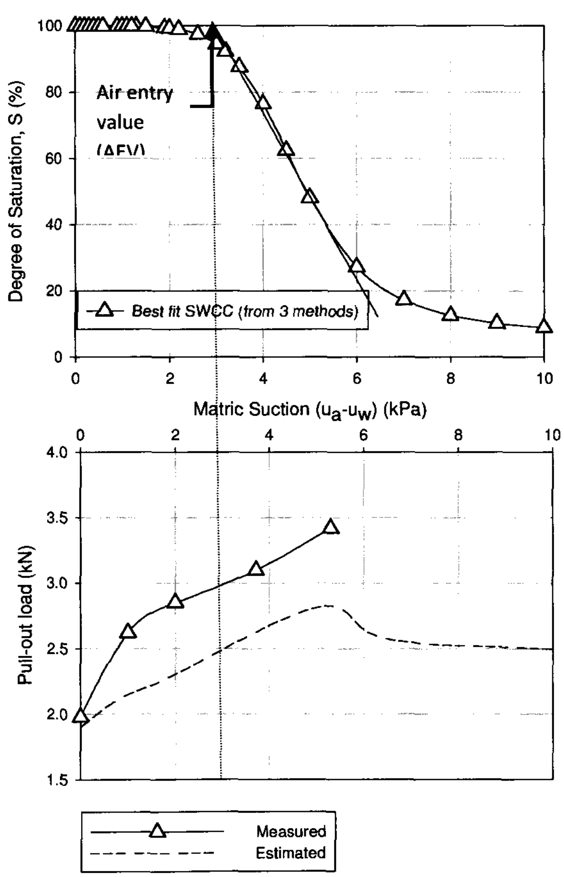


Figure 8. Variation of pull-out capacity with suction

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.

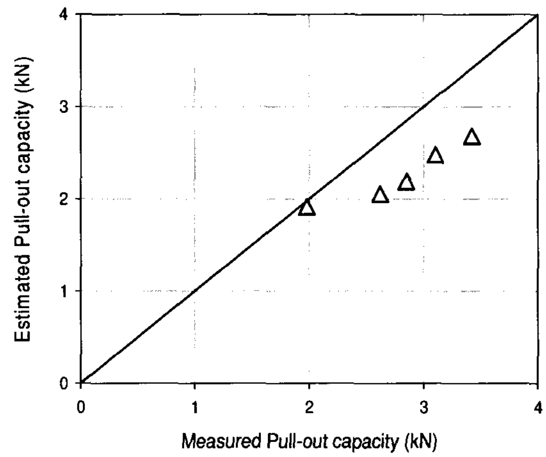


Figure 9. Comparison of measured and predicted pull-out capacity of soil nails

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.

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References

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

Canadian foundation engineering manual (CFEM). 2006. Canadian Geotechnical Society, Richmond, British Columbia.

Chai, X.J. and Hayashi, S. and Du, Y.J. 2004. Contribution of dilatancy to pullout capacity of nails in sandy clay. In Soil Nailing and Stability of Soil and Rock Engineering, Nanjing, China, pp. 73-80.

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.

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.

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

Hong, Y.S. and Wu, C.S. and Yang, S.H. 2003. Pull-out resistance of single and double nails in a model sandbox, Canadian Geotechnical Journal, 40(5): 1039-1047.

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.

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

Powell, G.E. and Watkins, A.T. 1990. Improvement of marginally stable existing slopes by soil nailing in Hong Kong. In Proceedings of the International Reinforced Soil Conference, Glasglow, U.K., pp. 241-247.

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.

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. and Fredlund, D.G. 2000. Comparison of empirical procedures to predict the shear strength of unsaturated soils uses the soil-water characteristic curve. Geo-Denver 2000, American Society of Civil Engineers, Special Publication, 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. In International Symposium on Advanced Experimental Unsaturated Soil Mechanics, Trento, pp. 401-407.

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.

Vanapalli, S.K. 2009. Shear strength of unsaturated soils and its applications in geotechnical engineering practice. Keynote Address. In Proceedings of the 4th Asia-Pacific Conference on Unsaturated Soils. New Castle, Australia. Nov. 23-25. Edited by O. Buzzi, S. Fityus and D. Sheng. 2010 Taylor & Francis Group, London , ISBN 978-0-415-80480-6. pp. 579-598.

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(7)-973.