DEVELOPMENT OF A MATHEMATICAL MODEL FOR QUANTIFYING THE EFFECT OF ROOT-REINFORCEMENT ON SHEAR STRENGTH OF SOIL

FARIA FAHIM BADHON

MASTER OF SCIENCE IN CIVIL ENGINEERING (GEOTECHNICAL)

DEPARTMENT OF CIVIL ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA-1000, BANGLADESH

MAY, 2018

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Submitted by-

Faria Fahim Badhon

Student ID: 1015042236F

A thesis submitted to the Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, in partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering (Geotechnical)

DEPARTMENT OF CIVIL ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA-1000

May, 2018

The thesis titled "Development of a Mathematical Model for Quantifying the Effect of Root-Reinforcement on Shear Strength of Soil", submitted by Faria Fahim Badhon, Student number- 1015042236F and session October/2015 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Geotechnical) on 15 May, 2018.

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Faria Fahim

Faria Fahim Badhon

Student ID: 1015042236F

ACKNOWLEDGEMENT

All praise is due to the Almighty, the most merciful and the most beneficent.

Then I would like to express my humble gratitude to my supervisor Dr. Mohammad Shariful Islam for his continuous guidance, invaluable constructive suggestions, encouragement, generous help and unfailing enthusiasm at every stage of the study.

Sincere appreciation goes to Dr. Shamal Chandra Das, Executive Engineer, Bangladesh Water Development Board for his valuable guidance, advice and thoughtful comments. I would also like to take the opportunity of expressing sincere appreciation to Dr. Robin Kumar Biswas, Executive Engineer, Bangladesh Water Development Board for his essential suggestions which helped me to understand the importance of research. I am also grateful to Dr. T. M. Al-Hussaini for providing valuable advices and financial support from HEQEP project to conduct this study.

I would like to express special gratitude to Mohammad Arifuzzaman Bhuyan, Executive Engineer, Bangladesh Water Development Board for his incessant encouragement, guidance and support without which this study would have been impossible.

I am thankful to Ms. Farnia Nayar Parshi and Md. Azijul Islam, Mr. Zia Uddin Ahmed, post graduate students, Department of Civil Engineering for their cordial help in laboratory work and support.

Thanks are due to all staffs and lab instructor of Geotechnical Engineering Laboratory in the Department of Civil Engineering for their help for successful completion of all lab experiments.

Finally and most importantly, I am forever grateful to my parents specially my mother and to my family for their love, concern, care and faith. Lastly, I want to dedicate this work in the memory of my late father who always inspires me silently to move forward.

ABSTRACT

The role of vegetation in the stability of slopes has gained increasing recognition in the last couple of decades. Performance of plants in stabilizing slopes is closely associated to the variation of the shear strength of root-reinforced soils. An attempt has been made in this study to investigate the root morphology; and to characterize the soil-root system. The main objective was to develop a mathematical model for predicting the additional shear strength of rooted soil. To determine the root architecture, at first three plants i.e. vetiver grass, tiger grass and wild cane were uprooted and their root morphology was closely monitored. It was found that vetiver has longer and denser network than the other two. Subsequently, vetiver was selected for detailed analysis. It has been found that, in sandy soil, vetiver root can grow up to 1 m within three months and the mean tensile strength of matured vetiver root is approximately 27 MPa. Extensive laboratory tests have been conducted to determine the additional shear strength of vetiver rooted soil. From laboratory test results, it has been found that due to inclusion of root, angle of internal friction (θ) increases for fine grained soil, however, for coarse and medium grained sand, θ decreases. Direct shear tests were also conducted on reconstituted samples by implanting roots at perpendicular root arrangement and an increase in shear strength up to 50% was observed. From unconfined compression test results, it has been found that axial stress of the rooted sample is 43% higher than that of the bare one. Tri-axial test results show 34% increase in shear strength of the rooted sample in comparison to that of the bare sample. Direct shear tests were also conducted on undisturbed samples. For both clayey and sandy samples, angle of internal friction of the rooted sample is higher but cohesion is lower than that of the bare soil. It has been found that vetiver root enhances the shear strength in most of the cases, but in some cases, inclusion of root decreases the shear strength of soil-root matrix. The effect of tensile force of the root acting at the base of slip plane which increases the stability of slope segment has not been evaluated by laboratory tests. In-situ shear strength tests were conducted in order to determine the shear strength parameters of vetiver rooted soil and additional shear strength for rooted soil was determined by comparing with bare sample. In this study, an approximately linear relationship between the additional shear strength provided by roots (Δs) and the tensile strength of roots per unit area of soils (t_R) was obtained and based on the experimental observation, a mathematical model was developed to predict the additional shear strength of soil-root system. The model developed in this study is $\Delta s = 5.14 t_R$ which is comparable to other models. This simple, straightforward model will provide a convenient mean for stability analysis of vegetated slopes.

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NOTATIONS

Symbol	Description
C	Cohesion
θ	Angle of internal friction
θ	Angle of shear distortion in the shear zone
β	Slope angle
δ	Deformation
η_{max}	Peak shear stress
ζ_n	Normal stress
$\Delta\eta_{max}$	Change in shear strength
$\Delta\gamma$	Change in shear strain
ω_n	Natural moisture content
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
FS	Factor of Safety
γ	Shear strain
D_{50}	Mean grain size
G_s	Specific gravity
ΔS	Additional shear strength
T_R	Root tensile strength
t_R	The mobilized tensile stress of root fibers per unit area of soil

Chapter 1
INTRODUCTION

1.1 General

The use of vegetation for slope stabilization started in ancient times. In more recent times, the role of vegetation in some specific geotechnical processes has been recognized (Islam, 2018; Islam et al., 2016). Vegetation may affect slope stability in many ways. Comprehensive reviews may be found in (Islam et al., 2017), (Islam and Badhon, 2017), (Mickovski and van Beek, 2009), (Coppin and Richards, 1990). The stability of slopes is governed by the load, which is the driving force that causes failure, and the resistance, which is the strength of the soil-root system. The weight of plants growing on a slope adds to the load whilst the roots of plants serve as soil reinforcements and increase the resistance. In addition, vegetation also influences slope stability indirectly through its effect on the soil moisture regime. Vegetation increases the shear strength of the soil, thus increases the resistance.

To evaluate the actual performance of vegetation for protection of embankments, it is necessary to estimate the factor of safety against the natural forces. Vegetation most prominently enhances the stability of earthen slopes by root reinforcement (Islam and Shahin, 2013). Different tests were conducted by different researchers (e.g., Verhagen et al., 2008, Islam et al., 2010) to know the strength of vegetation roots for the analysis of stability of slopes. Islam et al. (2013) conducted the in-situ test and also conducted direct shear test on laboratory reconstitute soil samples at different root content to know the shear strength of vetiver grass. But Parshi (2015) found that shear strength properties of rooted soil obtained from the laboratory tests and in-situ tests are significantly different. But it is very cumbersome process to measure the in-situ shear strength of soil root matrix i.e., factor of safety of the vegetated slopes. Fan and Su (2008) obtained a linear relationship between the additional shear strength provided by roots and the tensile strength of roots per unit area of soils by conducting in-situ tests. But no such relationship was established for our local soil condition and locally available grasses. If a mathematical model can be developed to determine the shear strength of rooted soil, it will be easy to calculate the stability of vegetated slope.

1.2 Background of the Research Work

The role of vegetation in the stability of slopes has gained increasing recognition in the functions of mechanical and hydrological mechanisms. To evaluate the actual performance of vegetation for protection of embankments, it is necessary to characterize the behavior of soil root system. Different tests were conducted by different researchers (Hengchaovanich, 1998; Islam et al., 2010; Islam et al., 2013) to know the shear strength of rooted soil for the analysis of stability of slopes. The beneficial effects of vegetation on the stability of slopes are root reinforcement, soil moisture depletion, buttressing and arching, and surcharge, etc. The most prominent source that vegetation enhances the stability of earthen slopes is via root reinforcement (Waldron and Dakessian, 1981).The effect of root reinforcement on the stability of slopes can be evaluated directly in terms of the additional shear strength provided by roots in root-reinforced soils (Fan and Su, 2008). Simple force equilibrium models for evaluating the additional shear strength that roots can provide in soils have been developed (Wu, 1976; Wu et al., 1979; Gray and Leiser, 1982).

Mathematical models for evaluating the additional shear strength by root in soils can provide useful insights into the mechanism of soil-root interaction and can be employed to analyze in situ shear test results. But no effort was made in developing a mathematical model for local soil condition and locally available plants in Bangladesh. Thus the necessity of developing a mathematical model to predict the additional shear strength of root-reinforced soils is felt.

1.3 Objectives

The main objectives of this research are as follows:

i) To investigate the root morphology (root length, root diameter, root distribution) of different long rooted grasses such as wild cane, tiger grass, vetiver grass. And also to determine the tensile strength of the selected roots.
ii) To determine the effect of root reinforcement on the shear strength of rooted soil matrix.
iii) To develop a mathematical model for soil-root matrix.

1.4 Methodology of the Research

The research work was conducted by following steps:

a) To determine the root architecture, at first wild cane, tiger grass and vetiver grass was uprooted and root morphology was observed. Based on the observation, a grass was selected which has deep and dense root matrix. Then the selected grass was planted in BUET premises for growth study in sandy soil. A series of laboratory tests was conducted on the sandy soil according to ASTM standards to determine index properties.

b) Tensile strength of selected grass root was measured by Regger. The capacity of this machine is 100 kN which is generally used for tensile strength test of steel fiber or thin sheet. Loading was applied at a constant rate of 10mm/min.

c) Selected grass was planted in 75 mm dia PVC pipe, containing both sandy soil and clayey soil. Undisturbed rooted soil specimen of 62.5 mm diameter was retrieved from pipes after 180 days of plantation. Direct shear tests were conducted on undisturbed samples to determine the shear strength of soil-root matrix.

d) Reconstituted samples were prepared by mixing grass root having 1.25-5 cm length at different arrangement with different types of soil. The root content varied from 3% to 6% of dry weight of soil sample. In laboratory, tests were conducted to determine the shear strength parameters of reconstituted rooted soil and bare soil after conducting the index property tests of these soils.

e) In-situ shear strength of grass rooted soil and bare soil was determined by using a device developed by Islam and Arifuzzaman (2010).

f) Finally, a mathematical model was developed based on test results to determine the shear strength of soil-root matrix.

1.5 Thesis Layout

This study consists of five chapters. The contents of these chapters are briefly described below:

Chapter One gives an overview of the whole research work including the background, objectives and scopes of the research, brief methodologies applied in research study.

In Chapter Two related literatures are reviewed such as, effectiveness of vegetation in the stability of slopes, root Architecture, i.e. structure classification and terminology, depth and distribution of root systems, root spread, factors affecting root development. Root strength, i.e. factors affecting strength, ranges in root tensile strength and modulus, root decay and strength loss are described. Recommended Vegetation, guidelines for maximizing benefits of vegetation, species selection, placement strategies, coppicing, planting and management strategies are also included. A brief description of root/fiber soil reinforcement i.e. force-equilibrium models is given at the end of the chapter.

Chapter Three describes the experimental program which includes site selection, plant selection, their physical properties and specification, tensile strength tests of grass root, preparation of samples for both laboratory tests and in-situ test, test procedure and test parameters.

Chapter Four deals with the test results obtained from the experiments such as shear strength parameters both in-situ condition and in laboratory with controlled condition and growth study.

Chapter Five is the conclusion chapter where the summary of the research findings has been provided. It also includes recommendations for further study.

Chapter 2
LITERATURE REVIEW

2.1 Introduction

Vegetation affects both the surficial and mass stability of slopes in significant and important ways. The stabilizing or protective benefits of vegetation depend both on the type of vegetation and type of slope degradation process. Various hydro-mechanical influences of vegetation, including methods for predicting and quantifying their magnitude and importance on stability are described in this chapter.

2.2 Effectiveness of Vegetation in the Stability of Slopes

For the most part, vegetation has a beneficial influence on the stability of slopes; however, it can occasionally affect stability adversely or have their undesirable impacts; for example, it can obstruct views, hinder slope inspection or interfere with flood fighting operations on leeves. Following some strategies and techniques such as the proper selection and placement of vegetation in addition to management techniques can maximize benefits and minimize liabilities of plants. The right choice of plant materials is critical. A tight, dense cover of grass or herbaceous vegetation for example, provides one of the best protections against surficial rainfall and wind erosion. Conversely, deep rooted, woody vegetation is more effective for mitigating or preventing shallow, mass stability failures. In a sense, soil bioengineering and biotechnical methods also can be viewed as strategies or procedures for minimizing the liabilities of vegetation while capitalizing on its benefits.

Vegetation plays an extremely important role in controlling rainfall erosion Soil losses due to rainfall erosion can be decreased a hundredfold (USDA Soil Conservation Service, 1978) by maintaining a dense cover of sod, grasses or herbaceous vegetation. The beneficial effects of herbaceous vegetation and grasses in preventing rainfall erosion are tabulated below:

i. Interception: Foliage and plant residues absorb rainfall energy and prevent soil detachment by raindrop splash.
ii. Restraint: Root systems physically bind or restrain soil particles while above ground portions filter sediment out of runoff.

iii. Retardation: Stems and foliage increase surface roughness and slow velocity of runoff.

iv. Infiltration: Plants and their residues help to maintain soil porosity and permeability, thereby delaying onset of runoff.

In case of surficial erosion, herbaceous vegetation and grasses are more effective than woody vegetation because they provide a dense ground cover.

A good gauge of the influence of vegetation in preventing soil erosion can be obtained by examining the universal soil loss equation (USLE). The annual soil loss from a site is predicted according to the following relationship:

$$A=R * K * LS * C * P \tag{2.1}$$

where: A= computed soil loss (e.g., tons) per acre for a given storm period or time interval

R= rainfall factor

K= soil erodibility value

L= slope length factor

S= steepness factor

C= vegetation cover

P= erosion control practice factor

The USLE provides a simple and straightforward method of estimating soil losses and it provides an idea of the range of variability of each of the parameters, their relative importance in affecting erosion, and the extent to which each can be changed or managed to limit soil losses. The climatic (R), topographic (LS), and erodibility (K) factors only vary within one order of magnitude. The vegetation or cover (C) factor, on the other hand, can vary over several orders of magnitude. Moreover, unlike the other factors, the cover (C) factor can be readily decreased by the selection, method of installation, and maintenance of a particular cover system. Factor C values tend to change with time following certain types of surface treatment, such as mulching, seeding, and transplanting. For example, factor C values for grass may decrease from 1.0 (for fallow, bare ground) to about 0.001 between time of initial seeding and full establishment with a dense grass sod.

2.3 Root Architecture

Different grasses have different root architecture. Several factors affect the development of root. Genetic type and environmental condition changes the depth and distribution of root systems.

2.3.1 Structure classification and terminology

Specific terms have been adopted to describe the various parts of a tree root system as noted in Figure 2.1. Tap-root refers to the main vertical root directly below the bole of the tree, sinker root refers to vertical roots coming either from the bole or from laterals and lateral root refers to roots growing from central bole but in horizontal orientation.

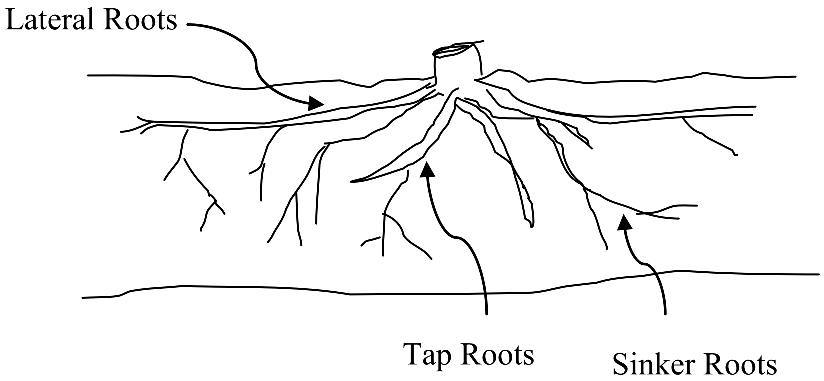


Figure 2.1: Main components of woody root system including lateral, tap and sinker roots (Patric et al., 1965)

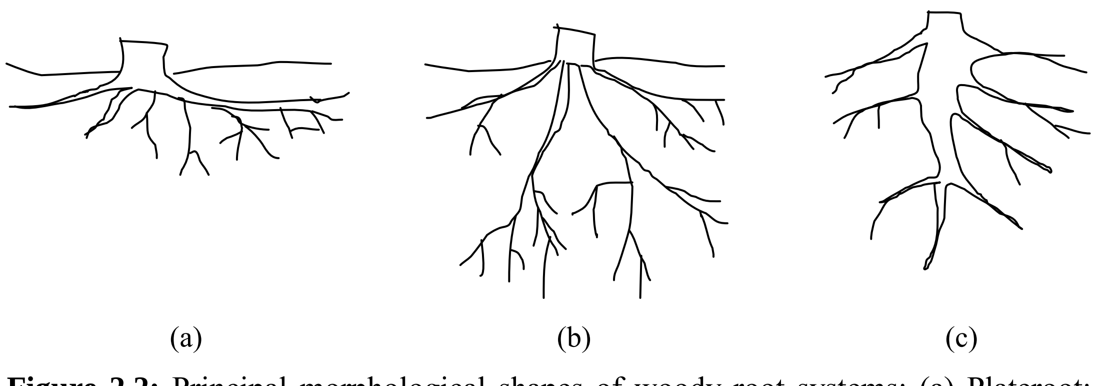


Figure 2.2: Principal morphological shapes of woody root systems: (a) Plateroot; (b) Heartroot; (c) Taproot (Patric et al., 1965)

The overall shape or morphology of a tree root system can also be categorized. Three distinct forms have been recognized, namely, taproot, heartroot, and plateroot shapes as shown schematically in Figure 2.2. Variants of these basic shapes may also occur.

Morphology is controlled both genetically and by environment conditions. The development of a particular root architecture in response to either of these factors dictates its contribution to slope stability. In general, root systems with strong, deeply penetrating vertical or sinker roots that penetrate potential shear surfaces are more likely to increase stability against shallow sliding. A high density or concentration of small-diameter fibrous roots is also more effective than a few large-diameter roots for increasing the shear strength of a root-permeated soil mass.

2.3.2 Depth and distribution of root systems

Deeply penetrating vertical taproots and sinker roots provide the main contribution to the stability of slopes. Mechanical restraint against sliding only extends as far as the depth of root penetration. In addition, the roots must penetrate across the failure surface to have a significant effect. The most effective restraint is provided where roots penetrate across the soil mantle into fractures or fissures in the underlying bedrock or where roots penetrate into a residual soil or transition zone whose density and shear strength increase with depth. Because of oxygen requirements, the roots of most trees tend to concentrated near the surface. As a rough rule of thumb the mechanical reinforcing or restraining influence of roots on a slope is probably limited to a zone about 1.5m from the surface. Studies by Patric et al. (1965) in a loblolly pine plantation showed that 80 to 90 percent of the roots in their test plots were concentrated in the first 0.9m. The bulk of the near-surface roots were laterals; in contrast, roots below 0.9m were generally oriented vertically.

Root morphology studies require careful excavation and are difficult and expensive to undertake, particularly in the case of large mature trees. The root architecture and distribution of mature Monterey pine (*Pinus radiate*) and other tree species have been reported by Watson and O'Loughlin (1990). At age 25 years the main laterals extended up to 10.4 m from the bole. The vertical roots penetrated a maximum depth of 3.10 m, but were about 2.4 m on average. Root area ratios were measured as a function of depth in a sandy levee along the Sacramento River in California (Shields and Gray, 1993) for a variety of woody plant species. The term "root area ratio" refers to the fraction of the total cross-sectional area of a soil that is occupied by roots. The stabilizing effect of roots is lowest when there is a little or no penetration across the shear interface.

However, even in these cases lateral roots can play an important role by maintaining the continuity of a root-permeated soil mantle on a slope.

2.3.3 Root spread

Tree roots can spread out for considerable distances; in one reported instance (Kozlowski, 1971) roots of poplars growing in a sandy soil extended out 65 m. The extend of root spread is normally reported in relative multiples of the tree height or crown radius. Kozlowski (1971) cites 10 year old pine trees growing on sandy soil with a root spread about 7 times the average height of the trees, probably an extreme case. More typical of root systems was the case of fruit trees growing on clay, which had roots extending 1.5 times the crown radius. Similar trees growing on loam extended 22 times and those on sand up to 3 times the crown radius. A useful rule of thumb is that a root system will spread out a distance at least equal to the 1.5 times the radius of the crown. The hydraulic influence of a tree, that is significant soil moisture reductions caused by evapotranspiration, can be felt to a distance of at least 1 times the tree height. These findings have implications with regard to both slope stability and safe placement of structures adjacent to trees growing on compressible soils.

2.3.4 Factors affecting root development

Root development and structure are affected initially by genetic disposition but ultimately are governed more by environmental and edaphic conditions. Henderson et al. (1983) have noted that root systems tend to grow wide and deep in well drained soils as opposed to developing a flat, platelike structure in surface soil underlain by a more dense or rocky substratum.

The degree to which roots are able to penetrate underlying bedrock depends to a large extent on the nature and extent of discontinuities (i.e., joints and fractures) in the bedrock. Trees growing in shallow, coarse-textured soils developed on granitic bedrock, for example, can develop sinker and taproots that penetrate into fissures and fractures in the underlying bedrock. The overlying soil developed on granitic bedrock is often coarse and incapable of holding much moisture; consequently, roots seek out water in the fractures and fissures in the underlying bedrock. This adaptation in turn insures that the trees will be well anchored to the slope and that they will help to restrain movement of the soil mantle by a combination of buttressing and arching action (Gray and Leiser, 1982).

2.4 Root Strength

Tesnile strength of roots plays an important role for reinforcing soil. Root tensile strength varies with individual roots as well as their morphological characteristics.

2.4.1 Factors affecting strength

Wide variations in tensile strength of roots have been reported in the technical literature, variations depending on species and on such site factors as growing environment, season, root diameter and orientation. Greenway (1987) has compiled an excellent review of root strength and factor affecting it. With regard to the influence of seasonal effects, Hathaway and Penny (1975) reported that variations in specific gravity and lignin/cellulose ratio within poplar and willow roots produced seasonal fluctuations in tensile strength. Schiechtl (1980) observed that roots growing in the uphill direction were stronger than those extending downhill.

Table 2.1: Nominal tensile strength of selected tree root (after Schiechtl (1980))

Species	Common name	Mean Tensile Strength (MPa)
Acacia confusa	Acacia	11
Alnus incana	Alder	52
Ficus benjinamina	Banyan	13
Hevea braziliensis	Rubber tree	11
Pinus densiflora	Japanese red pine	33
Pinus lambertiana	Suger pine	10
Pinus radiata	Monetary pine	18
Quercus robur	Oak	20
Salix helvetica	Willow	14
Tilia cordata	Linden	26

2.4.2 Ranges in root tensile strength and modulus

Root tensile strengths have been measured by a number of different investigators, notwithstanding difficulties in conducting such tests. Nominal tensile strengths reported in the technical literature are summarized in Table 2.1 for selected tree species. Tensile strengths vary significantly with diameter and method of testing (e.g., in a moist or air dry state). Accordingly, the values listed in Table should be considered only as rough or approximate averages. Nevertheless, some interesting trends can be observed in the tabulated strength values. The tensile strengths can approach 70 MPa but appear to lie in the range of 10 to 40 MPa for most species. The conifers as a group tend to have lower root strengths than deciduous trees. Shrubs appear to have root tensile strengths at least comparable to that of trees. This is an important finding because equivalent reinforcement can be supplied by shrubs at shallow depths without the concomitant liabilities of trees resulting from their greater weight, rigidity and tendency for windthrowing. This could be an important consideration, for example, in streambank or leeve slope stabilization. Willow species, which are frequently used in soil bio-engineering stabilization work, have root tensile strengths ranging from approximately 14 to 35 MPa .

It is important to recognize that root tensile strength is affected as much by differences in size (diameter) as by species. Several investigators (Turnanina, 1965; Wu, 1976; Burroughs and Thomas, 1977; Nilaweera, 1994) have reported a decrease in root tensile strength with increasing size (diameter). Roots are no different in this regard than fibers of other materials, which exhibit a similar trend. So finer roots can contribute significantly to soil reinforcement and shear strength increase. Finer roots have the advantage of not only higher tensile strengths but also superior pull out resistance because they have higher specific surface areas than larger roots at equivalent area ratios. The relationship between root tensile strength and diameter can be expresses in the form of a logarithmic equation as follows:

$$T_r = nD^m \tag{2.2}$$

where: T_r= root tensile strength

D= root diameter

n and m= empirical constants for a given tree species

The tensile modulus of roots is also of some interest because in many cases the full tensile strength of the root is not mobilized. Instead, the amount of mobilized tensile resistance will be a function of the modulus and amount of tensile strain or elongation in the root. Only limited data on tensile modulus of roots are available. Hathaway and Penny (1975) presented typical stress-strain curves for several species of poplar and willow. They tested root specimens, without bark, that had been air dried and then rewetted by soaking prior to testing. The ultimate breaking strains, Young's moduli, and tensile strengths measured in these tests are presented in Table 2.2.

Table 2.2: Tensile strength and stress-strain behavior of some Poplar and Willow roots (after Hathaway and penny (1975))

Species	Clone	Tensile strength (MPa)	Young's Modulus (MPa)	Ultimate strain (%)
Poplar	*Populus "I-78"*	45.6	16.4	17.1
	Populus "I-488"	32.3	8.4	16.8
	Populus yunnamensis	38.4	12.1	18.7
Willow	*Populus deltoides*	36.3	9.0	12.4
	Salix matsundana	36.4	10.8	16.9
	Salix "Booth"	35.9	15.8	17.3

2.4.3 Root decay and strength loss

Woody vegetation improves the strength and stability of soil on steep slopes; conversely, its removal by felling or wildfire tends to decrease stability. The main reason for the loss of stability and increase in frequency of slope failures following felling is root decay and loss of strength. The smallest roots, which, as noted earlier, have the highest tensile strengths and best interfacial friction or pullout resistance, are the first to disappear after cutting or felling. There will be a period of time between cutting and regeneration of new growth when stability will gradually decrease, reach a minimum and then increase again as new roots are established in the soil. The time to reach this minimum depends on the tree species, site conditions and timing reforestation efforts (Gray and Megahan, 1980).

Strength loss with time following cutting has been reported by a number of investigators. The decline of tensile root strength can be approximated by a negative exponential relationship (Ziemer and Swanston, 1977; O'Loughlin and Watson, 1979). The form of this relationship can be expressed as follows:

$$T_{rt}=T_{r0}e^{-bt} \tag{2.3}$$

where, T_{r0}= tensile strength of root wood sampled from live trees

T_{rt}= tensile strength of roots sampled from stumps cut t months before sampling

b= probability of decay

t= age of stump (time between felling and sampling)

The term e^{-b} is an expression of the strength decay rate; accordingly, the time for root strength to decline to half the living root strength is:

$$T_{0.5}=\log 0.5/\log e^{-b} \tag{2.4}$$

where: $t_{0.5}$= the root strength "half life" after felling

O'Loughlin and Watson (1979) measured the tensile strengths of Pinus radiate roots at different times after felling and for living trees; their results are listed in table 2.3.

The mean tensile strength of Pinus radiate roots in this study decreased from 18 to 3 MPa 29 months after cutting. The mean root diameter increased from 5.3 to 8.3 mm, reflecting the faster decay rate and disappearance of smaller roots. For Pinus radiate the strength decline curve from these data is:

$$T_{rt}=19.0e^{-0.056t}\ (r^2=0.95) \tag{2.5}$$

And the strength "half life" is: $T_{0.5}$=14.8 months

Similar relationships have been reported for other tree species. Burroughs and Thomas (1977) determined the tensile strength of Rocky Mountain and Pacific Coast species of Douglas fir as a function of both age after cutting and root diameter. A pronounced decrease in root tensile resistance with time was observed.

Table 2.3: Tensile strengths of Radiata Pine roots at different elapsed times after felling (after O'Loughlin and Watson (1979))

Root class	Mean tensile strength (MPa)	Mean root diameter (mm)	Number tested
Living trees	17.6	5.3	188
Cut 3 months	14.4	5.6	105
Cut 9 months	12.3	6.2	134
Cut 14 months	11.0	6.8	140
Cut 29 months	3.3	8.3	59

2.5 Recommended Vegetation

Under normal conditions, a dense cover of grass or herbaceous vegetation provides the best protection against surficial rainfall and wind erosion. A grass cover can be established by either seeding or sodding. Seed mixtures normally include grasses that germinate rapidly, such as rye or annual grass, to provide immediate short-term protection and slower-growing perennial grasses that take more time to establish, but provide long-term protection. The optimum seed mix depends on soil, site and climatic conditions. A horticulturist familiar with local conditions should be consulted for recommendations. Site preparation, mulching and fertilization may also be required to insure germination and establishment.

2.5.1 Guidelines for maximizing benefits of vegetation

Vegetation mostly has a beneficial influence on stability of slopes; it can have detrimental or adverse effect as well. Fortunately, a number of strategies and procedures can be adopted to maximize the benefits of vegetation while minimizing its liabilities. These strategies include selection of the appropriate species for particular site conditions and stabilization objectives, placement or location of vegetation in the right places and management of the vegetation to mitigate any undesirable characteristics. The latter includes such procedures coppicing, thinning, burning, weeding and fertilization.

2.5.1.1 Species selection

Vegetation should be selected for desired stabilization objectives and be compatible with soil and site conditions. The latter includes consideration of soil type, water availability, nutrient status, soil pH, climate, possible browsing pressure, regulations governing the use of exotic or nonnative species and so on.

Certain types of plants are intrinsically better suited than others for specific stabilization objectives. Woody vegetation is stronger and deeper rooted than herbaceous plants and grasses and provides greater mechanical reinforcement and buttressing action at depth. Accordingly, woody plants are superior for mass stability. Grasses and herbaceous vegetation, on the other hand, grow close to the surface and provide a tight, dense ground cover. They tend to be superior therefore, in intercepting rainfall and preventing surficial erosion. Shrubs are not as deep rooted as trees nor can they be expected to provide as much buttressing restraint. On the other hand, shrubs are more flexible, have less above ground biomass, and exert less surcharge on a slope. They may be preferable accordingly, in riverbank and levee stabilization, where these attributes would be advantageous.

2.5.1.2 Placement strategies

Several different placement or location strategies can be invoked to maximize the utility of slope plantings and minimize possible problems. One of the main objectives raised to vegetation on slopes is that it obstructs views and hinders access. These objections have been raised both the home owners living on hillslides and by inspectors examining river levees. These problems can be addressed by pruning and coppicing techniques. They can also be addressed by placement of vegetation on a slope according to its height and shape or density of the crown foliage. Smaller shrubs should be grown near the top of the slope and larger trees placed near the bottom. This simple procedure will improve views from the top, eliminate weight from the top of the slope and put maximum buttressing restraint and reinforcement near the base, where it is most needed. In the case of river levees plants can be located in such a way to meet both stabilization objectives and to create relatively clear fields of view for inspection and access purposes.

Another approach is to locate vegetation in conformance with “landform grading” practices (Schor, 1992). Landform grading replicates the irregular shapes of natural, stable slopes. Landform graded slopes are characterized by a continuous series of concave and convex forms interspersed with swales and berms that grade into profiles.

Revegetation in conjunction with landform grading entails planting vegetation in patterns that occur in nature, as opposed to specifying either uniform or random coverage. Trees and large shrubs tend to require more moisture, and they are also better at stabilizing against shallow slope failures than herbaceous vegetation. Accordingly, trees should be clustered in swales and valleys in a slope where runoff also be heavily concentrated along drainage flow lines of each swale. Conversely, seepage and runoff tend to be diverted away from convex-tolerant herbaceous vegetation. Irrigation needs are thus reduced by careful control of drainage pattern on a slope and selection and placement of appropriate plantings for different areas.

2.5.1.3 Coppicing

An interesting approach for mitigating the adverse effects of vegetation on slope stability is the practice of coppicing. Coppicing is a timber harvesting or pruning method that involves the production of new trees from the old stumps. This procedure leaves the root system intact while generating smaller, multiple stems near the cut area. Many tree species that have the ability to regenerate or sprout from dormant buds along their stems lend themselves to coppicing, especially northern hardwoods that have dormant buds on the lowest parts of their trunks. Examples include willows and most maples and locust trees. Some species, such as aspen, also produce new sprouts from their roots, which are referred to as root suckers. Thus whole new forests can be generated from stump sprouts and root suckers.

Best results with coppicing are obtained if the stumps are cut after leaf drop in the late fall or winter (Ecabert, 1993). Red maples, silver maples, and black locust sprouts can grow more than 6 feet the first season. As the stump sprouts grow, they can be thinned and pruned to the desires height and number of trees per stump. Coppicing mitigates two main adverse effects from the legend namely surcharge and wind throwing, while retaining benefits. There may be some initial loss of beneficial influence interception, but this is only temporary and greatly overweighed by the attendant benefits. Coppicing allows one to enjoy a view (a frequent reason for tree removal on slopes), use smaller trees and retain all the hydro-mechanical benefits provided by a tree’s living root system.

2.5.1.4 Planting and management strategies

Several different planting and/or management strategies can be employed to enhance desired characteristics of vegetation at a particular site. More vigorous and deeper rooting can be accomplished in a variety of ways, namely by:

i. Watering for longer times at less frequent intervals
ii. De-compacting or ripping a soil before planting
iii. Avoiding the use of overly rich topsoil dressings
iv. Weeding to maximize competition from unwanted plants

Fire is often as management tool- sometimes with unanticipated consequences. Levees are frequently fired to rid them of woody vegetation. Burning, however, promotes explosive growth of fire adapted species, which may not necessarily be the vegetation of choice for soil erosion control and other purposes.

Another simple yet effective management technique is to control pedestrian and vehicular traffic in critical areas that are protected by vegetation. Coastal dunes are a good case in point. Foredunes play a critical role in shoreline defense system. Dune vegetation is very effective at trapping drifting sand and helping to build and accrete dunes, but this same vegetation is very vulnerable to trampling and traffic. The use of broadwalks and walkover structures in beach dune areas is an effective way of protecting vegetation so that it can fulfill its own protective role.

2.6 Root/Fiber Soil Reinforcement: Force-Equilibrium Models

Important investigations have been carried out on a number of fronts during the past two decades, investigations that have greatly improved the understanding of root reinforcement of soils and the contribution of roots to slope stability. These studies include modeling of root-fiber soil interactions, laboratory testing of fiber/soil composites and in-situ shear tests of root-permeated soils.

Relatively simple and straightforward force equilibrium models (Waldron, 1977; Wu et al., 1979; Waldron and Dakessian, 1981) provide useful insights into the nature of root-fiber soil interactions and the contribution of root fiber to soil shear strength. More sophisticated models based on the deformational characteristics of fiber-reinforced composites (Shewbridge and Sitar, 1990) and statistical models that take into account the random distribution and branching characteristics of root systems have also been developed (Wu et al., 1988).

Root fibers increase the shear strength of soil primarily by transforming shear stresses that develop in the soil matrix into tensile resistance in the fiber inclusions via interface friction along the length of imbedded fibers. This process is shown schematically in Figure 2.3 for an imbedded fiber oriented perpendicularly to the shear surface. When shear occurs the fiber is deformed as shown. This deformation causes the fiber to elongate, provided there is sufficient interface friction and confining stress to lock the fiber in place and prevent slip or pullout. This fiber elongation mobilizes tensile resistance in the fiber. The component of this tension tangential to the shear zone directly resists shear, while the normal component increases the confining stress on the shear plane.

The assumption of initial fiber orientation perpendicular to the shear surface requires further discussion. Root fibers have many orientations and are unlikely to be oriented perpendicular to the shear failure surface. Furthermore, both theoretical analyses and laboratory studies (Gray and Ohashi, 1983) have shown a perpendicular orientation is not the optimal orientation. Fibers oriented initially at an acute angle (<90 degrees) in the direction of maximum principal tensile strain result in the highest increase in shear strength. This orientation corresponds to the angle of obliquity ($45+\theta/2$), or approximately 60 degrees in most sands. Conversely, an oblique orientation with the shear surface (>90 degrees) can actually result in a shear strength decrease because the fibers initially go into compression rather than tension. The simple, perpendicular model is actually a very useful simulation because it yields an average estimate of all possible orientations. This finding is supported by both laboratory studies on sand/fiber mixtures (Gray and Ohasi, 1983) and by statistical studies of sands with randomly distributed fibers (Maher and Gray, 1990).

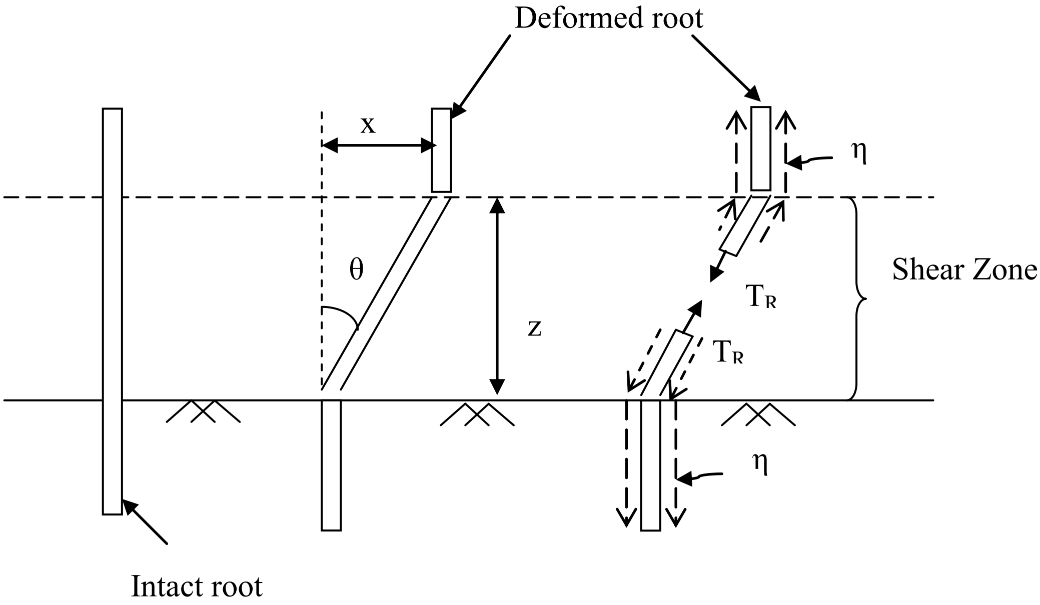


Figure 2.3: Schematic diagram of perpendicular root fiber reinforcement model (Voottipruex et al., 2008)

Based on this perpendicular model the increase in shear strength of fiber/soil composite will be given by the following expression (Wu et al., 1979):

$$\Delta s = t_R \, [\sin\theta + \cos\theta \tan\theta] \tag{2.6}$$

where: Δs= the shear strength increase

θ = the angle of internal friction

θ= the angle of shear distortion in the shear zone

t_R= the mobilized tensile stress of root fibers per unit area of soil

The mobilized tensile stress of root fibers (t_R) will depend upon the amount of fiber elongation and fixity of the fibers in the soil matrix. Full mobilization can occur only if the fibers elongate sufficiently and if imbedded root fibers are prevented from slipping or pulling out. The latter requires that the fibers be sufficiently long and frictional, constrained at their ends and/or subjected to high enough confining stresses to increase interface friction. Accordingly, three different response scenarios are possible during shearing of a fiber-reinforced soil composite, namely fibers break, stretch or slip.

2.6.1 Fiber break mode

Shear strength increase from full mobilization of root fiber tensile strength requires calculation of the average tensile strength of the root fibers, T_R, and fraction of soil cross section occupied by roots or (A_R/A). The mobilized tensile stress per unit area of soil (t_R) in this case is given by:

$$t_R = T_R(A_R/A) \quad (2.7)$$

The angle of shear distortion or angle is given by

$$\theta = \tan^{-1}(x/z) \quad (2.8)$$

where: x= the shear displacement

z= the shear zone thickness

The fraction of soil cross section occupied by roots, also termed the root area ratio, can be determined by counting roots by size class within a given soil as:

$$\frac{AR}{A} = \frac{\sum niai}{A} \quad (2.9)$$

where: n_i= the number of roots in size class i

a_i= the mean cross-sectional area of roots in size class i

Accounting for the variation in root fiber tensile strength with root diameter mean tensile strength of roots (T_R) can be determined by:

$$T_R = \frac{\sum Tiniai}{\sum niai} \quad (2.10)$$

where: T_i= the strength of roots in size class i

By substituting equation 2-7 into equation 2-6, the predicted shear strength increase from full mobilization of root tensile strength will be given by:

$$\Delta S = T_R(A_R/A)*[\sin\theta + \cos\theta \tan\theta] \quad (2.11)$$

The value of the bracketed term [$\sin\theta + \cos\theta \tan\theta$] in equation 2-11 is relatively insensitive to normal variations in θ and θ, so Wu et al. (1979) proposed an average value of 1.2 for this term. Equation 2-6 can then be simplified to:

$$\Delta S = 1.2T_R(A_R/A) \quad (2.12)$$

Thus the predicted shear strength increase depends entirely on the mean tensile strength of the roots and the root area ratio. This model assumes that the roots are well anchored and do not pull out under tension. The root fibers must be long enough and/or subjected to sufficient interface friction for this assumption to be satisfied. If a simple uniform distribution of bond or interface friction stress between soil and root is assumed, the minimum root length, L_{min}, required to prevent slippage and pullout is given by:

$$L_{min}=\frac{TRD}{4\tau b} \quad (2.13)$$

where: T_R= the root tensile strength

D= the root diameter

η_b= the limiting bond or interface friction stress between root and soil

The bond stress between root fibers and soil can be estimated from the confining stress acting on the fibers and the coefficient of friction. For vertical fibers, this bond stress varies with depth and can be calculated by:

$$\eta_b= z\gamma(1\text{-}\sin\theta)*f*\tan\theta \quad (2.14)$$

where: z= the depth below the ground surface

γ= the soil density

θ= the angle of internal friction of the soil

f= the coefficient of friction between the root fiber and soil

The coefficient of friction between soil and wood ranges from 0.7 to 0.9 (Henderson et al., 1983). The rough texture and kinky shape of roots mean that their friction coefficients will likely lie closer to the high end.

Roots will generally exceed the length criteria given in equation 2-13 except close to the ground surface where the confining stress and hence the bond stresses will be low. This claim is supported by field observations where a preponderance of broken roots, compared to roots that have been pulled out, can be seen in landslide scars or failure surfaces.

2.6.2 Fiber stretch mode

Lack of sufficient fiber elongation coupled with strain compatibility requirements may prevent mobilization of root fiber tensile or breaking strength. In this case the calculation of mobilized tensile strength (t_R) will be governed by the amount of fiber elongation and the fiber tensile modulus, E_R. A force-equilibrium analysis yields the following expression for the mobilized tensile stress per unit area of soil (Waldron and Dakessian, 1981):

$$t_R = k\alpha(A_R/A) \tag{2.15}$$

$$\text{where, } k = (4z\eta_b E_R/D)^{1/2};\ \alpha = (\sec\theta - 1)^{1/2} \tag{2.16}$$

where: E_R= the tensile modulus of the root fiber

z= the thickness of the shear zone

D= the fiber diameter

η_b= the root/soil bond stress

θ= the angle of shear distortion

Equation 2-10 assumes a linear tensile stress distribution in the fiber, zero at the ends to a maximum value at the shear plane. A parabolic stress distribution would yield a slightly higher value (Waldron, 1977). By substituting equation 2-16 into equation 2-6, the predicted shear strength increase from mobilization of root tensile resistance from stretching will be given by:

$$\Delta s = k\alpha(A_R/A)\,[\sin\theta + \cos\theta \tan\theta] \tag{2.17}$$

This expression reveals that shear strength increases vary inversely with the square root of the fiber diameter. Accordingly, at equal root area ratios, small diameter fibers will be more effective than large fibers.

2.6.3 Fiber slip mode

If the fibers are very short, unconstrained, and subject to low confining stresses, they will tend to slip or pull out when the soil/fiber composite is sheared. They will nevertheless continue to contribute a reinforcing increment. At incipient slippage, the maximum tension in a root fiber, T_N is given by:

$$T_N = 2\eta_b L/D \quad (2.18)$$

where: D= the root diameter

L= the root length in which the maximum stress occurs at the center.

The shear strength increase or reinforcement from n slipping roots of one size class is given by:

$$\Delta S = \{\pi\eta_b nLD/2A\}[\sin\theta + \cos\theta \tan\theta] \quad (2.19)$$

If there are j slipping root size classes with n_i roots n which size class, then the shear strength increase is given by:

$$\Delta S = \{\pi\eta_b/2A\}[\sin\theta + \cos\theta \tan\theta] \sum n_i L_i D_i \quad (2.20)$$

Under field conditions roots occur in different sizes and lengths, and can have different tensile strengths and degrees of fixity. Accordingly, all three mechanisms may occur simultaneously. Waldron and Dakessian (1981) present procedures for systematically accounting for each. These models are idealizations of actual conditions, but they show what parameters are important and how they affect shear strength.

2.7 Past Researches

Several case studies have shown that slope failures may be attributed to the loss of tree roots as soil reinforcement (O'Loughlin, 1974; Riestenberg, 1987; Wu et al., 1979). Field and laboratory studies have shown that vegetation reduces water content and increases soil-moisture suction in the soil (Greenway, 1987; Gray, 1970; Gray and Brenner, 1970; William and Pidgeon, 1983). Greenway (1987) has given an extensive summary of observations on the effect of vegetation on slope stability.

The roots and rhizomes of the vegetation interact with the soil to produce a composite material in which the roots are fibres of relatively high tensile strength and adhesion embedded in a matrix of lower tensile strength. The shear strength of the soil is therefore enhanced by the root matrix. Field studies of forested slopes (O'Loughlin, 1984) indicate that it is the fine roots, 1–20 mm in diameter, that contribute most to soil reinforcement. Grasses, legumes and small shrubs can have a significant reinforcing effect down to depths of 0.75–1.5 m. Trees have deeper-seated effects and can enhance soil strength to depths of 3 m or more depending upon the root morphology of the species (Yen, 1972). Root systems lead to an increase in soil strength brought about by their binding action in the fibre/soil composite and adhesion of the soil particles to the roots.

Tengbeh (1989) found that root reinforcement can make significant contributions to soil strength, even at low root densities and low shear strengths. This implies that vegetation can have its greatest effect close to the soil surface where the root density is generally highest and the soil is otherwise weakest. Since shear strength affects the resistance of the soil to detachment by raindrop impact (Al-Durah and Bradford, 1982) and the susceptibility of the soil to rill erosion as well as the likelihood of mass soil failure, root systems can have a considerable influence on all these processes. The maximum effect on resistance to soil failure occurs when the tensile strength of the roots is fully mobilized and that, under strain, the behavior of the roots and the soil are compatible. This requires roots of high stiffness or tensile modulus to mobilize sufficient strength and the 8–10% failure strains of most soils. The tensile effect is limited with shallow-rooted vegetation where the roots fail by pullout, i.e., slipping due to loss of bonding between the root and the soil, before peak tensile strength is reached. The tensile effect is most marked with trees where the roots penetrate several meters into the soil and their tortuous paths around stones and other roots provide good anchorage. Root failure may still occur, however, by rupture, i.e., breaking of the roots when their tensile strength is exceeded. The strengthening effect of the roots will also be minimized in situations where the soil is held in compression instead of tension, e.g., at the bottom of hill slopes. Root failure here occurs by buckling.

Vetiver grass (Vetiveria zizanioides), also known as Chrysopogan zizanioidesis a graminaceous plant and is commonly found in different district in Bangladesh. It is a densely tufted, perennial grass that is considered sterile outside its natural habitat. It grows 0.5 to 1.5 m high, stiff stems in large clumps from a much branched root stock. The roots of vetiver grass are fibrous and reported to reach depths up to 3 m thus being able to stabilize the soil and its use for this purpose is promoted by the World Bank. Many researches have been conducted in home and abroad to know the propagation of vetiver, performance of vetiver grass against climatic change, slope protection, embankment protection, soil erosion control etc.

The most impressive characteristic of the vetiver grass is its root system. Hengchaovanich (1999) studied the strength properties of vetiver grass roots in relation to slope stabilization. They observed that the tensile strength of vetiver roots is as strong as, or even stronger, that of many hardwoods. In fact, it is better than many types of trees because of its long (2.0 to 3.5 m) and massive root networks which are also very fast-growing and essential for embankment stabilization. He observed the strength vs. diameter curve of vetiver root and found that the strength derived from 0.66 mm diameter is about 80 MPa. According to his observation he mentioned that the high mean tensile strength of vetiver root is 75 MPa or approximately 1/6th of strength of mild steel. Ke et al. (2003) tested vetiver as a bank protection measure on several sites. Their tests showed promising results for the use of vetiver grass as a bank protection measures.

Islam (2003) studied the performance of vetiver grass on eighteen coastal polders over eighty-seven kilometers of earthen coastal embankment of Bangladesh during the period from September 2000 to October 2001. He observed that the main problem in maintaining those earthen embankments is water borne erosion either through surface run-off or from wave action or both. Human and animal interference, seasonal variations in soil moisture content and coastal peculiarities like changing sea water level, salinity, threat of washing away by cyclones or tidal surges etc also affect the performance of vetiver grass. He provided some guide lines on vetiver application which is helpful for better performance. He achieved successful cases where initial protection and watering could be ensured.

Islam and Arifuzzaman (2010) developed a device to determine the in-situ shear strength of the vetiver rooted soil matrix for silty sand soil in coastal zone. They tested block samples (approx. 29x15x19 cm^3) at different depths under different normal loads at the field to know the in-situ shear strength of vetiver rooted soil matrix. They found that for a particular normal stresses the shear strength of vetiver rooted soil is 87% higher than that of bared soil. Again, the failure strain is 770% higher than that of bared soil. He also compared factor of safety between bared and rooted slope by using different methods of slope stability.

Islam et al. (2010) determined the soil characteristics of coastal region in Bangladesh, in-situ strength of vetiver rooted soil and unrooted soil, and its effectiveness for protecting the embankment against erosion and surge. Islam (2013) used vegetation and geo-jute for slope protection in different region in Bangladesh. Islam et al. (2013a) conducted direct shear test on laboratory reconstituted soil samples at different root content to know the shear strength of vetiver grass. Laboratory results are also compared with that of field tests. Islam et al. (2013b) conducted field trials in road embankment and slope protection with vetiver at different sites. Slope stability analyses showed that vegetation increase the factor of safety significantly. They also compared the cost of vetiver with other traditional practices used for slope protection and found that plantation of vetiver grass is cost effective than other methods.

Biswas et al. (2013) describes some eco-friendly water resources management approaches in Bangladesh. Bangladesh Water Development Board has used vetiver grass in some of its projects like Dampara Water Management Project (DWMP) and Coastal Embankment Rehabilitation Project (CERP) (Das and Tanaka, 2009). In DWMP, Vetiver grass was used on the 28 km of embankment. Vetiver was made an integral part of vegetation model in Coastal Embankment Rehabilitation Project (CERP). Outstanding protection against erosion has been observed in DWMP demonstration site with the Vetiver. But coastal polders under CERP showed some setbacks such as washing away by cyclone or tidal surges etc. due to coastal peculiarities. Even there are successful cases as well where initial protection and watering could be ensured by using it. It has been observed that root development was shorter in CERP than expected (about 0.7 m in one year) probably due to adverse saline environment.

2.8 Summary

All the knowledge and topics including substantive findings of past researches related to this research paper, as well as theoretical and methodological description has been discussed in this chapter which can be summarized as follows:

a) The effectiveness of vegetation on slope stabilization has been described briefly in this chapter. Vegetation plays an extremely important role in controlling rainfall erosion by absorbing rainfall energy, by binding soil particles, by increasing surface roughness and by slowing runoff velocity.

b) Specific terms used to describe the various parts of a tree root system have been described. Long root penetrating across failure surface provide the main contribution to the stability of slopes. Both genetic disposition and environmental condition affect root development and structure.
c) Tensile strength also depends on species and site factors. These factors affecting root strength are described in this chapter.
d) Vegetation mostly has a beneficial influence on stability of slopes but proper selection of vegetation is essential. Guidelines for maximizing benefits of vegetation i.e. species selection placement strategies, planting and management strategies are also discussed in this chapter.
e) Force equilibrium models provide useful insights into the nature of root-fiber soil interactions and the contributions of root fiber to soil shear strength. The model and its three different response scenario are described also.
f) Findings of the past researches related to this study have been discussed here.

Chapter 3
EXPERIMENTAL AND ANALYTICAL PROGRAM

3.1 Introduction

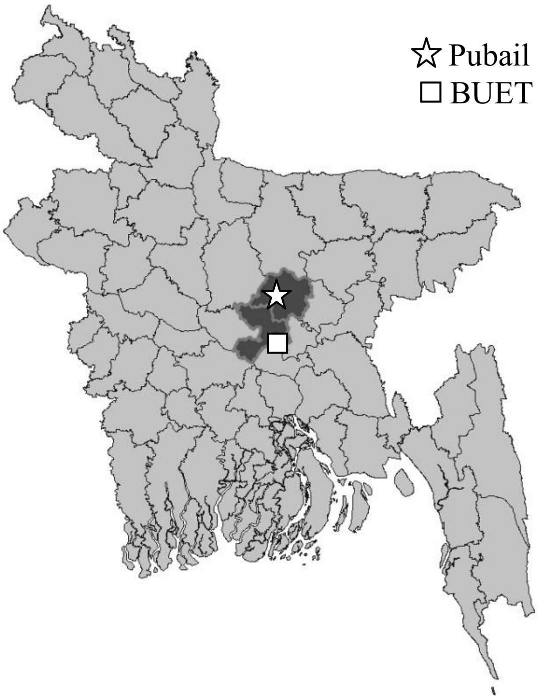
Protection of slopes using vegetation is a very effective and low cost solution. Performance of plants in stabilizing slopes against shallow landslides in a rainfall event is closely relevant to the variation of the shear strength of root-reinforced soils. The effect of root reinforcement on the stability of slopes can be evaluated directly in terms of the additional shear strength provided by roots in root-reinforced soils. If the addition shear strength due to the contribution of root can be predicted by a mathematical model, it will be easy to calculate the stability of vegetated slopes. The process of sample preparation and test procedures including both in-situ test and laboratory investigations to determine the additional shear strength of rooted soil are discussed in the chapter. Finally the procedure for developing a mathematical model for predicting the additional shear strength of rooted soil is also discussed.

3.2 Study Areas

To determine the additional shear strength of rooted soil from laboratory and in-situ tests and finally develop a mathematical model based on test results is the main objective of this study. The plant used for this study is vetiver (*Vetiveria Zizanioides*). Vetiver was collected from Pubail, Gazipur where vetiver grass is naturally grown. In-situ tests have also been conducted there. A detailed growth study of vetiver grass has been conducted at BUET premises. Soil sample for laboratory test was collected from Buriganga river bank and river bed. Figure 3.1 shows the map of study area.

3.3 Experimental Program

Root architecture of different long rooted grass (wild cane, tiger grass, vetiver) was investigated and a grass was selected based on investigation. A detailed growth study was conducted for the selected grass and the tensile strength of the grass root was measured. Then laboratory tests and in-situ tests were conducted to determine the shear strength and failure strain of rooted and bare soil. Laboratory investigations include both index property tests and shear strength tests.



(a)

(b)

Figure 3.1: Map showing the study areas (a) Location of study areas on Bangladesh, (b) Pubail, Gazipur

3.3.1 Investigation of root morphology

To determine the root architecture, at first wild cane, tiger grass and vetiver grass were uprooted and root morphology was observed. Based on the observation, a grass was selected which has deep and dense root matrix. Then the selected grass was planted in BUET premises for growth study in sandy soil. A series of laboratory tests were conducted on the sandy soil according to ASTM standards to determine index properties.

3.3.1.1 Root architecture of different long rooted grasses

Tiger grass, wild cane and veiver grass were found in BUET premises. Pictures of these plants are shown in Figure 3.2. Then the grasses were uprooted carefully and root morphology was observed. Root length and root diameter were measured by measuring tape and micrometer respectively. Root distribution was also observed.

(a) (b) (c)

Figure 3.2: Grasses planted in BUET premises (a) Wild cane, (b) Tiger grass, (c) Vetiver

3.3.1.2 Growth study of selected grass

The test was conducted at BUET campus in BUET premises. Temperature and humidity of this area ranges between 14°C and 34°C and between 45% and 79%, respectively. Average annual rainfall is 1875mm. The soil sample used for growth study was dredged sand of Buriganga river bed. Vetiver grasses were collected from the BUET premises where vetiver grasses were previously planted.

A frame of 2.75m×1.75m×0.60 m dimension was prepared by wood (local name is kerosene wood) having 2.54 cm thickness. Two wooden stick was attached with the wooden frame in the long side of the frame to resist lateral supports of the sand. 97 plastic bottles (25 cm height and 10 cm diameter at bottom and 3 cm diameter at top) were placed at the top of the sand in the wooden frame and filled with sand. One tiller of vetiver has been planted in each bottle by 14 × 7 matrix on 14^{th} August 2016 at 12.5 cm center to center spacing (Figure 3.3). Artificial watering was applied every day after plantation. For observing the growth of vetiver in sand, a single vetiver tiller was carefully uprooted in every week after five weeks of plantation and the length of root, shoot and diameter of root was measured during this observation process. With a view to observing the root matrix carefully, after uprooting, the sand in between the root system was carefully washed. After the monitoring process was done, the tiller was planted in the same location again. And final reading was taken at 110 days after plantation. A frame was made with bamboo surrounding the wooden frame and steel wire was tied with the bamboo frame from the top. Plants were tied with nylon rope and hanged from the steel wire so that tillers can withstand vertical after removal of sands. Woods from all side was removed first and sands were washed out through water flow.

(a)

(b)

Figure 3.3: 2.75m×1.75m×0.60 m wooden frame (a) Filled with sand for vetiver plantation, (b) Just after the plantation was done

3.3.1.3 Index property tests of soil samples

Sandy soil was used for the growth study of vetiver because it is easy to remove the sandy soil from root after uprooting vetiver clump. Soil sample was collected from

Buriganga river bed. A series of laboratory tests were conducted to determine the index properties of soil samples (Table 3.2). All tests were conducted in Geotechnical laboratory in Civil Engineering Department of BUET. Laboratory tests for determining index properties include specific gravity test, grain size analyses and hydrometer test.

Table 3.1: Locations of collected soil sample

Sample ID	Location	Latitude	Longitude
Pubail soil	Pubail, Gazipur	23.9115	90.3889
Dredged sand	Buriganga river bed soil	23.7258	90.3881
Buriganga river bank soil	Collected from Buriganga river bank	23.8471	90.3886

Table 3.2: Test scheme to determine the properties of soil samples

Properties of soil	Name of the test	ASTM reference	Test performed on the soil samples	Parameters to be determined from test
Index Properties	Grain size distribution	ASTM C 136	All three samples	Grain size distribution curve
	Natural Moisture Content	ASTM D 2974	All three samples	Natural Moisture content
	Specific Gravity Test	ASTM D 854	All three samples	Specific gravity
	Atterberg Limit test	ASTM D 4318	All three samples	Liquid Limit & Plastic Limit
Engineering Properties	Direct Shear Test (CU)	ASTM D 6528	All three samples	Shear strength parameters (c &ϕ)
	Unconfined compression test	ASTM D2166	Buriganga river bank soil	Cohesion (c)
	Tri-axial test	ASTM D 4767	Dredged sand	Shear strength parameters (c &ϕ)

3.3.2 Tensile strength test of grass root

Tensile strength of selected grass root has been measured by a tensile test apparatus. The capacity of this machine is 100 kN which is generally used for tensile strength test of steel fiber or thin sheet. Loading has been applied at a constant rate of 10mm/min.

Vetiver root was collected from uprooted vetiver clump and roots were chopped to 10 cm. Then the sample to be tested was clamped between two grips of tensile test apparatus. After clamping the roots into wedge grips, the motor of tensile test apparatus was driven to apply initial tension into the roots and the reading was set at zero. Figure 3.4 shows the schematic diagram of test set up and the actual photograph of tensile test apparatus was placed in Figure 3.5. Root diameters at either ends were taken. The motor drive unit will be then put on subjecting the sample to a movement of the clamps at a constant rate of 10mm/min., and test commence. Loading was recorded at the time of failure.

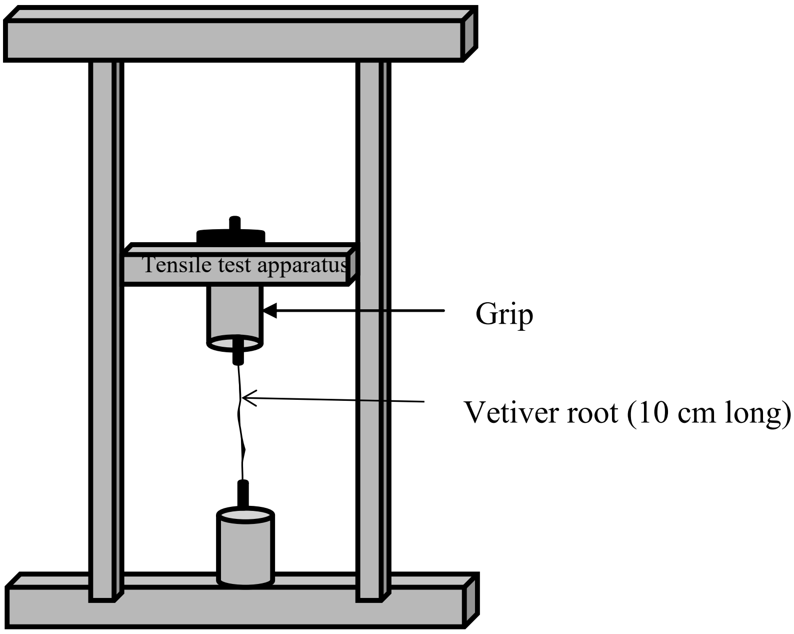


Figure 3.4: Schematic diagram of tensile strength test set up

The following formula has been used to calculate tensile strength, T.

$$T=\frac{F\max}{\pi(\frac{D}{4})^2} \quad (3.1)$$

where, F_{max} is the maximum force (N) needed to break the root and

D is the mean root diameter (mm) before stretching.

(a) (b)

Figure 3.5: Tensile strength test of vetiver root (a) Vetiver root chopped to 10 cm long, (b) Vetiver root clamped between two grips of tensile test apparatus

3.3.3 Laboratory tests on undisturbed samples

Vetiver grass was planted in 75 mm dia PVC pipe, containing both sandy soil and clayey soil. Undisturbed rooted soil specimen of 62.5 mm diameter was retrieved from pipes after 180 days of plantation. Direct shear tests was conducted on undisturbed samples to determine the shear strength of soil-root matrix.

3.3.3.1 Collection of vetiver clump

Naturally grown healthy and green vetiver grasses were collected from Pubail, Gazipur. Figure 3.6 shows the photograph of the ground from where vetiver has been collected and vetiver clumps.

3.3.3.2 Sample preparation and Index property tests of collected samples

<u>Preparation of sand samples</u>

Grease layer was given at the inner side of the pipe so that soil can be extruded easily during testing. Cement (5% of dry weight of sand) was mixed with sand so that sand soil sample does not collapse during testing. 20% water was added to the sand cement mixture. This moist soil sample was poured in 75mm dia and 300mm long PVC pipe. Soil was compacted in three layers having approximately 100mm equal layer thickness. Each layer was compacted by 300mm long steel tamping rod. 25 blows were given in each layer. Vetiver was planted in 8 soil samples, prepared in PVC pipe 20 April, 2016 and 4 samples were kept bare.

(a) (b)

Figure 3.6: Collection of vetiver clumps (a) The field from where vetiver has been collected (b) Collected vetiver clumps

(a) (b)

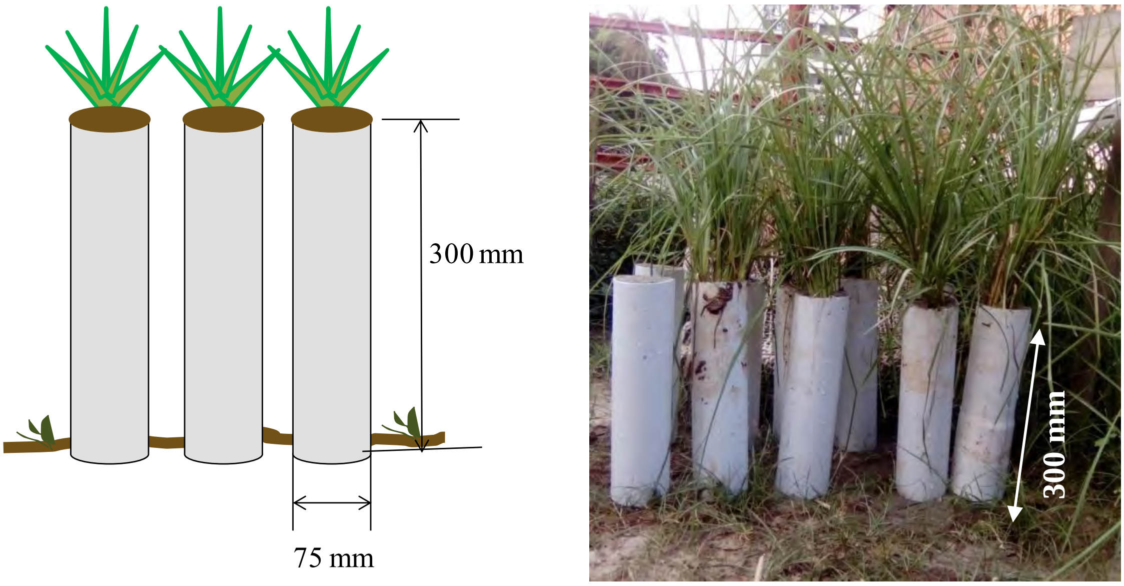
Figure 3.7: Collection of undisturbed soil sample (a) 75 mm dia PVC pipe was being inserted in Buriganga river bank soil to collect undisturbed sample, (b) Inserted PVC pipe

Preparation of clay samples

Clay sample was collected from Buriganga river bank. Undisturbed sample from Buriganga river bank has been collected in 75mm dia PVC pipe. The undisturbed samples collection by PVC pipe is shown in Figure 3.7. Then vetiver clump was planted in the pipes on 30 April, 2016.

3.3.3.3 Plantation in PVC pipes and collection of undisturbed sample

Vetiver grass has been planted in 75 mm dia PVC pipe (Figure 3.8), containing sandy soil (collected from Buriganga river bed) with 5% cement and clayey soil (collected from Buriganga river bank). Plantation was done by the early monsoon. Undisturbed samples of rooted soil were retrieved from thus planted pipes after 180 days.



(a) (b)

Figure 3.8: Vetiver plantation scheme (a) Schematic diagram of vetiver plantation in PVC pipe; (b) Vetiver grass planted in PVC pipe

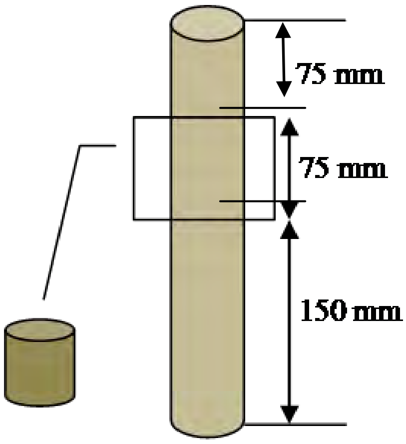


Figure 3.9: Schematic diagram of retrieving undisturbed sample from PVC pipe

Figure 3.9 demonstrates the procedure of retrieving undisturbed rooted soil specimen of 63.5 mm diameter for direct shear tests. Samples were collected 75 mm below from the top surface as shown in the figure 3.9 to avoid the disturbance and nonuniformity of top layer soil.

In the laboratory, direct shear tests was conducted to determine the shear strength parameters of undisturbed rooted soil and bare soil collected from pipes (Figure 3.10).

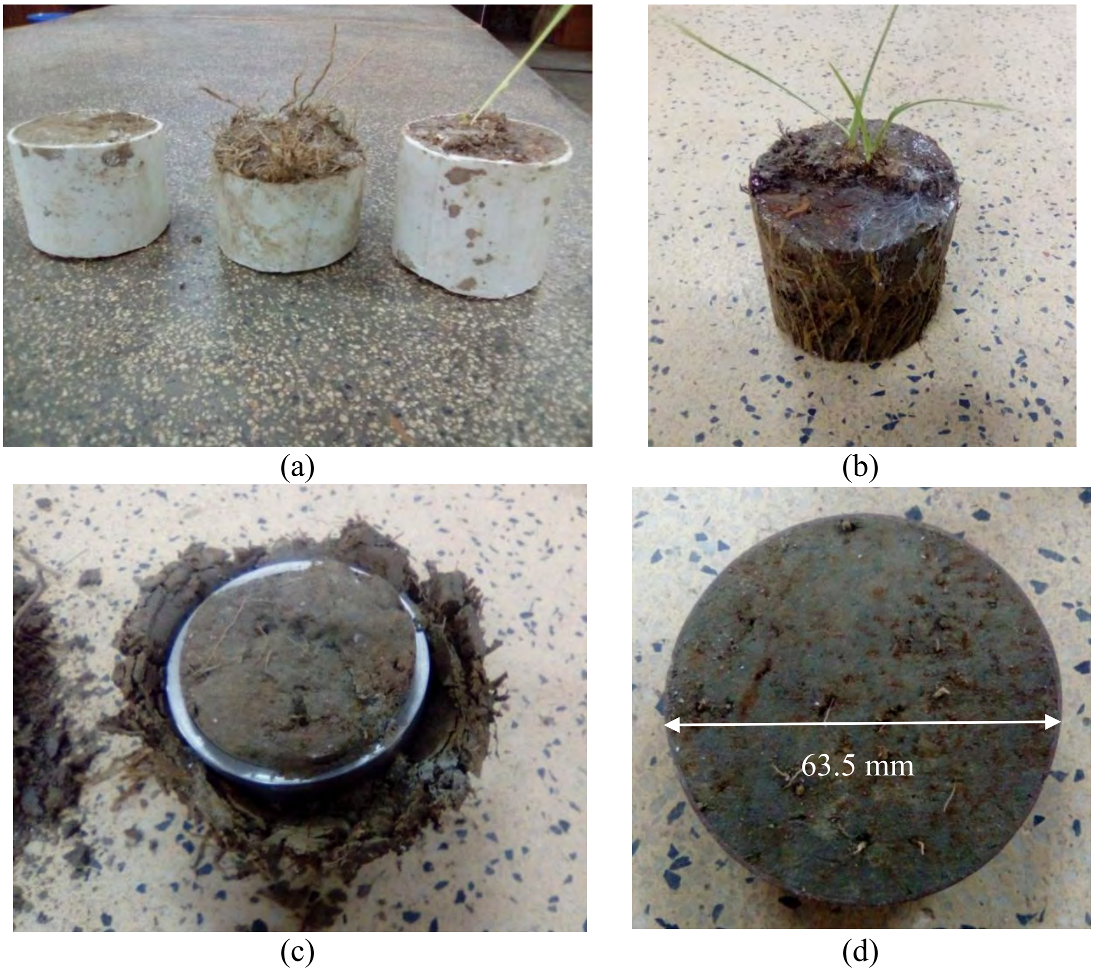


Figure 3.10: Steps of sample preparation (a) 75 mm pipe cut from 300 mm long pipe, (b) Soil retrieved from pipe, (c) Collection of 62.5 mm dia specimen from 75 dia soil sample, (d) Specimen in probing ring

Test Set-up

The remolded soil sample was placed carefully in the shear box from the ring. Then the desired normal load was applied. Normal stresses for the in-situ tests were arbitrarily selected in the range between 15.49 kPa and 30.98 kPa. Vertical displacement dial gauge was attached to record the vertical deformation with respect to time. Enough time was allowed for consolidation before applying the shear force. When two consecutive vertical deformation dial readings were same, the shear force was applied to the soil sample with a constant strain rate of 0.75 to 1.25 mm/min. The lateral deformation was recorded by a lateral constant strain rate of 0.75 to 1.25 mm/min. The lateral deformation was recorded by a lateral displacement dial gauge of 25 mm capacity. The applied shear force was recorded by a load dial gauge of 2.22 kN capacity.

3.3.4 Laboratory tests on reconstituted samples

Reconstituted samples were prepared by mixing grass root having 1.25-5 cm length at different arrangement with different types of soil. The root content was 3% of dry weight of soil sample. In laboratory, tests were conducted to determine the shear strength parameters of reconstituted rooted soil and bare soil after conducting the index property tests of these soils.

Root collection

Naturally grown healthy and green vetiver grasses were collected from Pubail, Gazipur. Roots were obtained from the collected vetiver grass.

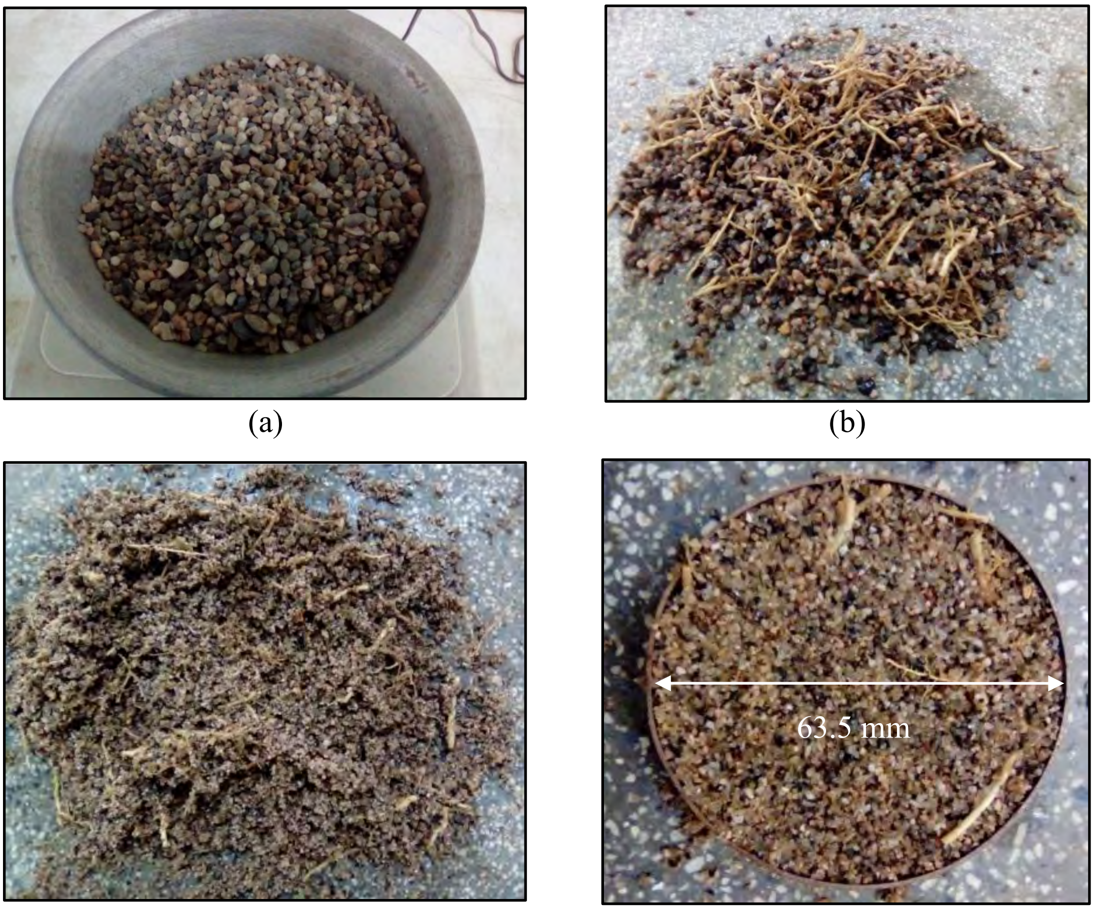
3.3.4.1 Direct shear tests on rooted sandy soil having various particle sizes

In this study, the sand used for testing was Sylhet sand. The reconstituted sandy samples were prepared by oven drying the sand firstly and cooling them before measuring the weight. Then the samples were sieved through sieve No 4, No 8, No 16, No 30, No 50 and No 100. Sand passing through No 4 and retaining on No 8 has been taken as course grained sand. Similarly sand passing through No 16 and retaining on No 30 has been considered as medium grained and sand passing through No 50 and retaining on 100 has been considered as fine sand. Soil classification has been done according to Unified Soil Classification System.

Direct shear tests were conducted in Consolidated Undrained (CU) condition on reconstituted soil samples. Tests were conducted on both bare and root mixed composite soil samples. Samples were prepared with 2.54 cm long vetiver root at 15% water content. Root content was 3% of dry weight of soil. Normal stresses were arbitrary selected in the range between 15.49 kPa and 30.98kPa.

Preparation of Reconstituted Soil Samples

At first, roots were collected and then preserved in the refrigerator with arbitrary moisture content to keep the roots fresh. Roots were chopped to the desired length (2.54 cm).



(a) (b) (c) (d)

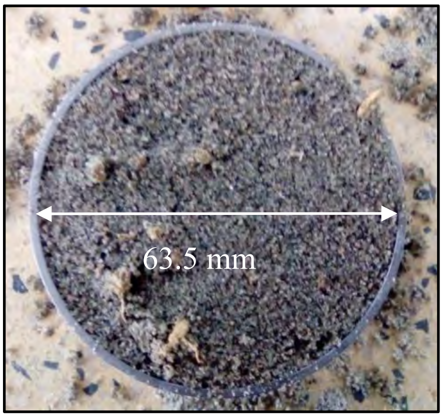
Figure 3.11: Sample preparation (a) Sand particles passing #4 and retaining on #8 sieve (b) Root mixed course sand (c) Root mixed fine sand and (d) soil sample inside the ring of 63.5 mm diameter

After that, water (equal to 25% moisture content) was added to the dry soil. Chopped vetiver roots were randomly mixed with the wet soil. The soil was then compacted by a wooden rod inside a probing ring of the size 63.5 mm in diameter and 25.4 mm in height from a falling height of 100 mm. The compaction was done in three layers where 25 blows were applied in each layer. The prepared samples were kept in a desiccator to keep the moisture content unchanged. Direct shear test was conducted on those prepared specimens according to ASTM standards. Test set up same as describes in 3.3.3.4. Figure 3.11 shows the photographs of different stages of reconstituted soil sample preparation.

3.3.4.2 Direct shear tests on rooted soil at predetermined root arrangement

Vetiver rooted sample was prepared by inserting the root perpendicularly. At first, desired water content was mixed with oven dry soil. Soil was poured in the probing ring and compaction was done by three layers. When compaction of the second layer was done, chopped vetiver root was inserted manually as shown in Figure 3.12. After that, again sand was poured and third layer compaction was done. The length of vetiver root was 2.54 cm and root content was 3% of dry weight of soil.

(a)



(b)

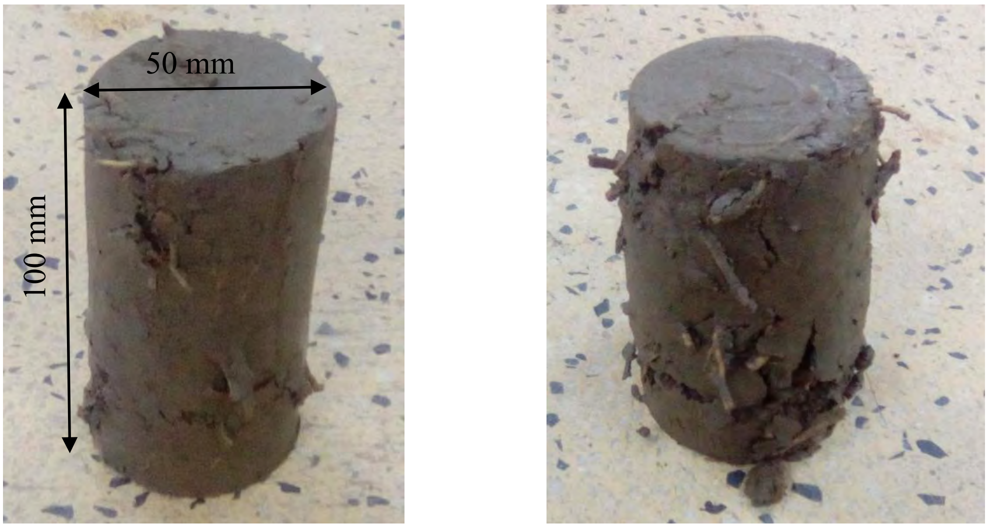
Figure 3.12: Sample preparation (a) Root inserted vertically in the soil sample, (b) Sample in probing ring

3.3.4.3 Unconfined compressive strength test on rooted soil

Soil sample used for unconfined compression strength test was collected from buriganga river bank. Two specimens were prepared as shown in Figure 3.13. One was mixed with vetiver root and another was bare soil. For rooted specimen, chopped vetiver root was added manually. The length of root is 2.54 cm and root content was 3% of dry weight of soil. The diameter of prepared sample was 2 inch and length was 4 inch. Compaction was done by three layers and 25 blows were given in each layer.

3.3.4.4 Tri-axial tests on rooted soil

Triaxial test was also conducted on vetiver rooted soil. Sample was prepared as it was done for unconfined compression strength test. Then triaxial test was done in Unconsolidated Drained condition.



(a) (b)

Figure 3.13: Sample (a) Before test, (b) After test

3.3.5 In-situ test

In-situ tests were conducted to determine the in-situ shear strength of vetiver rooted and bare soil in Pubail, Gazipur. Soil samples from in-situ test sites were collected to conduct laboratory investigations to determine the index properties. In-situ shear strength tests were conducted in the field on 9 block samples under same normal load. No of roots in the failure plane which were broken was counted and diameter of roots was measured by micrometer.

a) Equipments Used for In-Situ Test

For determination of in-situ shear strength of soil, a device was used with slight modification that developed by Islam and Arifuzzaman (2010). The apparatus that were used for these tests are hydraulic jack (capacity 5 ton), pressure gauge (capacity 100 psi), wooden plate, metal plates, metal box (approximately 40×20×19 cm^3), normal load (100 kg) and Linear Variable Displacement Transducer (LVDT) with capacity 50 mm. Both pressure gauge and LVDT were calibrated before using in the test. A list of materials and equipments used for experimental set up in field test is given below.

1) Steel model box
2) Weight
3) Steel tape (1 meter)
4) Hydraulic jack and pump (Capacity 5 Ton)
5) LVDT (Range 50 mm)

6) Pressure gauge (Capacity 100 psi)

7) Metal plates

8) Spade

9) Sabol

10) Hydraulic oil Grade No. 32

11) Sickle and Hoe

12) Wrench

13) Micrometer

b) Sample Preparation

Grass clump were cut at the ground level with a sickle. Keeping the root position undisturbed a trench of the size around (1m×1m) was made up to the desired depth (19 cm). The rooted area was made in desired block sample i.e., $40\times20\times19$ cm^3 shape by sharp knife. Then the metal box was placed around the earth block sample.

c) Experimental Set-Up

A metal cover plate was placed over the earthen block sample for uniform vertical loading. Then weights were placed over the metal cover plate centrally. The hydraulic jack was placed one side of the metal box in a manner that the plunger touch metal surface and force was applied. On the opposite side of the metal box, LVDT was placed to measure the strain. Figure 3.14 illustrates the experimental set up for in-situ shear strength of soil.

d) Test Procedure

Vertical load 100 kg (12.26 kPa) was applied. With hydraulic hand pump, pressure applied through the hydraulic jack, and strain measured with Lateral variable displacement transducer (LVDT). No of roots in the failure plane was counted and diameter of broken roots was measured with micrometer.

(a)

(b)

Figure 3.14: In-situ test (a) Earth block in metal box, (b) Test arrangement for in-situ shear test

3.4 Development of a Mathematical Model

The additional shear strength, ΔS, provided by roots, is important in evaluating the quantitative contribution of vegetation to the stability of slopes. The limit-state model, which assumes that roots are firmly anchored in the soil and the tensile strength of roots is fully mobilized, is normally used to estimate the value of ΔS in the engineering practice (Wu et al., 1979; Greenway, 1987; Coppin and Richards, 1990). Thus, the experimental results obtained in this research were used to establish the relationship between ΔS and the tensile strength of roots by assuming that the tensile strength of all roots permeated in the specimens is fully mobilized after shearing. Root diameter near the shear plane for all the roots were measured after the tests for each root system. The average mobilized tensile force in roots per unit area of soil, t_R, is expressed as

$$t_R = \sum(\frac{Ti*ni*ai}{A}) \quad (3.2)$$

where T_i is the ultimate tensile strength of roots in size class i, n_i is the number of roots in size class i, a_i is the mean cross sectional area of roots in size class i and A is area of the shear plane. Nine experimental data were used to establish the relationship between the additional shear strength and t_R. This equation provide a convenient mean to assess the additional shear strength provided by roots based on simply the tensile strength of roots and are easy to use in engineering practice.

3.5 Summary

In this chapter, a brief description about selected sites, soil collection, growth study, sample preparation, testing procedure for both in-situ tests and laboratory tests is given.

a) Investigation of root morphology has been described and finally a grass has been selected for detailed growth study. The selected site for growth study and entire procedure has been described with detailed pictures.
b) Index property tests for soil samples have been conducted according to standard ASTM procedure and that procedures have been described briefly.
c) Tensile strength of vetiver root has been tested by Regger which has been discussed in details.
d) Sample preparation for undisturbed and disturbed rooted soil sample has been discussed and their shear strength parameters were determined by standard shear tests. The test set up has also been described briefly.
e) In-situ tests were conducted to determine the in-situ shear strength of vetiver rooted soil and bare soil. Equipments used for in-situ tests, sample preparation and experimental set up have been enunciated.
f) Finally the necessary terms for developing a mathematical model have been explained.

Chapter 4
RESULTS AND DISCUSSIONS

4.1 Introduction

To develop a mathematical model to predict the additional shear strength of root-reinforced soils is the main objective of this research. The root morphology (root length, root diameter, root distribution) of different long rooted grasses such as wild cane, tiger grass, vetiver grass was investigated. And the tensile strength of the selected roots was also determined. The effect of root reinforcement on the shear strength of rooted soil matrix was determined by laboratory investigations. Some field tests were also conducted for determination of in-situ shear strength of rooted soil. Analysis has been done on the results of laboratory and field tests to develop a mathematical model. Detail laboratory test results, in-situ test results and growth study results are presented in this chapter.

4.2 Index Properties of Soil

The index properties of the collected soil samples obtained from laboratory investigations are described below. The grain size distribution curves of these soil samples are shown in Figure 4.1.

Pubail soil

The specific gravity of the soil sample collected from Pubail region is 2.68. Natural moisture content is 16%. Clay, silt and sand fractions of the soils have been determined according to ASTM D 422. Clay, silt and sand content of the soil are respectively 24%, 60%, 16%. The liquid limit is 44%, plastic limit is 21% and plasticity index is 23%. It is found that the soil sample collected from Pubail is Clay of low plasticity or Lean clay and the designated group symbol according to ASTM D 2487 is CL.

Dredged sand

Specific gravity of the soil is 2.74. Its grain size distribution curve is shown in Figure 4.1. From the graph, it has been found that the soil is poorly graded having coefficient of uniformity c_u=1.86 and coefficient of curvature c_c=1.1.

Buriganga river bank soil

The specific gravity of the soil sample collected from Buriganga river bank is 2.55. Natural moisture content is 28%. Clay, silt and sand fractions of the soils have been determined according to ASTM D 422. Clay, silt and sand content of the soil are respectively 11%, 79%, 10%. The liquid limit is 42%, plastic limit is 23% and plasticity index is 19%. It is found that the soil sample collected from Buriganga river bank is Clay of low plasticity or Lean clay and the designated group symbol according to ASTM D 2487 is CL.

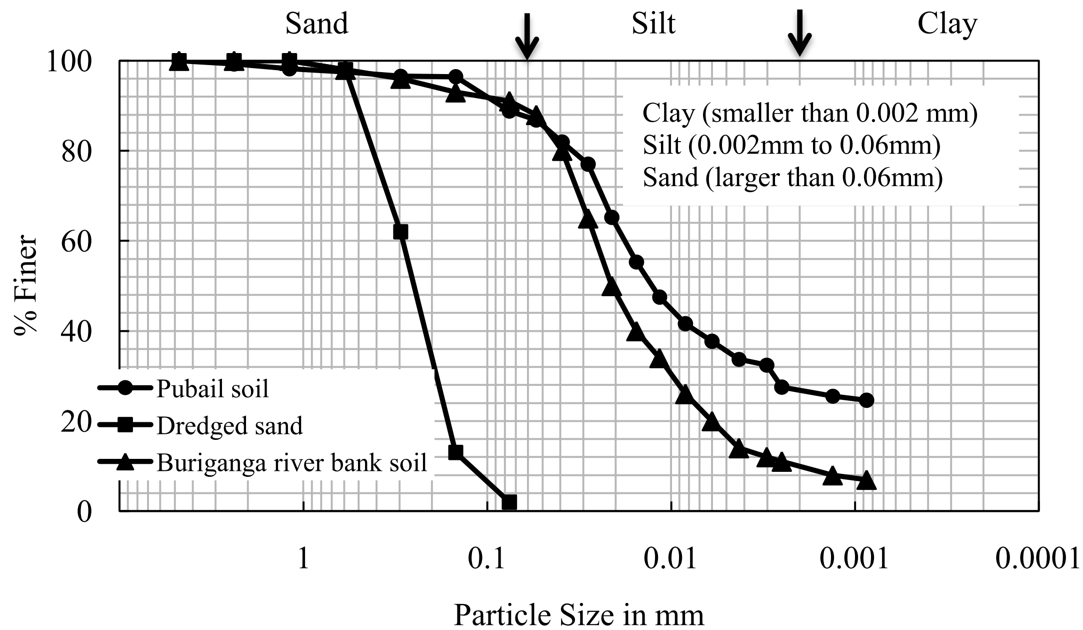


Figure 4.1: Grain size distribution curves for selected soils

4.3 Root Morphology

After studying previous researches on increasing soil shear strength using plants root system, few plants were selected. As a bio-engineering plant, vetiver grass (*Vetiveria zizanioides (L.) Nash*) is well accepted all over the world. But there are some other locally available plants which are being used for soil protection purposes by the local people and also have soil binding capacity. Some of such plants are nol khagra (*Phragmites kark*), hardy sugarcane (*Saccharum arundinaceum*), wild cane (*Saccharum spontaneum*), tiger grass (*Thysanolaena maxima*) etc.

Vetiver grasss (locally known as binna or binna shoba) is common throughout the country. It can grow on sandy loams to clay soils, on strongly acid to slightly alkaline soils with a pH range from 4-7.5, but prefers neutral to slightly alkaline soils. It has a high degree of tolerance to drought and flooding. Rainfall requirement for this plant is 500-5000 mm. Its shoot height is normally 1-3m.

Wild cane (locally known as kans) is common throughout the country. It can be adapted to a wide range of soils, generally of rather sandy types. It has a good degree of drought tolerance and will tolerate some flooding. It prefers a high rainfall, usually in excess of 1 500 mm. Its shoot height grows upto 3m.

Tiger grass (locally known as Jharu ful) very commonly occurs in the eastern parts of the country. It prefers acid to slightly alkaline soil pH 4.5-7.2, any soil texture, well drained to medium drained soil moisture, partial shade to full sun, medium salt tolerance. It has a good degree of drought tolerance and can survive high rainfall. Normal range of shoot height is 3- 4m.

4.3.1 Root architecture of different long rooted grass

Figure 4.2 contains the photographs of uprooted tiger grass, wild cane and vetver grass.

(a) (b) (c)

Figure 4.2: Uprooted grasses (a) tiger grass, (b) wild cane, (c) vetiver grass

Table 4.1: Root characteristics of different plants

Parameter	Wild cane	Tiger grass	Vetiver
Color	Black	Light brown	Yellowish brown
Diameter (mm)	0.2 – 2.5	0.2 – 2	0.2 – 2.2
Max root length (mm)	86	59	175
Root hairs	Fiberous	Fiberous	Very fiberous

All four types of roots have difference in many characteristics like in their colors, surface conditions, surface texture, presence of root hair etc. which are presented in Table 4.1. Among them vetiver root has more root hairs and root lengths than the other three. So vetiver grass has been selected for detailed growth study.

4.3.2 Growth of selected grass

Observed vetiver root growth has been shown in Figure 4.3. All results are based upon the observations with respect to length increase of root and shoot in time. Growth study was conducted on sandy soil because sandy soil can be removed easily from roots. The root network of the vetiver grown in sandy soil is found to be massive. Vetiver grasses were planted with 4 cm long root. Summary of the investigation has been presented in Table 4.2. Vetiver root length was measured at different time interval (39 days, 46 days, 51 days, 90 days and 110 days) and maximum root length was found 114.4 cm at 110 days. Root matrix diameter increases with time as per expectation. Root matrix diameter also depends on sunlight exposure and availability of water. The average diameter of root was found from 0.11 cm to 0.12 cm. Shoot length of vetiver was measured at different time interval (39 days, 46 days, 51 days, 90 days and 110 days) and maximum length of shoot was found 142 cm at 110 days. Vetiver mass creates a matrix (Figure 4.4) which contributes immensely in slope protection, by providing resistance to soil particles from moving.

Table 4.2: Growth of vetiver root and shoot with time

Parameters	Unit	Plantation Day	39 Days	46 Days	51 Days	90 Days	110 Days
Overall range of shoot	cm	30.48	23-117	23-125	05-121	11-125	48-142
Average root diameter	cm	0.12	0.11	0.12	0.12	0.13	0.13
Sample maximum root length	cm	17.48	58.42	72.39	86.36	96.52	114.40
Sample minimum root length	cm	10.16	8.89	6.35	5.08	10.16	12.34
Root matrix diameter	cm	8.00	12.70	15.24	10.16	17.78	18.72

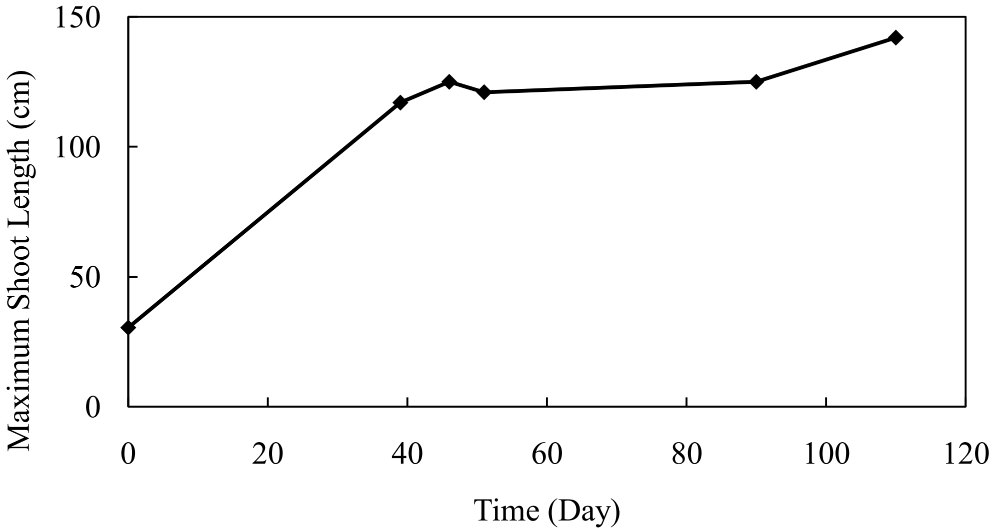
Islam et. al (2013) studied on the growth of vetiver grass in tropical region for slope protection. From this study, it was found that the root grew up to 25.4cm and shoot grew up to 80cm in 6 months in sandy silt (at *barind* tract zone in Rajshahi). In sandy soil (at Keraniganj site), length of root was grew up to about 30 cm. But in the present study, it was found that root was grew up to 114.4 cm in pure sand in about 3 months only which indicates vetiver root grows very fast in sand than that of other cases. This may occur due to the heavy rainfall during the growth time.

(a) (b) (c)

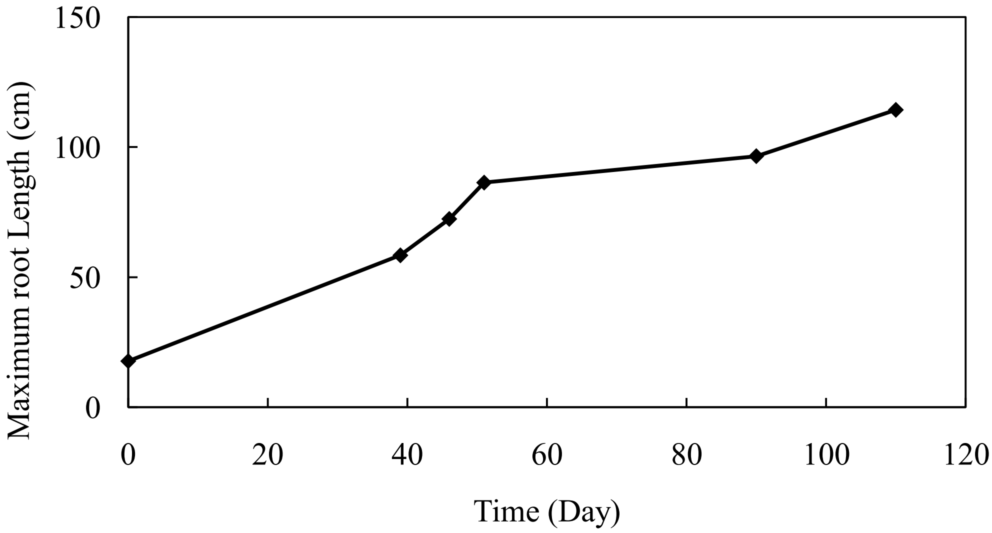
(d) (e) (f)

Figure 4.3: Root (a) at the day of plantation (b) after 39 days (c) after 46 days (d) after 51 days (e) after 90 days (f) after 110 days

Figure 4.4: Vetiver root matrix in sandy soil after 110 days of plantation



(a)



(b)

Figure 4.5: (a) Growth of vetiver shoot with time; (b) Growth of vetiver root with time

4.4 Tensile Strength of Grass Root

The ultimate tensile strength of roots of Vetiver Grass (*Vetiveria zizanioides*) with various diameters were measured using a computerized-controlled tensile tester. Roots with approximately uniform diameter were taken from the specimens. Root diameters used in the tensile tests range from 0.3 to 1.2 mm. Roots with a length greater than 20cm were selected and used in the tensile tests. Root length between the top and bottom grips of the tensile tester is 10 cm. The rate of extension is 0.01 m/min. The experimental data with rupture in roots was used to evaluate the ultimate tensile strength of roots. Thirty three roots were tested successfully in the tensile tests. The root diameter near the location of rupture was measured using micrometer and used to compute the ultimate tensile strength. The relationship between the ultimate tensile strength, T_{ult}, and root diameter, D, for roots of Vetiver grass is shown in Figure 4.6. The mean exponential relationship was established to be

$$T_{ult} = 18.878 \times 10^3 D^{-1.12}, \quad \text{with } R^2 = 0.614 \tag{4.1}$$

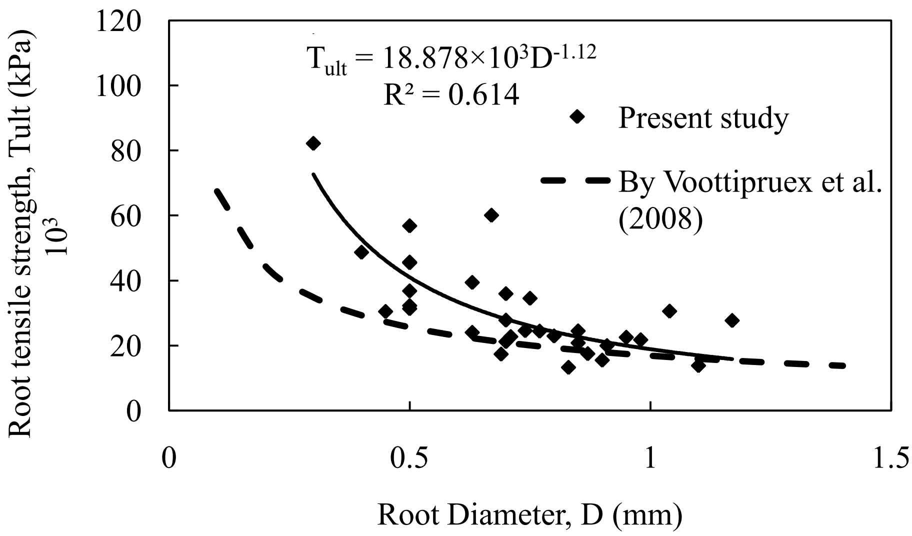


Figure 4.6: The tensile test results for roots of Vetiver grass: the ultimate tensile strength (T_{ult}) vs. root diameter (D)

Accounting for the variation in root fiber tensile strength with root diameter mean tensile strength of roots (T_R) was found to be 26.63 MPa.

4.5 Evaluation of Additional Shear Strength of Rooted Soil by Laboratory Tests

Root of vetiver grasses was used to determine the effect of root on strength-deformation characteristics of rooted soil. Reconstituted samples have been prepared by mixing vetiver root with different types of soil samples. Root content was 3% of dry weight of soil sample and root length was 2.54 cm.

4.5.1 Unconfined compression test results

Unconfined compressive tests were conducted on bare and rooted clay samples. Figure 4.7 shows stress vs strain curves. Bare clay sample failed at 30.12 kPa whereas rooted sample failed at 43.19 kPa. Due to addition of root, the increase in axial stress is 43.4%.

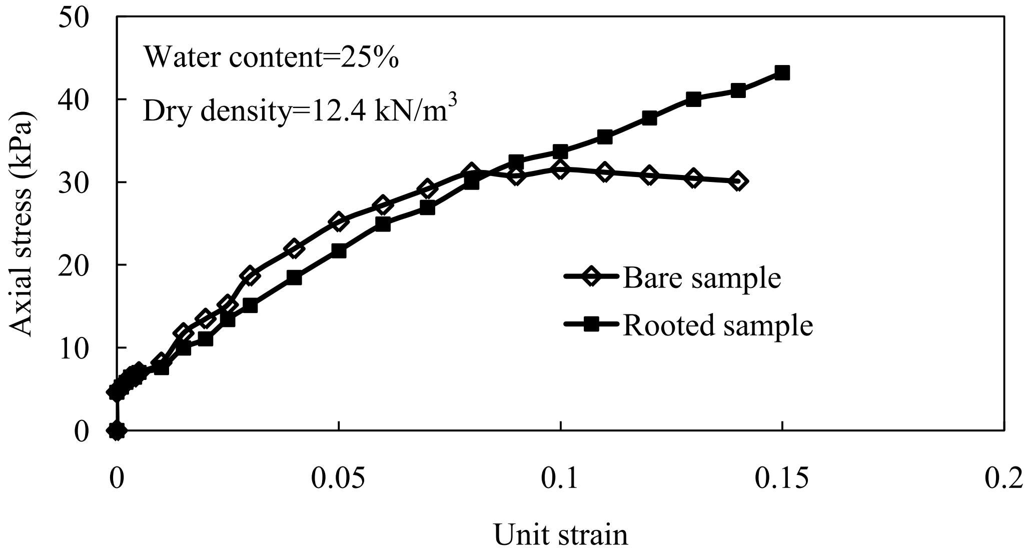


Figure 4.7: Axial stress vs unit strain curves for bare and rooted soil

4.5.4 Tri-axial test results

Tri-axial tests were also conducted on bare and rooted soil in Consolidated-Undrained condition. Figure 4.8 shows stress vs strain curves. Figure 4.8 shows that rooted sample failed at 667.4 kPa deviator stress and bare sample failed at 497.1 kPa deviator stress.

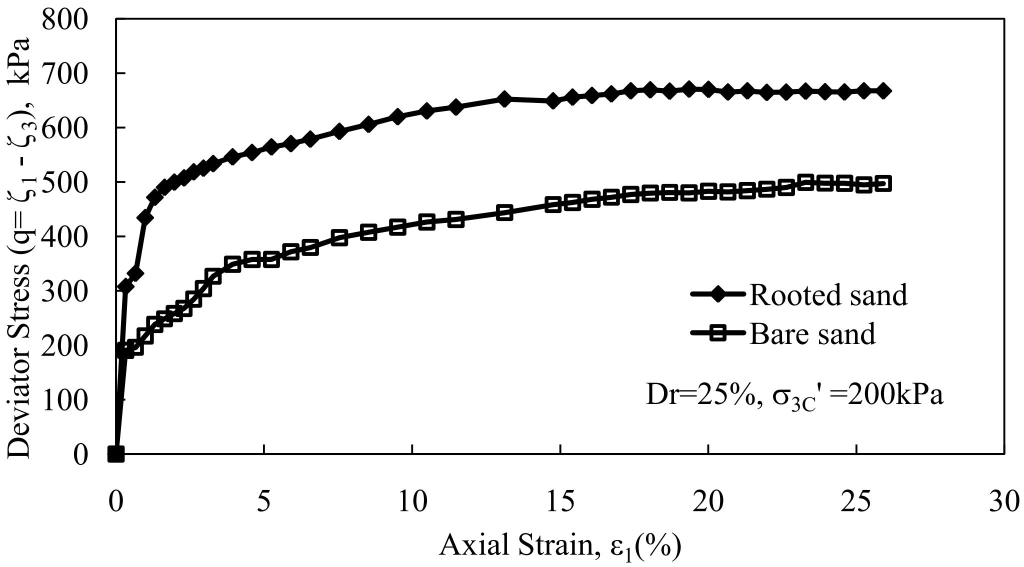


Figure 4.8: Stress vs strain curves for bare and rooted sand

4.5.3 Direct shear test results

Direct shear tests were conducted on different types of soil samples.

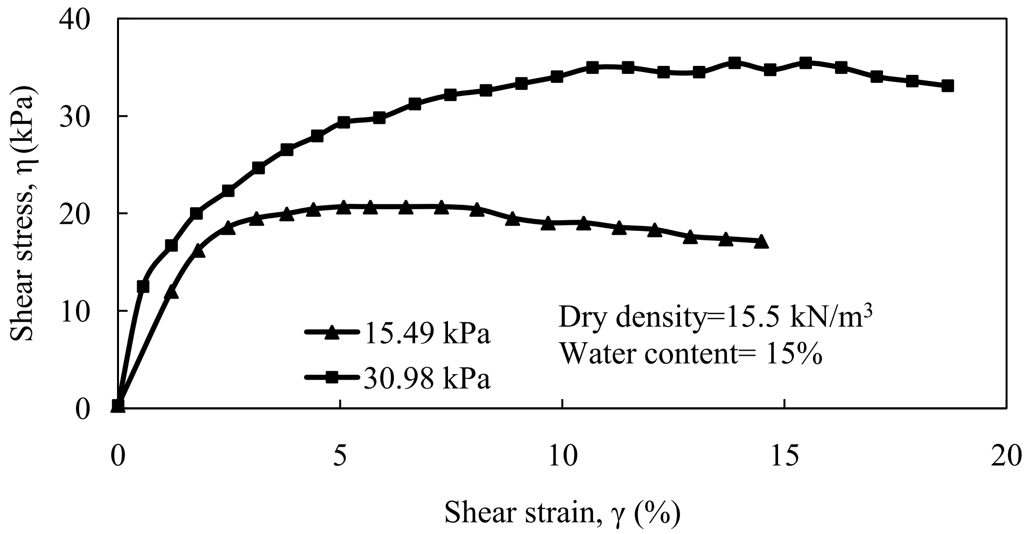
4.5.3.1 Effect of various particle size

The test result of soil samples having various particle size is presented in Table 4.3. The shear strength increases only for fine sand at both normal loads. In other cases, shear strength decreases. Direct shear tests were conducted for two normal load assuming that shear stress vs normal stress curve will pass through (0,0) point as sand has no cohesion Typical shear stress vs shear strain and shear stress vs normal stress graphs are presented in Figure 4.9.

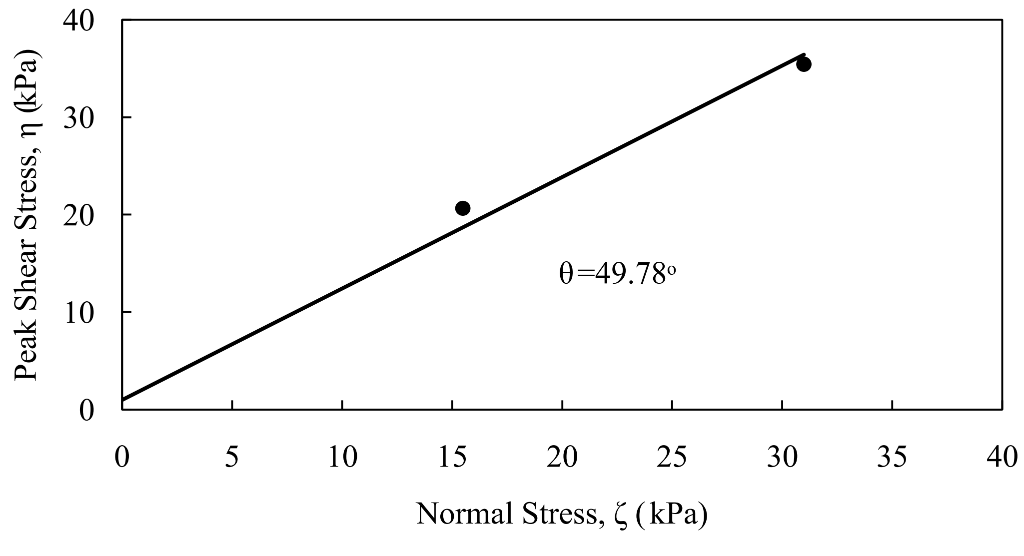
Table 4.3: Comparison of peak shear strength and shear strain of reconstituted bare and rooted soil

Sample type	ζ_n(kPa)	Bare sample		Rooted sample		$\Delta\eta_{max}$ (kPa)	$\Delta\gamma$ (%)
		η_{max} (kPa)	γ (%)	η_{max} (kPa)	γ (%)		
Course sand	15.49	31.7	15.32	30.76	6.6	-0.94	-8.72
	30.98	51.37	15.6	45.28	10.28	-6.09	-5.32
Medium sand	15.49	20.93	7.72	20.69	7.28	-0.24	-0.44
	30.98	38.26	9.44	35.45	13.88	-2.81	4.44
Fine sand	15.49	18.59	15.32	19.99	15.2	1.4	-0.12
	30.98	30.29	15.04	31.23	12.68	0.94	-2.36

Variation of angle of internal friction is presented in Figure 4.10. From test results, it is found that angle of internal friction, θ decreases with the decrease of particle size for the case of both bare and rooted sand samples. But for the case of coarse sand and medium sand, angle of internal friction of vetiver rooted sand sample is 4.3% and 3.6% lower than that of bare soil respectively. Again for fine sand, angle of internal friction of rooted sand is 2.5% higher than that of bare sand.

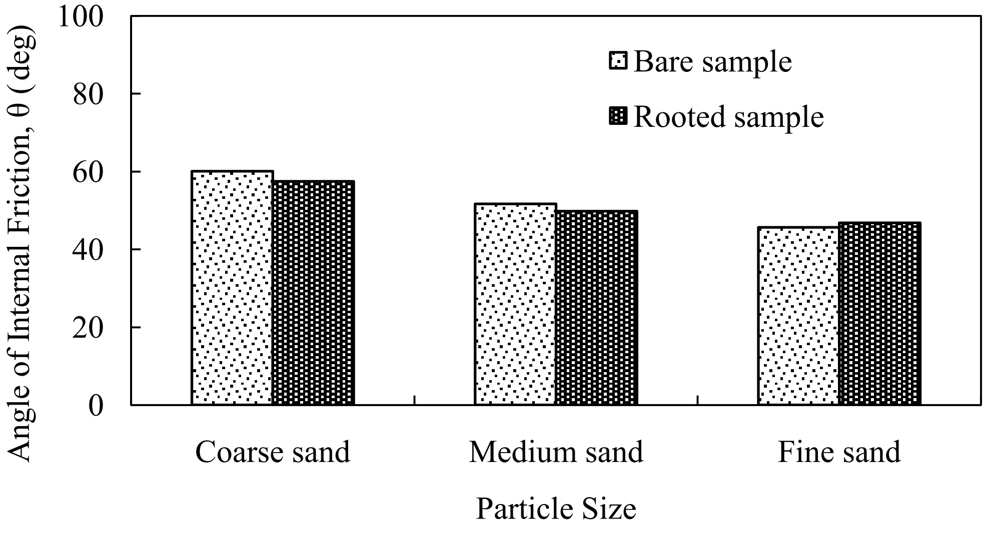


(a)

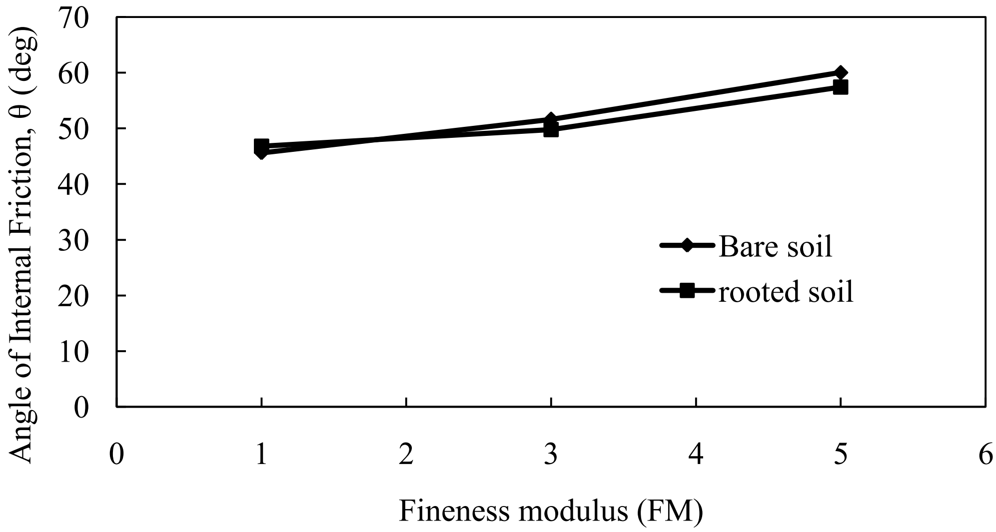


(b)

Figure 4.9: (a) Shear stress vs shear strain for medium rooted sand sample and (b) Peak shear stress vs normal stress for medium rooted sand



(a)



(b)

Figure 4.10: (a) Bar chart of comparing angle of internal friction of bare samples and rooted samples for coarse, medium and fine sand, (b) Angle of internal friction vs fineness modulus for bare and rooted sand

So it is seen that presence of root has apparently no effect on shear strength of sand root matrix. Sometimes peak shear stress reduces after adding roots. This phenomenon can be explained by the root position inside the specimen. Roots are arranged randomly within the soil specimen. So if significant amount of roots were parallel to the failure plane in the failure plane zone, then neither root nor soil can act against shear force. As a result, shear stress reduced. Again though the interaction between roots and soil particles is not significant for cohesionless soil, the tensile root force acting at the base of slip plane increases the stability of slope segment which has not been evaluated by these direct shear tests.

4.5.3.2 Effect of root arrangement

Direct shear tests were conducted on six samples. Three were bare sand samples and in other three samples, 2.54 cm long vetiver roots were inserted vertically. Figure 4.11 shows typical stress strain curve for rooted soil at three different normal stress conditions and 4.12 shows the comparison of shear strength parameters of rooted and bare soil. Table 4.4 shows the test results. From test results it has been found that, addition of root has increased the strength and ductility of soil. Firstly soil resisted the axial stress and after its failure, root took place and took stress with large strains. So after adding roots in the soil specimen, ductility has increased. Here all roots were arranged perpendicularly to the failure plane, more stress required to torn the roots. As a result shear stress of the specimen under all normal load conditions increases.

Table 4.4: Comparison of peak shear strength and shear strain of reconstituted bare and rooted soil

Sample type	ζ_n (kPa)	Bare sample		Rooted sample		$\Delta\eta_{max}$ (kPa)	$\Delta\gamma$ (kPa)
		η_{max} (kPa)	γ (kPa)	η_{max} (kPa)	γ (kPa)		
Sand	10.84	16.71	5.80	25.14	15.60	8.43	9.8
	15.49	22.80	6.60	32.64	15.20	9.84	8.6
	30.98	34.51	7.80	49.96	15.60	15.46	7.8

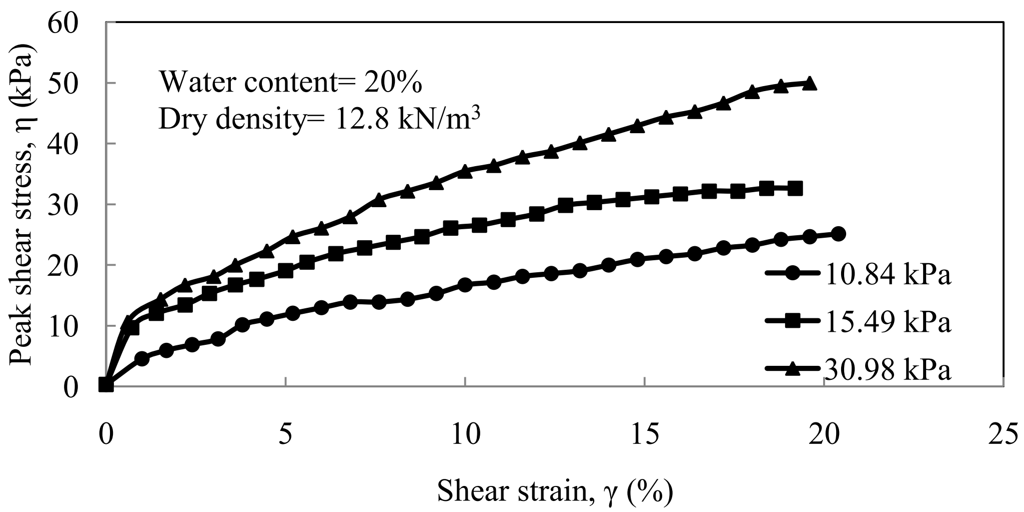


Figure 4.11: Shear stress vs strain curves for rooted sand

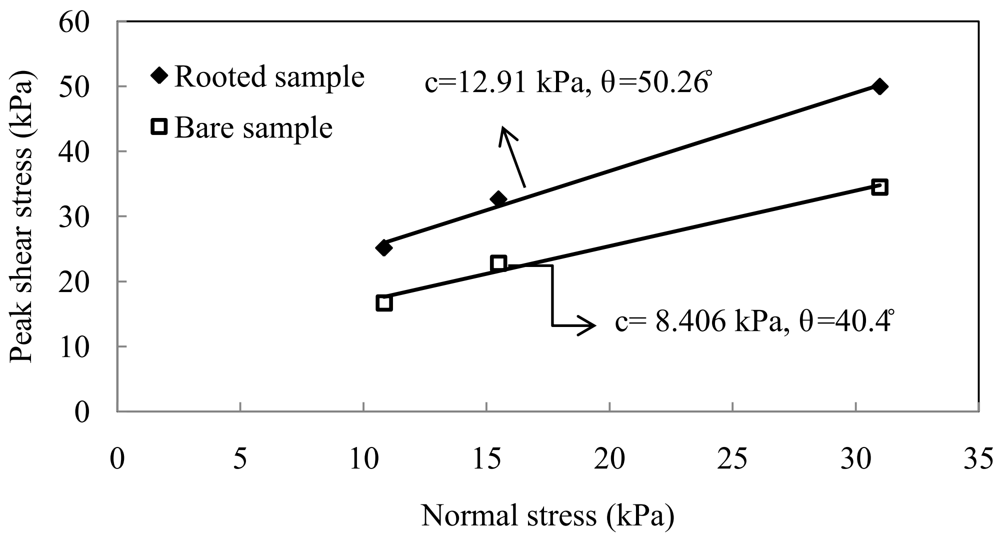


Figure 4.12: Shear stress vs normal stress curves

4.5.3.3 Test results from undisturbed samples

Direct shear tests were conducted on undisturbed clayey and sandy sample collected from PVC pipes. The cement mixed with sand was Basundhara Portland Composite Cement. Three bare soil specimens and three rooted soil specimens were tested for both sandy soil and clayey soil under three different normal loads. The selected normal loads were 10.84 kPa, 15.49 kPa and 30.98 kPa. Figure 4.13 shows the shear stress vs shear strain curves for these normal loads. Water content was 21% for bare and rooted clayey samples and 19% for bare and rooted sandy samples. The direct shear test results have been shown in table 4.5.

Table 4.5: Comparison of peak shear strength and shear strain of undisturbed bare and rooted soil

Sample type	ζ_n (kPa)	Bare sample		Rooted sample		$\Delta\eta_{max}$	$\Delta\gamma$
		η_{max} (kPa)	γ (kPa)	η_{max} (kPa)	γ (kPa)		
Clay	10.84	38.72	2.4	34.51	6.4	-4.21	4
	15.49	42.47	4.2	40.13	0.96	-2.34	-3.24
	30.98	49.5	5.4	74.79	5.24	25.29	-0.16
Sand	10.84	22.57	7.2	20.93	15.4	-1.64	8.2
	15.49	23.91	14.4	23.74	9.2	-0.17	-5.2
	30.98	32.17	8.8	35.91	15.2	3.74	6.4

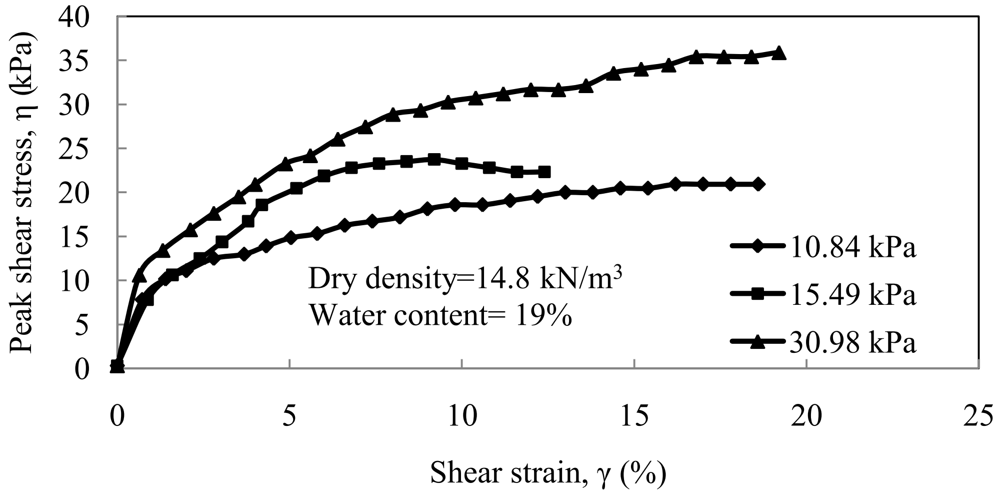
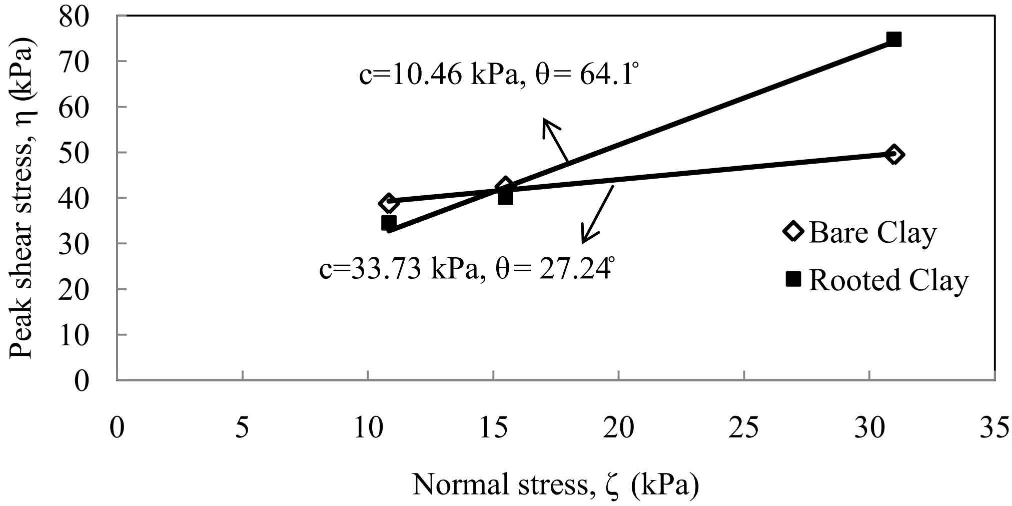
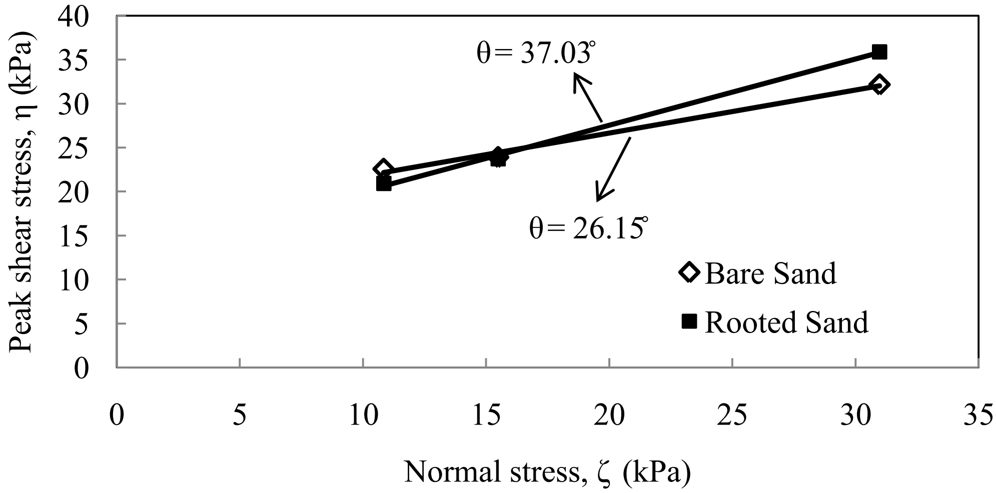


Figure 4.13: Stress vs strain curves for rooted sand sample



(a)



(b)

Figure 4.14: Shear stress vs normal stress curves for undisturbed (a) clay sample, (b) sand sample

From Figure 4.14, it has been seen that for both clayey and sandy samples, angle of internal friction of rooted sample is higher than that of bare soil but cohesion of rooted sample is lower than that of bare soil for both cases.

From shear test result, it has been observed that the change of shear strength of rooted soil in comparison to bare soil is not significant. Root fibers increase the shear strength of soil primarily by transferring shear stresses that develop in the soil matrix into tensile resistance in the fiber inclusions via interface friction along the length of imbedded fibers.

The mobilized tensile stress of root fibers depends upon the amount of fiber elongation and fixity of the fibers in the soil matrix. Full mobilization can occur only if the fibers elongate sufficiently and if the imbedded root fibers are prevented from slipping or pulling out.

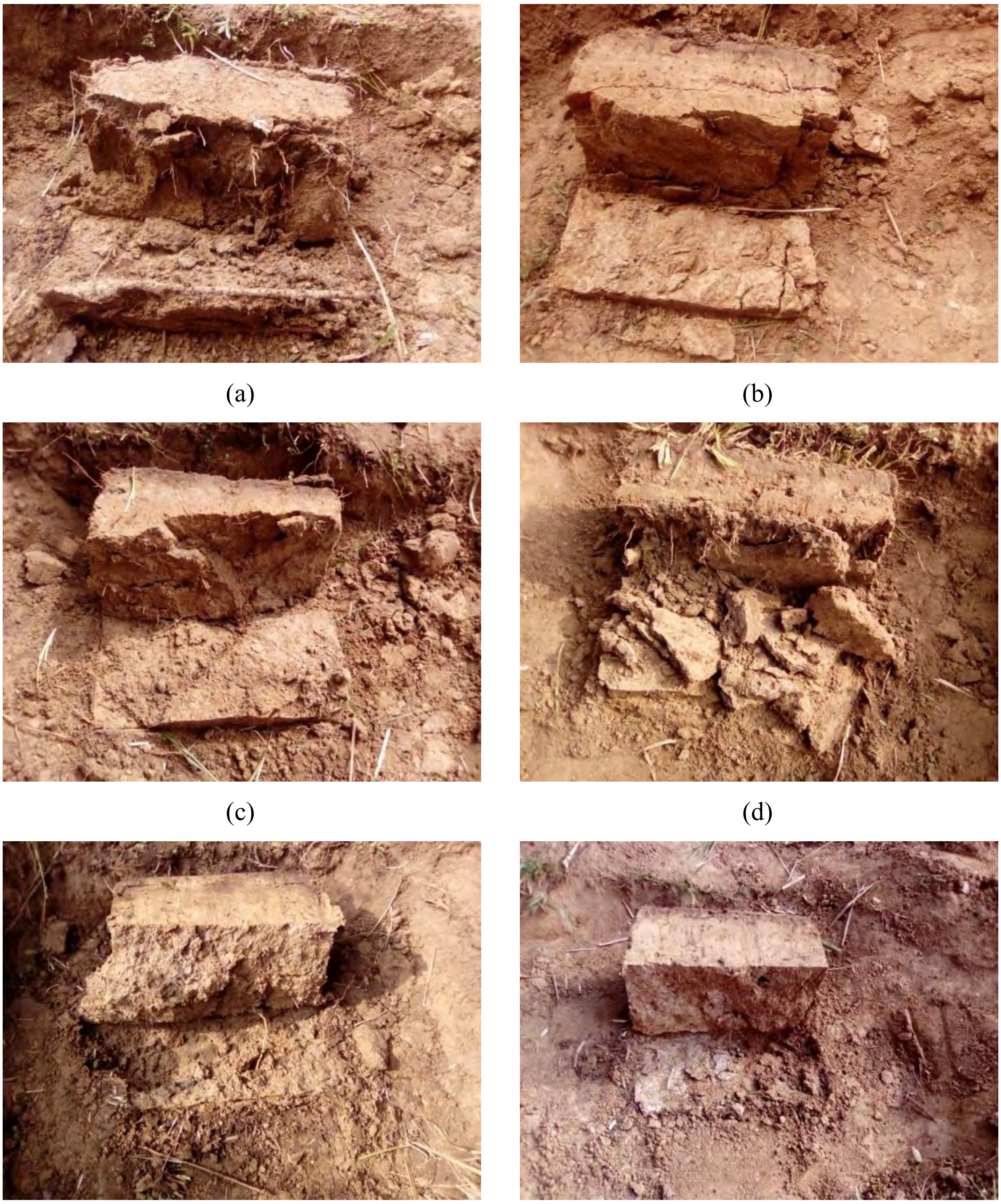
The latter requires that the fibers be sufficiently-

i. long and frictional,
ii. constrained at their ends and/or
iii. subjected to high enough confining stresses to increase interface friction.

These may lack in laboratory shear test samples. In case of clay samples when the shear force come, the bond between root and soil particles fails. For sand samples, friction between soil particles and root cannot contribute. So, the effect of root content on shear strength of rooted soil cannot be evaluated through laboratory shear tests.

4.6 Evaluation of Additional Shear Strength of Rooted Soil by In-situ Test

Tests were conducted at EGL for both rooted and bare soil under 12.26 kPa normal stress. Total 9 block samples were tested in the field under the same normal stress at same depth. Out of nine samples, one sample was bare soil and rest eight samples were vetiver rooted. Figure 4.15 shows the failed block samples. Torn roots are clearly visible in these photographs. No of torn root was counted and diameter was measured by a micrometer. The shear stress versus shear strain graphs of block samples are presented in Figure 4.16.



(a) (b) (c) (d) (e) (f)

Figure 4.15: Failed block sample having mobilized tensile strength per unit area of soil (t_R) (a) t_R = 1.04 kPa (b) t_R = 1.13 kPa (c) t_R = 2.54 kPa (d) t_R = 1.18 kPa (e) t_R = 3.06 kPa (f) t_R = 2.13 kPa

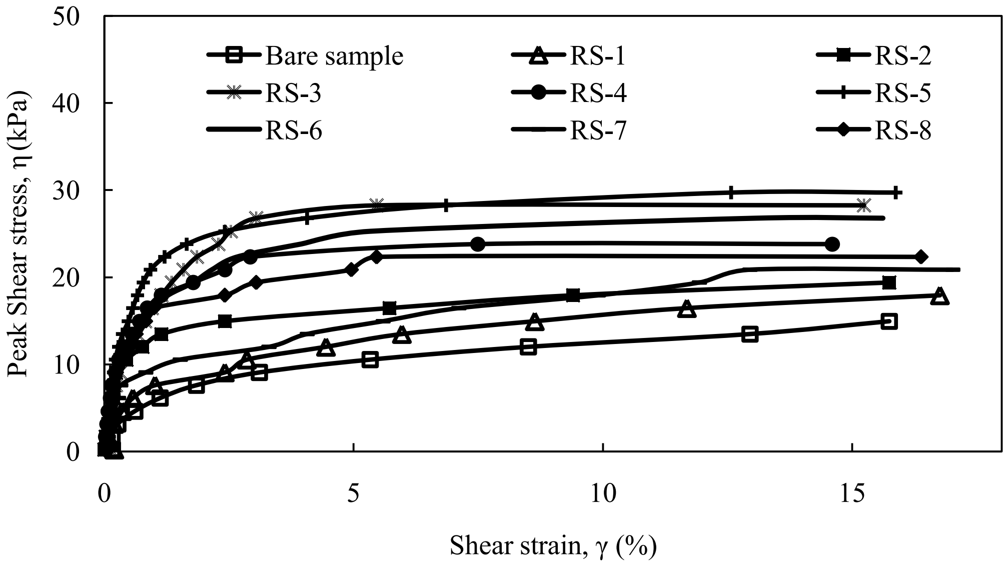


Figure 4.16: Shear stress vs shear strain curves for block samples

4.7 Development of a Mathematical Model

Figure 4.17 shows the model of the soil-root system subjected to shear.

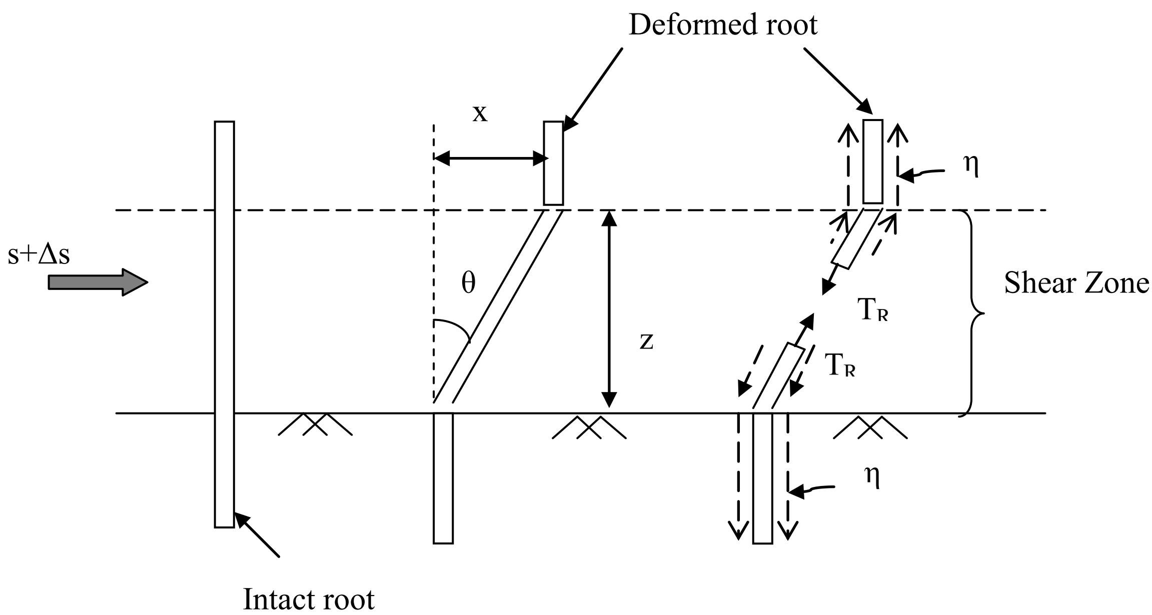


Figure 4.17: Schematic diagram of perpendicular root fiber reinforcement model (Voottipruex et al., 2008)

Before shear, the root was assumed to be perpendicular. After shear, root is deformed at an angle θ as shown in Figure 4.17.The tensile strength, T_R in the root is resolved into components perpendicular and parallel to shear zone. Then

$$\zeta_R = T_R\cos\theta, \qquad \eta_R = T_R\sin\theta$$

where, ζ_R and η_R is the normal and shear stresses applied to soil by T_R. The root's contribution to shear strength is,

$$\Delta s = \zeta_R\tan\theta + \eta_R$$
$$= T_R(\cos\theta\tan\theta + \sin\theta)$$

If all the roots in shear area are considered, then

$$t_R = \Sigma T_R \times A_R / A$$

Wu et al. (1979) found that (cosθtanθ+sinθ) is insensitive to the value of θ and is close to 1.2 for the range of θ from 48-72˚. Hence a constant value of the term was proposed by Wu et al. (1979). Figure 4.18 shows the variation of (sinθ+cosθtanθ) with angle of shear distortion in shear zone, θ.

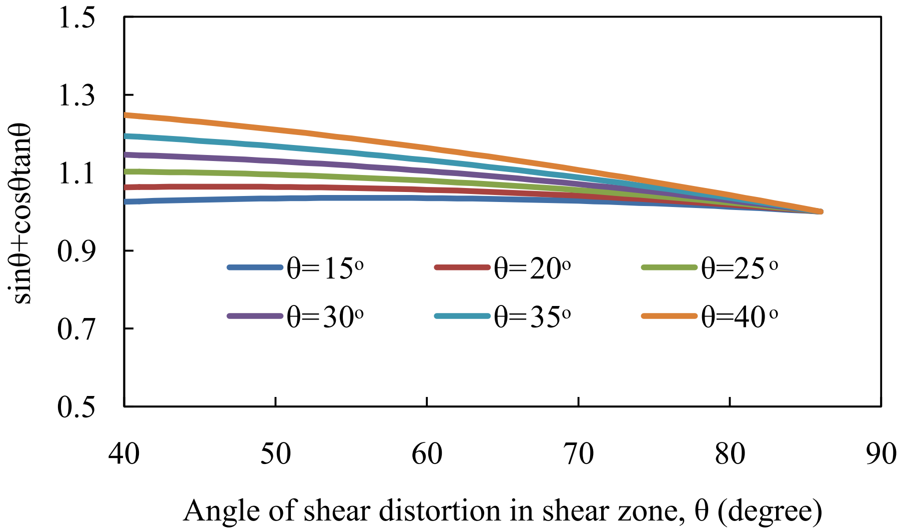


Figure 4.18: (sinθ+cosθtanθ) vs angle of shear distortion in shear zone

Nine experimental data were used to establish the relationship between the additional shear strength and t_R. Plots of the additional peak shear strength, ΔS versus t_R are shown in Figure 4.19 and Figure 4.20 shows the relation between additional shear strength and Root area ratio. Approximately linear relationships between ΔS and t_R was obtained and represented by-

$$\Delta S = 5.14\, t_R$$

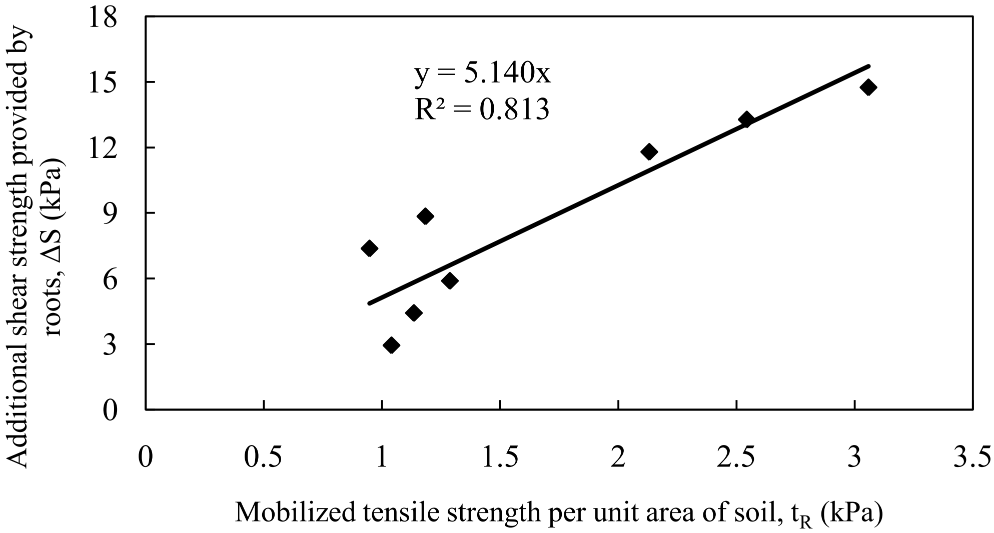


Figure 4.19: The experimental relationship between the additional shear strength provided by roots, ΔS and the mobilized tensile strength per unit area of soil, t_R

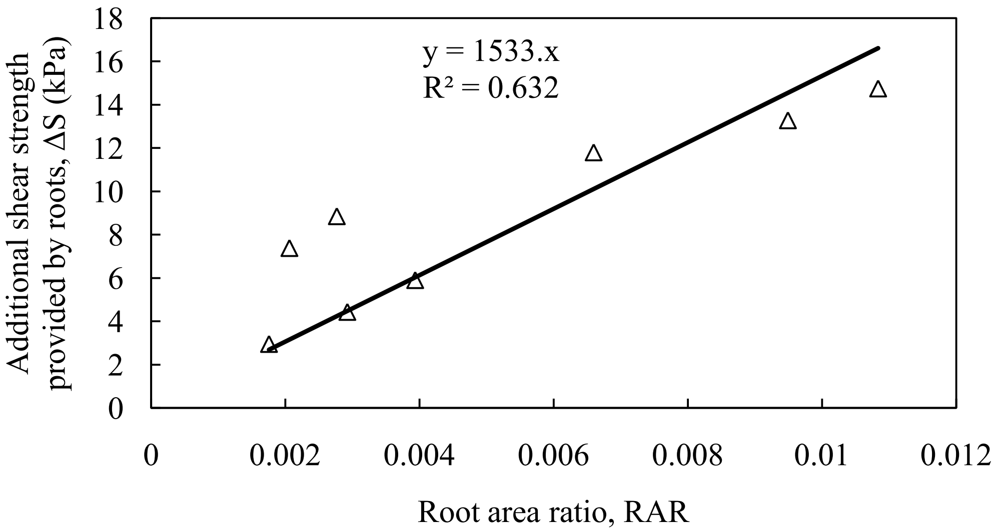


Figure 4.20: Relation between additional shear strength provided by root and Root Area Ratio

The ratios of the additional shear strength over the ultimate tensile force in roots per unit area of soil, t_R, established by Fan and Su, (2008) for the roots of Prickly Sesban are considerably less than that based on the simple force equilibrium theory, where $\Delta S = 1.15–1.2 t_R$.

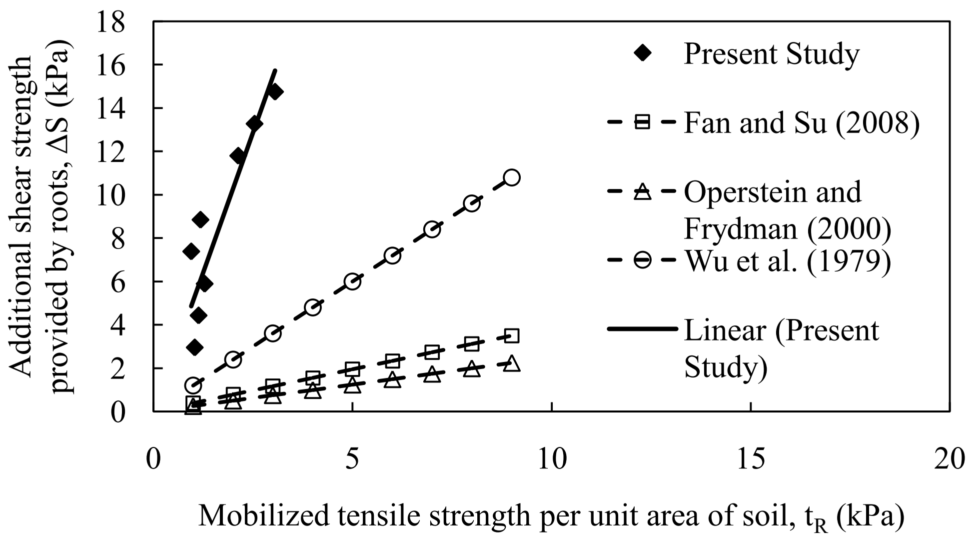


Figure 4.21: Comparison of the model developed in present study with other study.

Operstein and Frydman (2000) conducted direct shear tests on soil samples, 20cm in diameter, with roots of alfalfa, rosemary, *Pistacia lentiscus*, and *Meoporum parvifolium* in the laboratory. The test results show that the additional peak shear strength, ΔSp, provided by roots is equal to about $0.25t_R$, where t_R was computed by assuming that tensile stresses of all roots reach the ultimate state. In addition, Wu and Watson (1998) conducted field shear tests on 1m×1m root-permeated soil samples with *Pinus radiata*, diameters of most of the roots are less than about 20mm. The results show that the average measured root force is about one-third of that fails in tension. Whereas, in present study, it has been found that the additional shear strength, Δs provided by vetiver roots is equal to $5.14t_R$ for Lean Clay. This may occur due to the presence of foreign root content.

4.9 Summary

Use of vegetation for protecting earthen slopes is becoming more and more now-a-days. Effectiveness of vegetation in increasing soil shear strength was investigated and a mathematical model for determining the additional shear strength provided by vegetation root was developed in this study. Main findings obtained from this research are:

a) Three plants i.e. vetiver grass, tiger grass and wild cane were uprooted and their root architecture was observed. Based on long busy root network, vetiver grass was selected for detailed growth study. From growth study, it has been found that vetiver can grow up to 1 m in only 3 months with massive root network. The average root diameter was found from 0.115 cm. Maximum length of shoot was found 142 cm at 110 days.

b) Thirty three vetiver roots were tested successfully in the tensile tests. The root diameter near the location of rupture was measured and used to compute the ultimate tensile strength. The mean tensile strength of root (T_R) was found to be 26.63 MPa.

c) Laboratory investigations were conducted on reconstituted samples by mixing 3 % vetiver root with soil (root content was 3% of dry weight of soil sample). From test results, it has been found that angle of internal friction, θ for course grained soil is higher than that of medium and fine grained soil for both rooted and bare soil. But angle of internal friction, θ only increases for fine grained sand due to the inclusion of vetiver root. For coarse grained and medium grained soil, θ decreases.

d) Direct shear tests were also conducted on reconstituted samples by adding root at predetermined root arrangement and shear strength increases up to 50.45% for rooted samples than that of bare samples.

e) From unconfined compressive strength test results, it has been found that axial stress of rooted sample is 43.4% higher than that of bare sample.

f) Tri-axial test results show 34.26% increase in shear strength of rooted sample in comparison to that of bare sample.

g) Direct shear tests were also conducted on undisturbed samples collected from UPVC pipe. Normal stresses were 10 kPa to 35kPa. 51.1 % strength increase occurs for rooted clay sample and 11.63% strength increase occurs for rooted sand sample at 31kPa. For other two normal stress conditions, shear stress of rooted soil decreases. Hence, no general trend was not found from laboratory test data.

h) In-situ shear tests were occurred on one bare sample and eight (08) rooted samples at EGL and additional shear strength for rooted samples was determined by comparing with bare sample. Finally a correlation of additional shear strength with tensile strength of root was developed.

Chapter 5
CONCLUSIONS AND SUGGESTIONS

5.1 Findings of the Study

The main findings of the study are as follows:

i) Vetiver has longer and denser busy root network than tiger grass and wild cane. So vetiver grass was selected for detailed growth study. It can grow up to 1 m in only 3 months with massive root network. Maximum length of shoot was found 142 cm at 110 days. The mean tensile strength of root (T_R) was approximately 27 MPa and the relationship between the ultimate tensile strength, T_{ult}, and root diameter, D, for roots of Vetiver grass was found to be $T_{ult} = 18.878 \times 10^3 D^{-1.12}$ with 0.614 regression coefficient (R^2).

ii) From extensive laboratory investigations, it has been found that angle of internal friction, θ for course grained soil is higher than that of medium and fine grained soil for both rooted and bare soil. But angle of internal friction, θ only increases for fine grained sand due to the inclusion of vetiver root. Strength increase was occurred when roots were added perpendicularly in sandy soil specimen. In unconfined compression test and tri-axial test, shear strength increase was observed. But from direct shear tests on undisturbed samples, it was found that for both clayey and sandy samples, angle of internal friction of rooted sample is higher than that of bare soil but cohesion of rooted sample is lower than that of bare soil for both cases. That means, from laboratory investigations, no consistent trend was found.

iii) In-situ shear tests were conducted on one bare sample and eight (08) rooted samples at EGL and additional shear strength for rooted samples was determined. Finally, a correlation of additional shear strength with tensile strength of root was developed. This simple model ($\Delta S = 5.14\ t_R$) can be used to determine the shear shear strength of rooted soil without conducting cumbersome in-situ tests which will help to calculate the stability of vegetated slope.

5.2 Limitations

In this study, no common trend in laboratory test results was found. In some cases, shear strength increases due to addition of root but in other cases shear strength decreases. The mobilized tensile stress of root fibers depends upon the amount of fiber elongation and fixity of the fibers in the soil matrix. Full mobilization can occur only if the fibers elongate sufficiently and if the imbedded root fibers are prevented from slipping or pulling out. The latter requires that the fibers be sufficiently long and frictional, constrained at their ends and/or subjected to high enough confining stresses to increase interface friction. These were lack in laboratory shear test samples. So in-situ tests were conducted to develop the mathematical model. The in-situ tests were done for vetiver grass grown in lean clay and all tests were conducted in the same depth of soil. As the vetiver grasses were naturally grown in the soil, the presence of other plant root could not be ensured.

5.3 Suggestions for Future Study

The main objective of this research is to develop a mathematical model for quantifying the effect of root reinforcement on shear strength of soil. During this study it was felt that following studies may be conducted in future.

i) Tensile strength tests of different grass root such as tiger grass, wild cane, sugar cane etc can be determined and the model developed in this study can be tested for other grass root.
ii) Numerical models need to be performed to check the accuracy of the model developed in this study.
iii) In-situ tests can be done for different soil conditions and other locally available plants.
iv) The change of shear strength of soil root matrix with depth can be observed by conducting in-situ tests at different depth.
v) Shear strength of soil-root matrix can be determined at different growth stages of plant.

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APPENDIX A
LABORATORY TEST RESULTS

Direct shear test results on reconstituted soil sample having various particle size

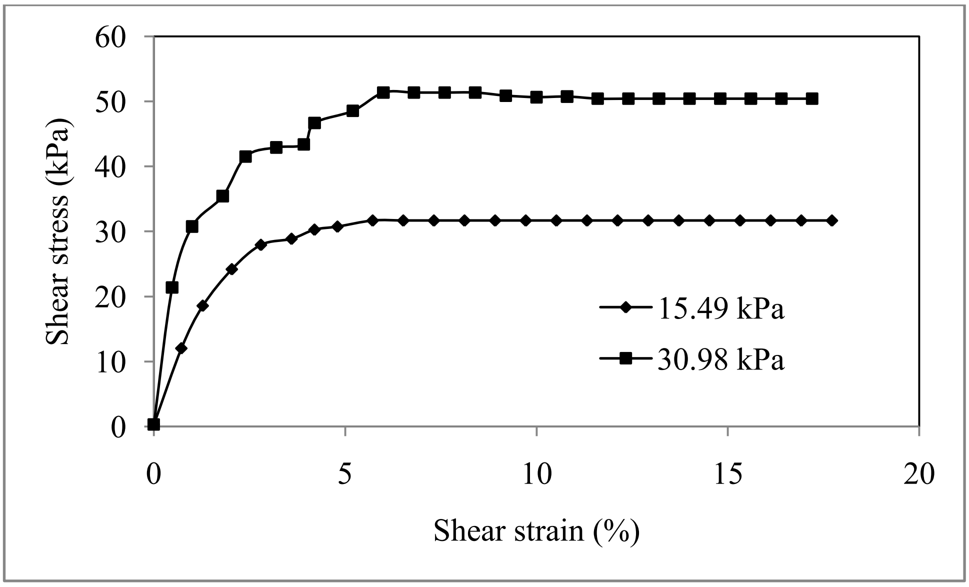
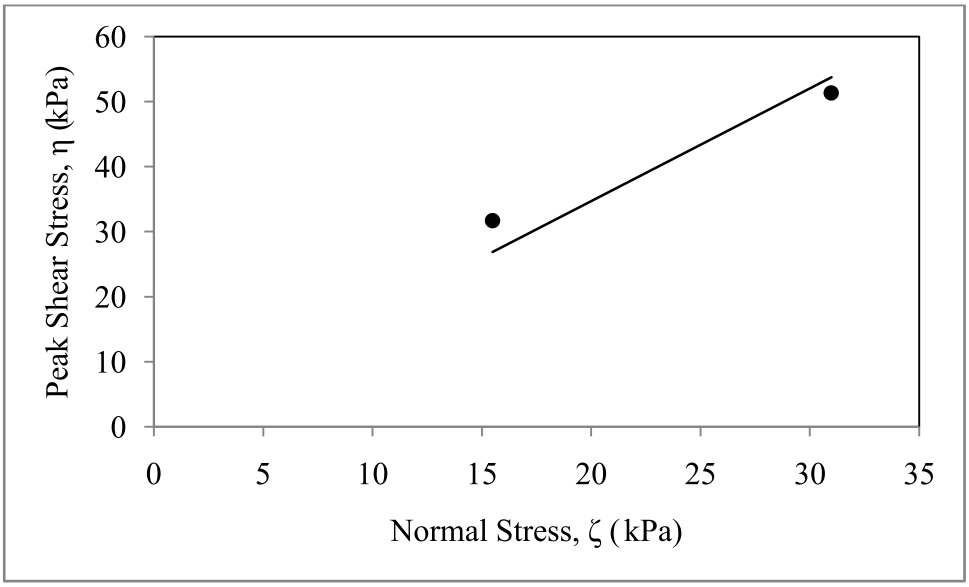


Figure A-1: Shear stress vs shear curve for coarse grained bare soil



FigureA-2: Shear stress vs normal stress curve for coarse grained bare soil

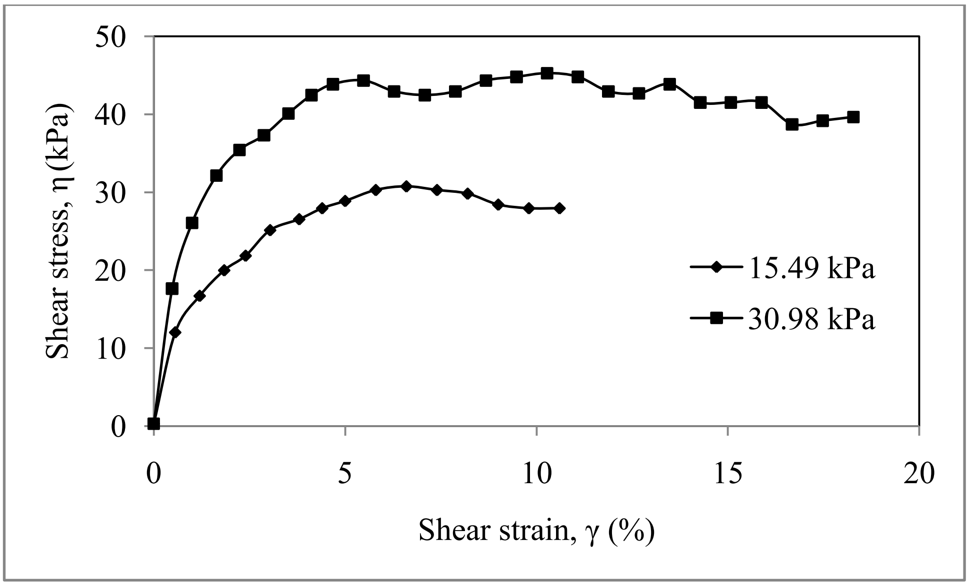


Figure A-3: Shear stress vs shear strain curve for coarse grained rooted soil

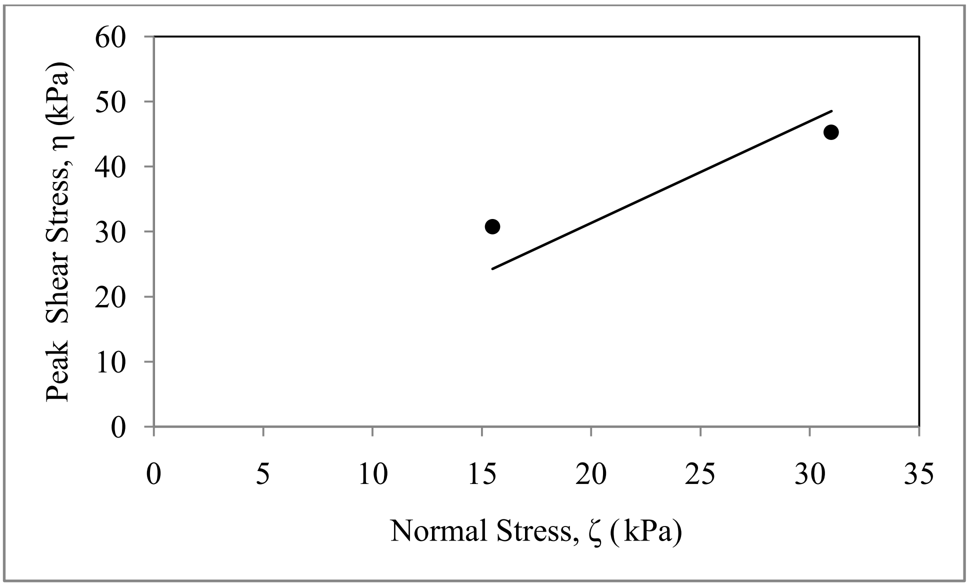


Figure A-4: Shear stress vs normal stress curve for coarse grained rooted soil

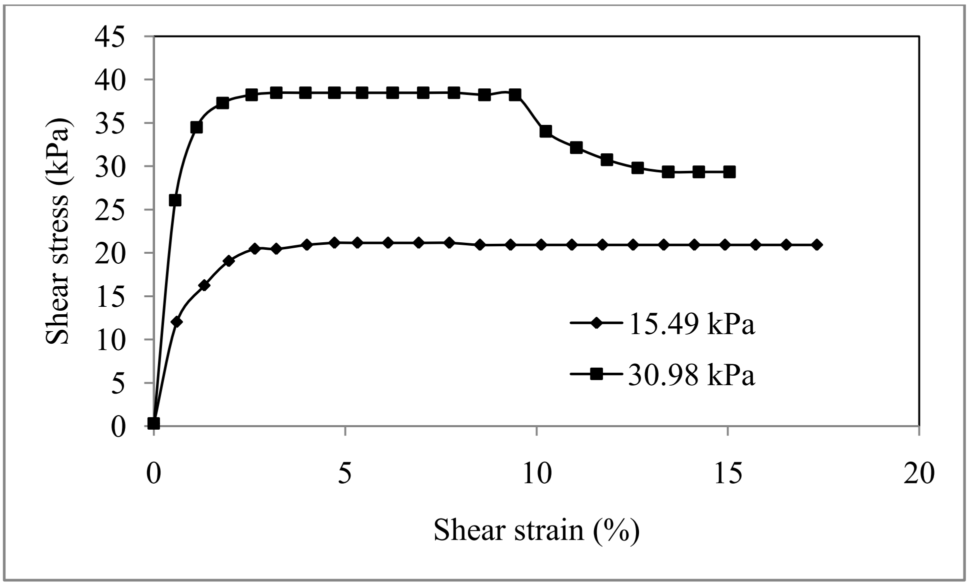


Figure A-5: Shear stress vs shear strain curve for medium grained bare soil

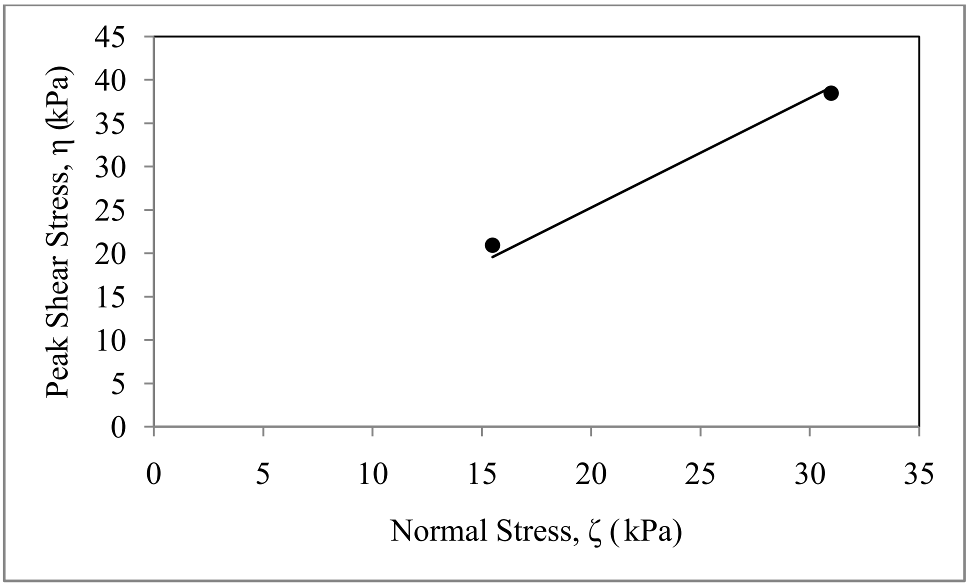


Figure A-6: Shear stress vs normal stress curve for medium grained bare soil

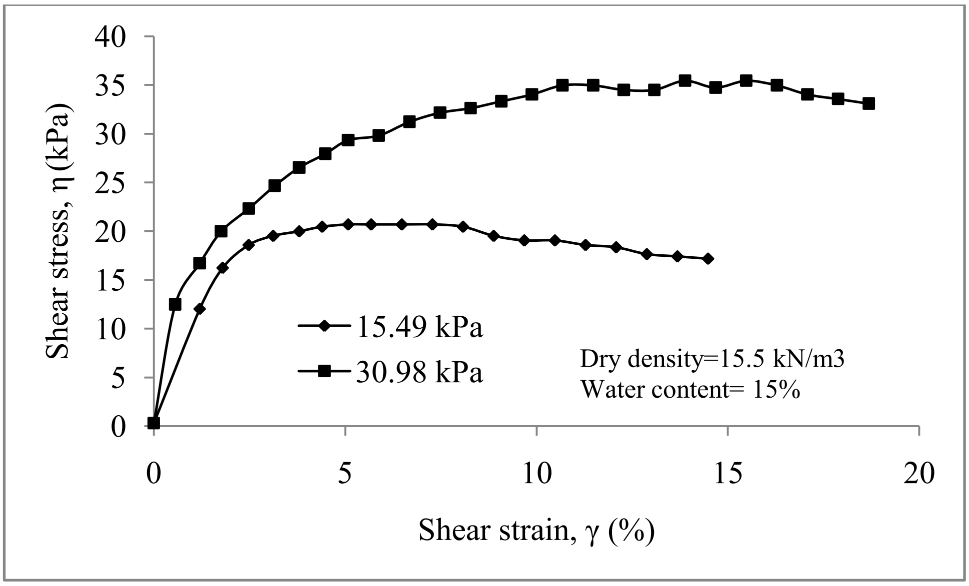


Figure A-7: Shear stress vs shear strain curve for medium grained rooted soil

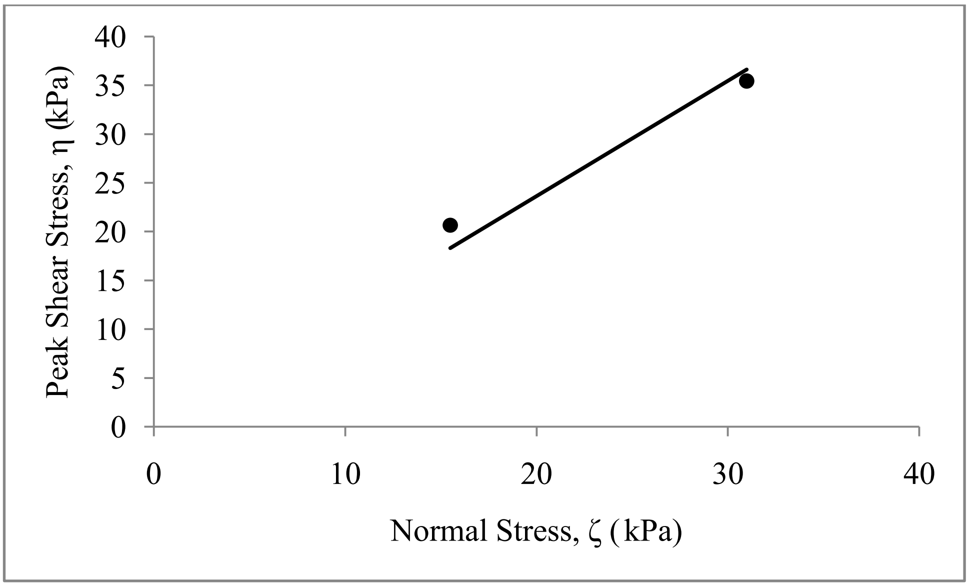


Figure A-8: Shear stress vs normal stress curve for medium grained rooted soil

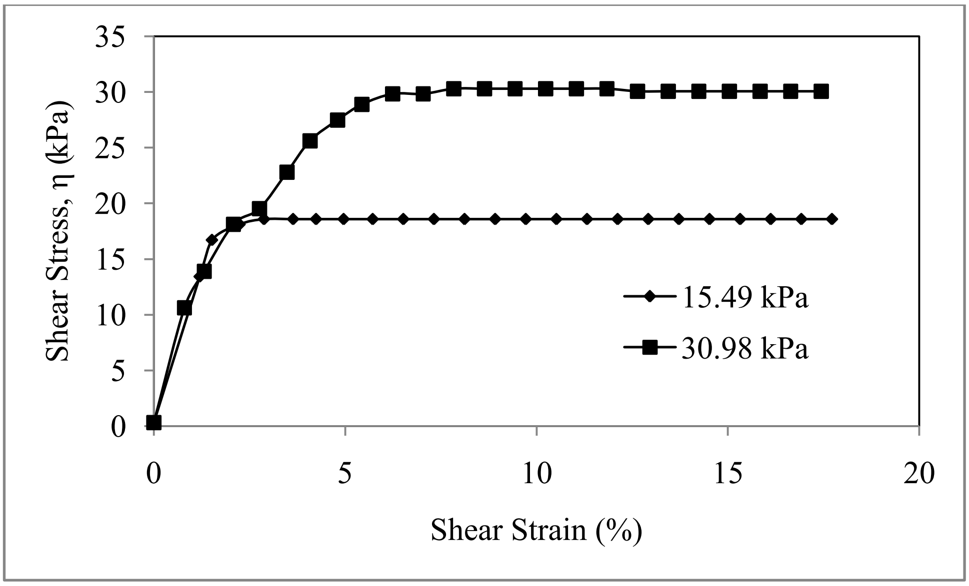


Figure A-9: Shear stress vs shear strain curve for fine grained bare soil

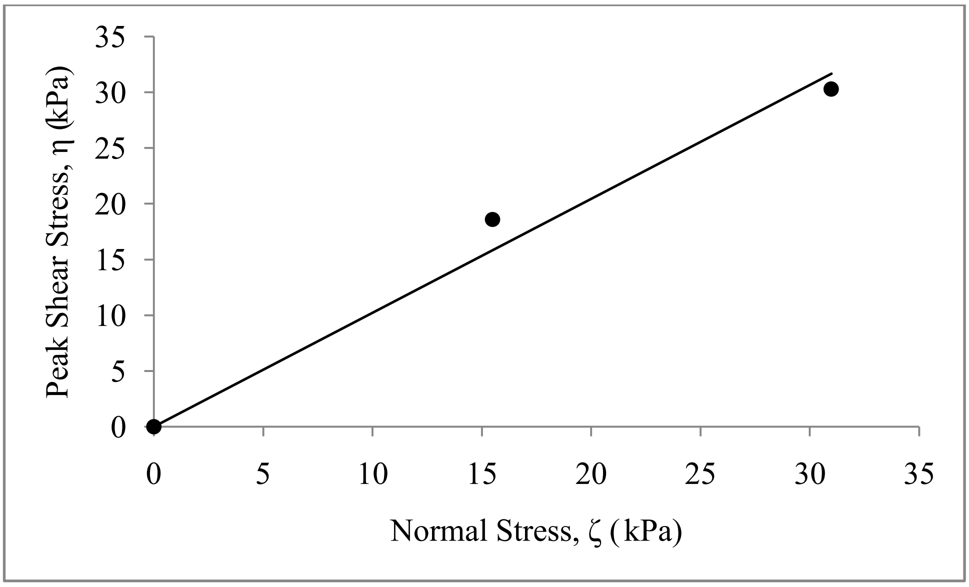


Figure A-10: Shear stress vs normal stress curve for fine grained bare soil

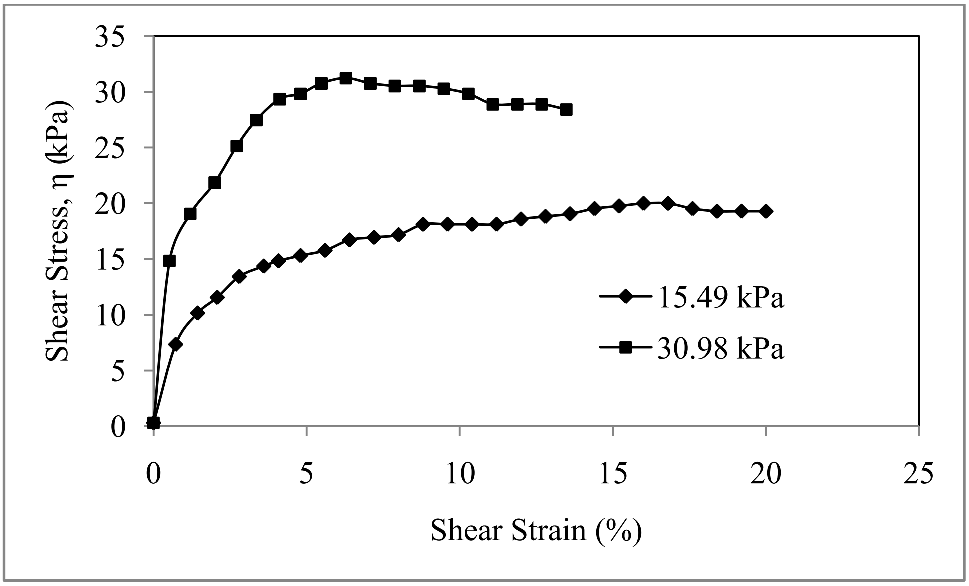
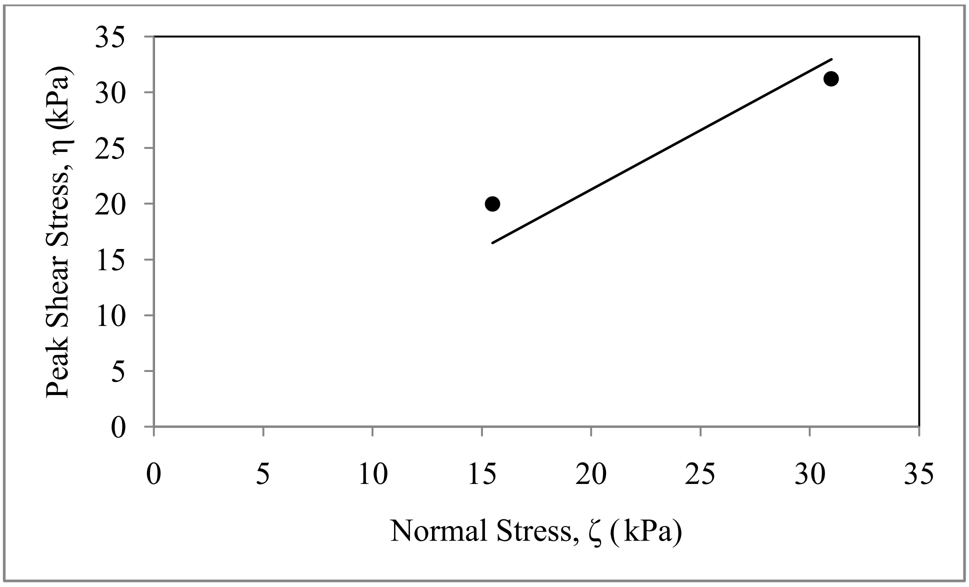


Figure A-11: Shear stress vs shear strain curve for fine grained rooted soil



FigureA-12: Shear stress vs normal stress curve for fine grained rooted soil

Direct shear test results on reconstituted soil sample at predetermined root arrangement

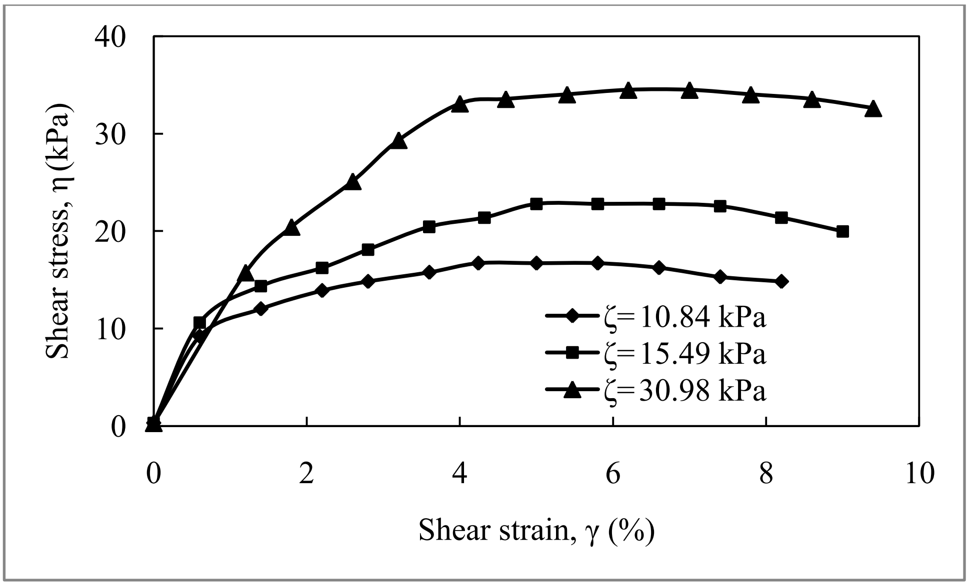


Figure A-13: Shear stress vs shear strain curve for bare sand

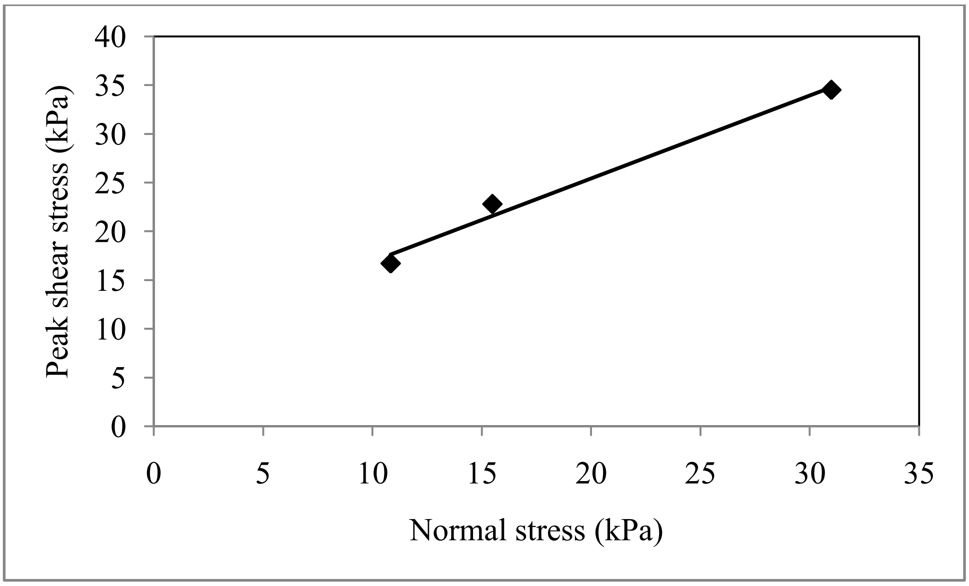


Figure A-14: Shear stress vs normal stress curve for bare sand

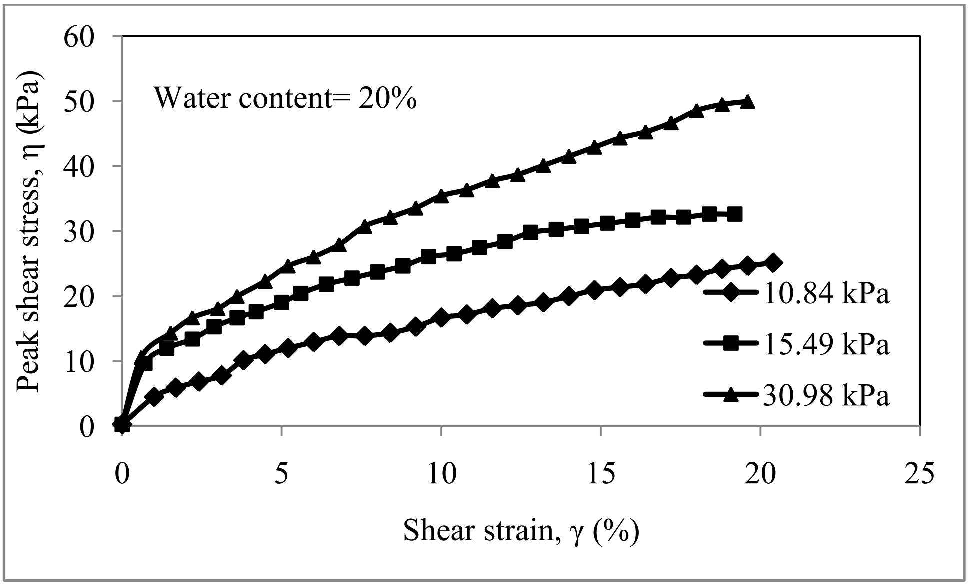


Figure A-15: Shear stress vs shear strain curve for rooted sand

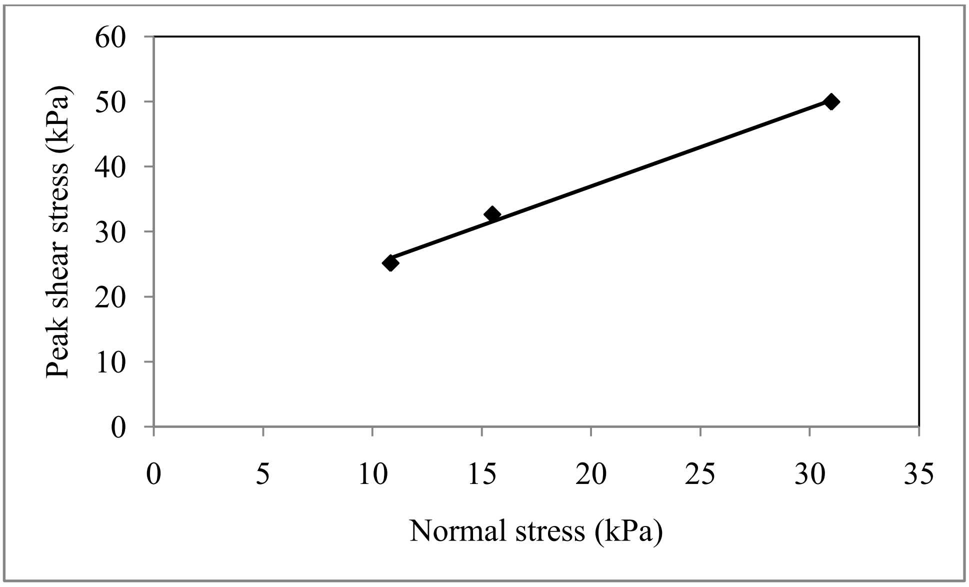


Figure A-16: Shear stress vs normal stress curve for rooted sand

Direct shear test results on undisturbed soil sample

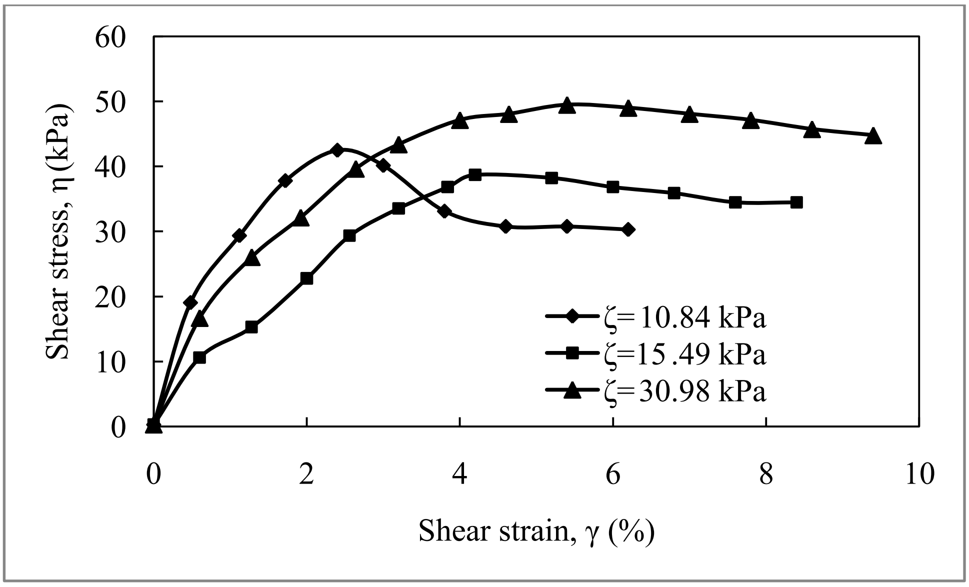


Figure A-17: Shear stress vs shear strain curve for bare clay

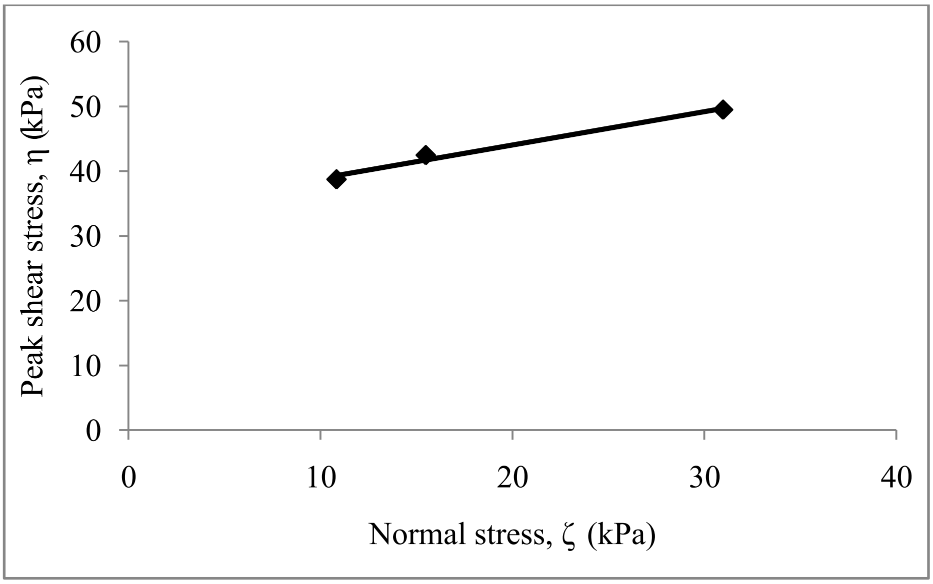


Figure A-18: Shear stress vs normal curve for bare clay

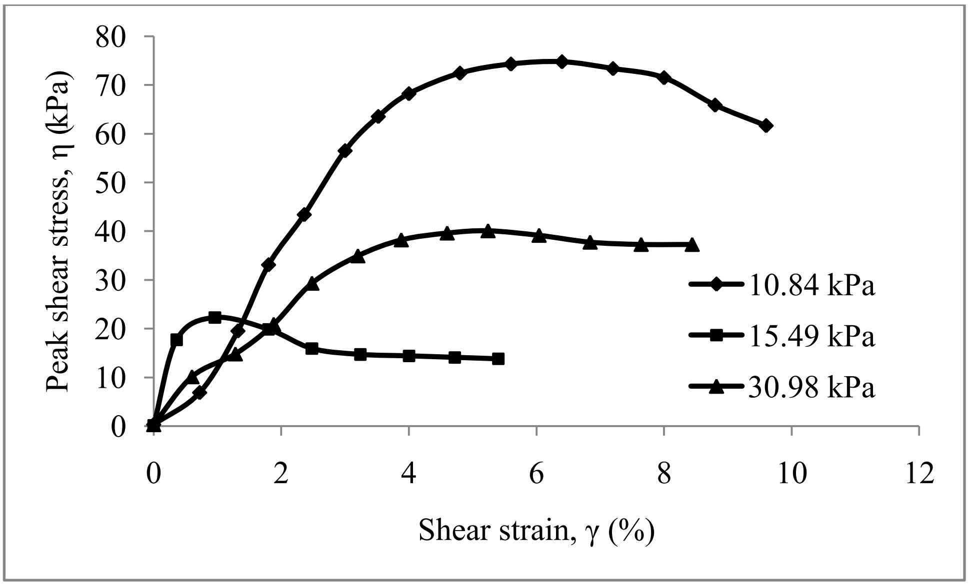


Figure A-19: Shear stress vs shear strain curve for rooted clay

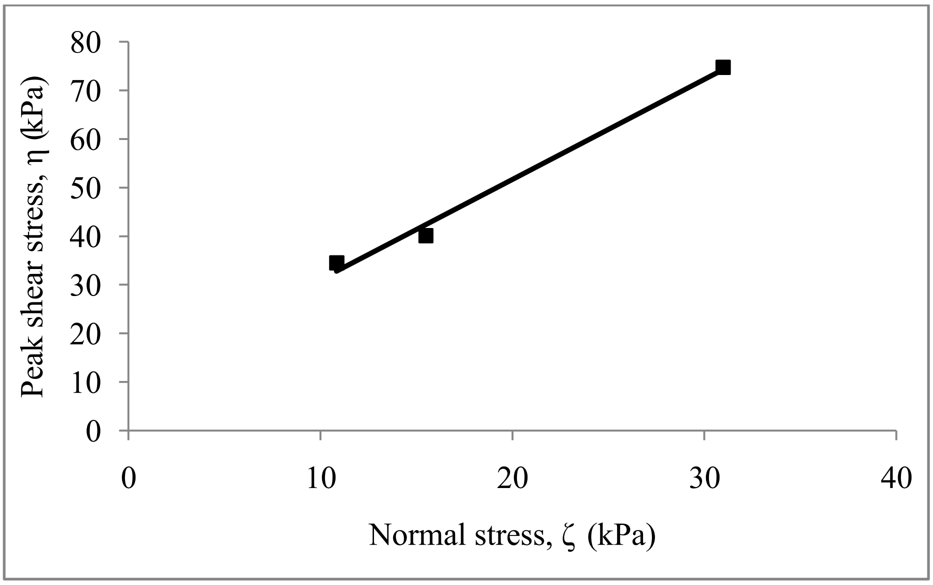


Figure A-20: Shear stress vs normal stress curve for rooted clay

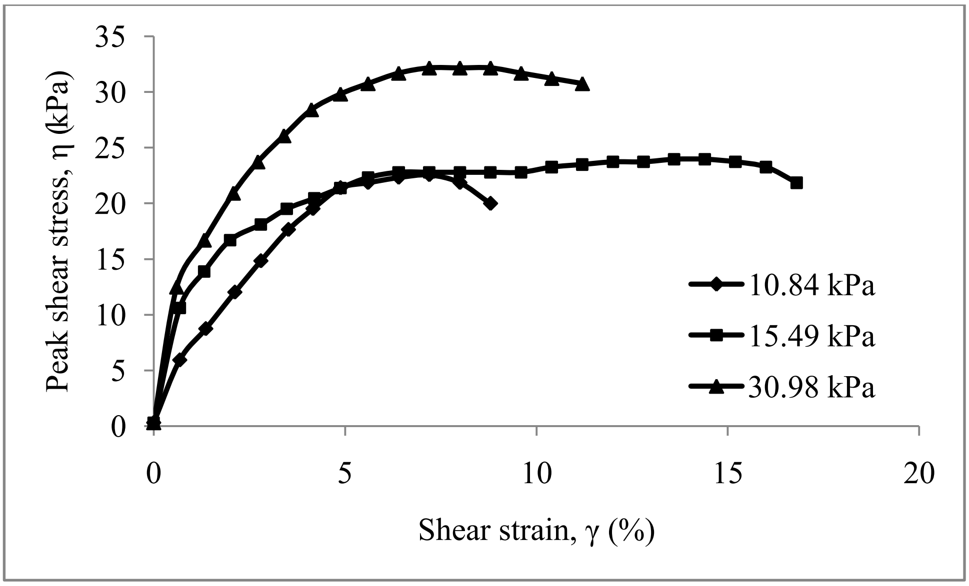


Figure A-21: Shear stress vs shear strain curve for bare sand

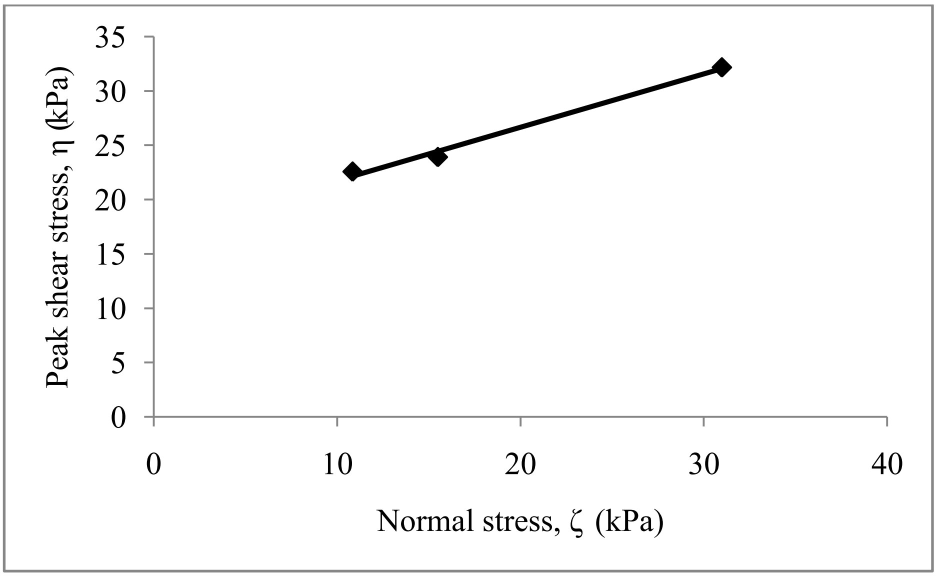


Figure A-22: Shear stress vs normal stress curve for bare sand

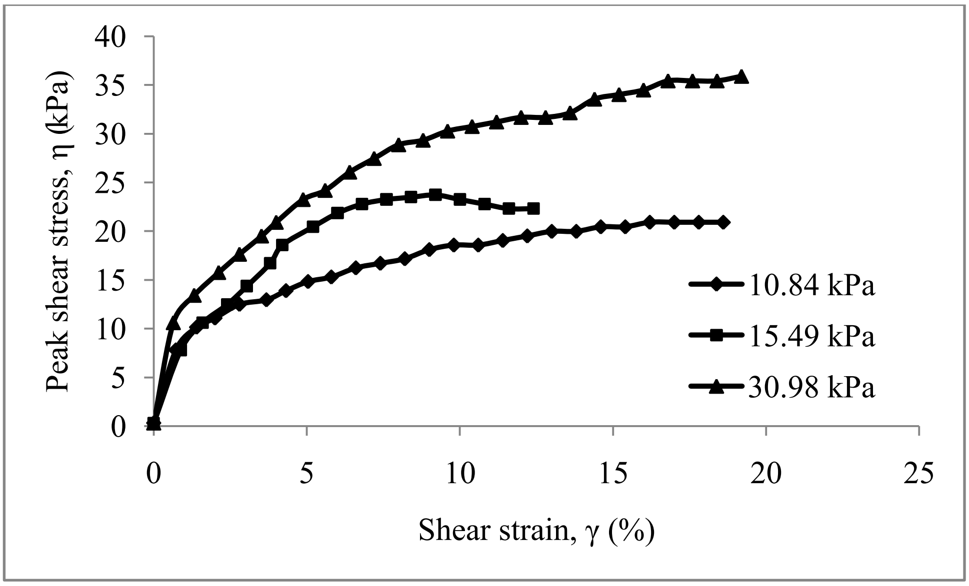


Figure A-23: Shear stress vs shear strain curve for rooted sand

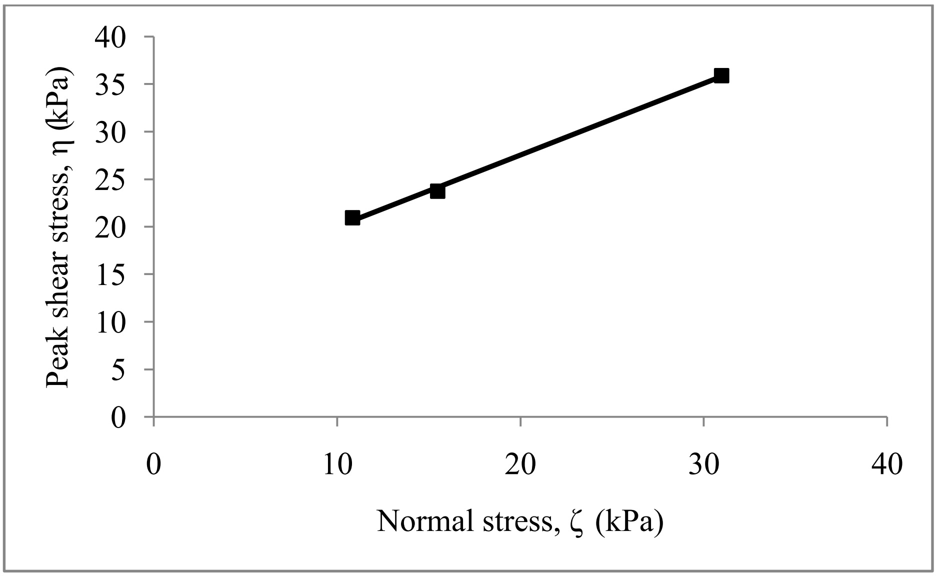


Figure A-24: Shear stress vs normal stress curve for rooted sand

Unconfined compression test results

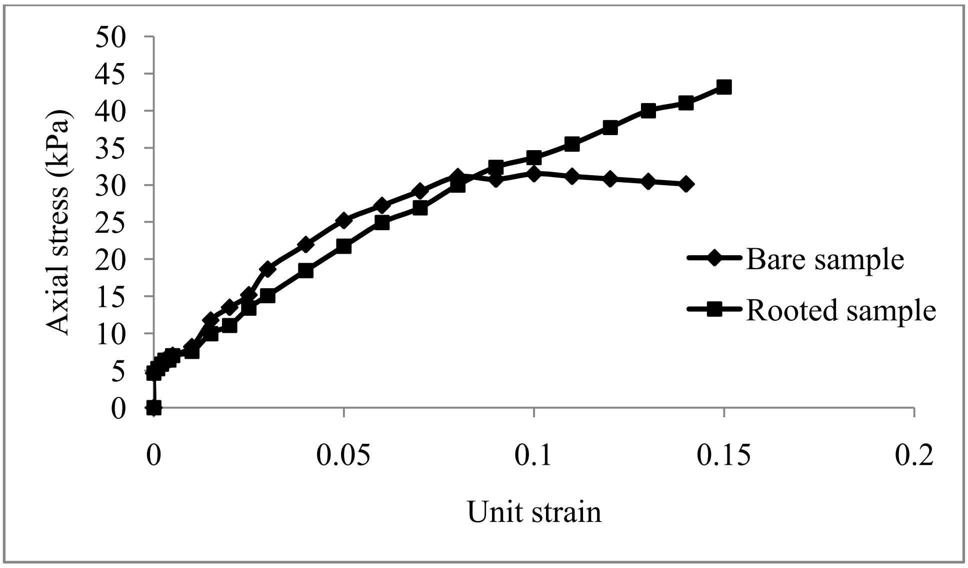


Figure A-25: Axial stress vs unit strain curve

Triaxial test results

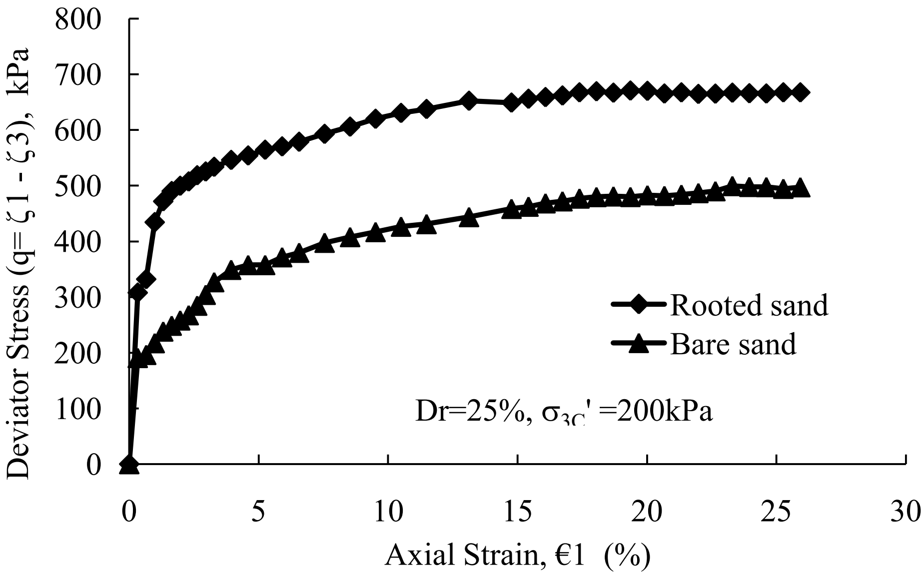


Figure A-26: Deviator stress vs axial strain curve

APPENDIX B

IN-SITU TEST RESULTS

Table B-1: In-situ shear test data for bare sample

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
4	0.004	0.1016	0.16	6	0.016	0.20
12	0.012	0.3048	0.1524	8	0.134	1.68
21	0.021	0.5334	0.2667	10	0.252	3.15
48	0.048	1.2192	0.6096	12	0.37	4.63
88	0.088	2.2352	1.1176	14	0.488	6.10
145	0.145	3.683	1.8415	16	0.606	7.58
245	0.245	6.223	3.1115	18	0.724	9.05
420	0.42	10.668	5.334	20	0.842	10.53
670	0.67	17.018	8.509	22	0.96	12.00
1020	1.02	25.908	12.954	24	1.078	13.48
1240	1.24	31.496	15.748	26	1.196	14.95

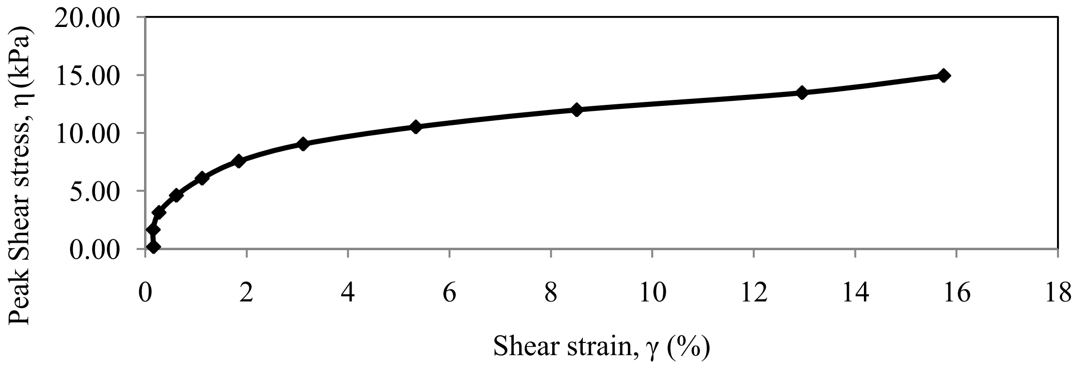


Figure B-1: Shear stress vs shear strain curve for bare sample

Table B-2: In-situ shear test data for rooted sample 1

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	Shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
5	0.005	0.1270	0.2	6	0.016	0.20
6	0.006	0.1524	0.0762	8	0.134	1.68
15	0.015	0.3810	0.1905	10	0.252	3.15
28	0.028	0.7112	0.3556	12	0.37	4.63
45	0.045	1.1430	0.5715	14	0.488	6.10
80	0.080	2.0320	1.016	16	0.606	7.58
190	0.190	4.8260	2.413	18	0.724	9.05
225	0.225	5.7150	2.8575	20	0.842	10.53
350	0.350	8.8900	4.445	22	0.96	12.00
470	0.470	11.938	5.969	24	1.078	13.48
680	0.680	17.272	8.636	26	1.196	14.95
920	0.920	23.368	11.684	28	1.314	16.43
1320	1.320	33.528	16.764	30	1.432	17.90

Table B-3: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 1

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5	2	3909.101
0.2	0.031416	114499.2	8	28776.85
0.3	0.070686	72707.66	2	10278.83
0.4	0.125664	52680.37	1	6620.026
0.5	0.19635	41030.76	3	24169.17
0.6	0.282744	33452.35	1	9458.45
			$\Sigma T_i*n_i*a_i$=	83212.42

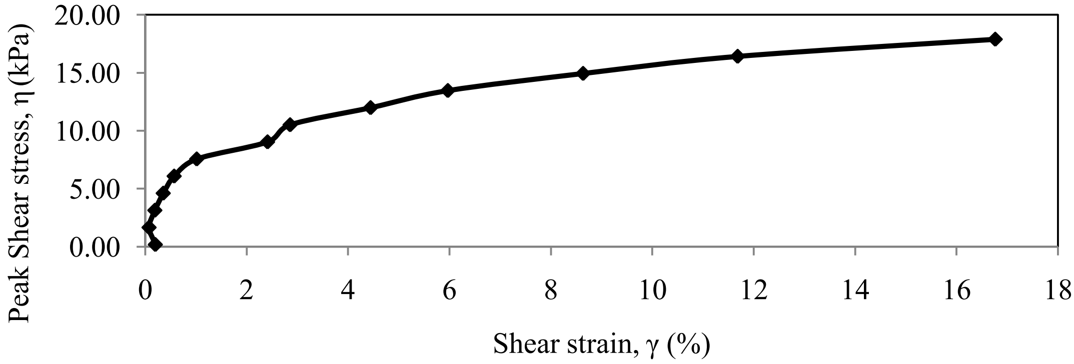


Figure B-2: Shear stress vs shear strain curve for rooted sample 1

Table B-4: In-situ shear test data for rooted sample 2

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
0	0	0	0	6	0.016	0.20
2	0.002	0.0508	0.0254	8	0.134	1.68
6	0.006	0.1524	0.0762	10	0.252	3.15
10	0.01	0.254	0.127	12	0.37	4.63
14	0.014	0.3556	0.1778	14	0.488	6.10
15	0.015	0.381	0.1905	16	0.606	7.58
18	0.018	0.4572	0.2286	18	0.724	9.05
35	0.035	0.889	0.4445	20	0.842	10.53
60	0.06	1.524	0.762	22	0.96	12.00
90	0.09	2.286	1.143	24	1.078	13.48
190	0.19	4.826	2.413	26	1.196	14.95
450	0.45	11.43	5.715	28	1.314	16.43
740	0.74	18.796	9.398	30	1.432	17.90
1240	1.24	31.496	15.748	32	1.55	19.38

Table B-5: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 2

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2	3	10791.32
0.3	0.070686	72707.66	2	10278.83
0.4	0.125664	52680.37	3	19860.08
0.5	0.19635	41030.76	3	24169.17
0.6	0.282744	33452.35		0
0.7	0.384846	28147.91		0
0.8	0.502656	24237.91	1	12183.33
0.9	0.636174	21242.44	1	13513.89
1	0.7854	18878		0
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	90796.61

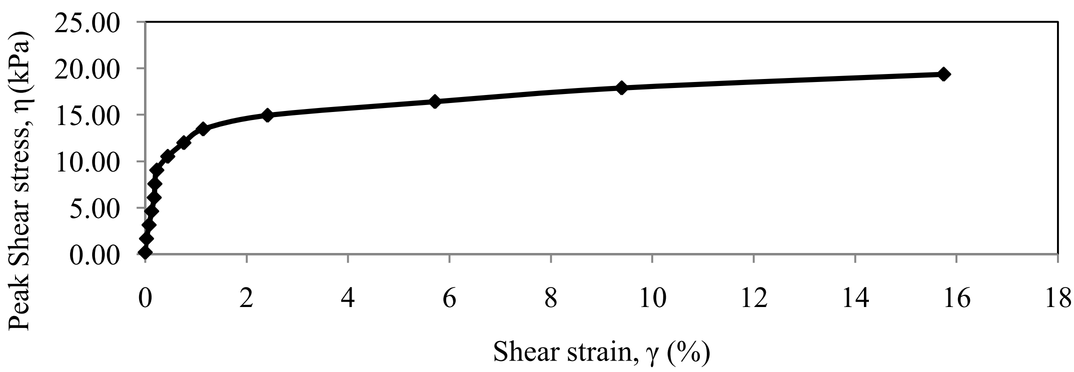


Figure B-3: Shear stress vs shear strain curve for rooted sample 2

Table B-6: In-situ shear test data for rooted sample 3

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
3	0.003	0.0762	0.12	6	0.016	0.20
4	0.004	0.1016	0.0508	8	0.134	1.68
7	0.007	0.1778	0.0889	10	0.252	3.15
10	0.01	0.254	0.127	12	0.37	4.63
12	0.012	0.3048	0.1524	14	0.488	6.10
18	0.018	0.4572	0.2286	16	0.606	7.58
25	0.025	0.635	0.3175	18	0.724	9.05
35	0.035	0.889	0.4445	20	0.842	10.53
43	0.043	1.0922	0.5461	22	0.96	12.00
52	0.052	1.3208	0.6604	24	1.078	13.48
64	0.064	1.6256	0.8128	26	1.196	14.95
75	0.075	1.905	0.9525	28	1.314	16.43
90	0.09	2.286	1.143	30	1.432	17.90
106	0.106	2.6924	1.3462	32	1.55	19.38
125	0.125	3.175	1.5875	34	1.668	20.85
146	0.146	3.7084	1.8542	36	1.786	22.33
180	0.18	4.572	2.286	38	1.904	23.80
200	0.2	5.08	2.54	40	2.022	25.28
240	0.24	6.096	3.048	42	2.14	26.75
430	0.43	10.922	5.461	44	2.258	28.23
1200	1.2	30.48	15.24	44	2.258	28.23

Table B-7: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 3

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2		0
0.3	0.070686	72707.66	6	30836.48
0.4	0.125664	52680.37	1	6620.026
0.5	0.19635	41030.76	2	16112.78
0.6	0.282744	33452.35	2	18916.9
0.7	0.384846	28147.91	3	32497.83
0.8	0.502656	24237.91	1	12183.33
0.9	0.636174	21242.44	3	40541.66
1	0.7854	18878	2	29653.56
1.1	0.950334	16966.65	1	16123.99
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	203486.6

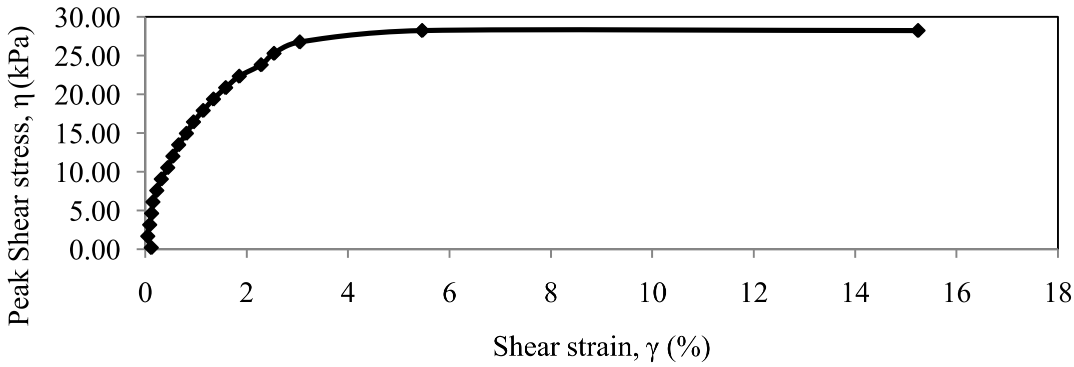


Figure B-4: Shear stress vs shear strain curve for rooted sample 3

Table B-8: In-situ shear test data for rooted sample 4

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
1	0.001	0.0254	0.04	6	0.016	0.20
2	0.002	0.0508	0.0254	8	0.134	1.68
4	0.004	0.1016	0.0508	10	0.252	3.15
6	0.006	0.1524	0.0762	12	0.37	4.63
9	0.009	0.2286	0.1143	14	0.488	6.10
11	0.011	0.2794	0.1397	16	0.606	7.58
17	0.017	0.4318	0.2159	18	0.724	9.05
22	0.022	0.5588	0.2794	20	0.842	10.53
30	0.03	0.762	0.381	22	0.96	12.00
44	0.044	1.1176	0.5588	24	1.078	13.48
55	0.055	1.397	0.6985	26	1.196	14.95
68	0.068	1.7272	0.8636	28	1.314	16.43
90	0.09	2.286	1.143	30	1.432	17.90
140	0.14	3.556	1.778	32	1.55	19.38
190	0.19	4.826	2.413	34	1.668	20.85
230	0.23	5.842	2.921	36	1.786	22.33
590	0.59	14.986	7.493	38	1.904	23.80
1150	1.15	29.21	14.605	38	1.904	23.80

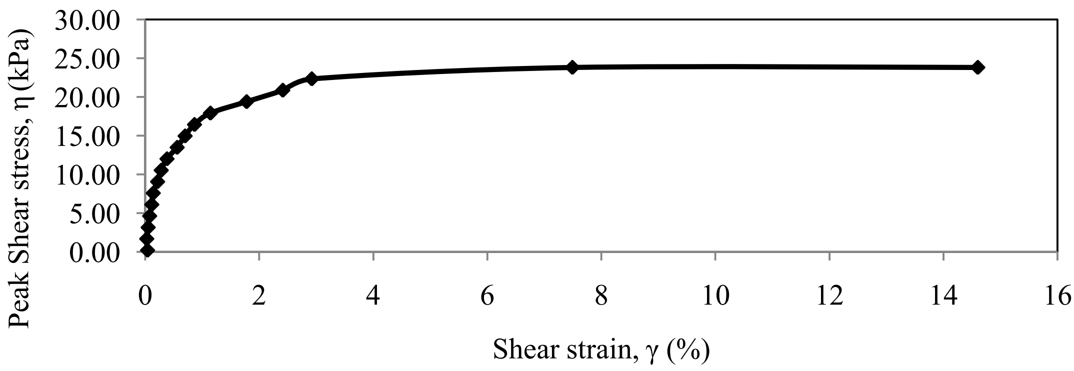


Figure B-5: Shear stress vs shear strain curve for rooted sample 4

Table B-9: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 4

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2	3	10791.32
0.3	0.070686	72707.66	4	20557.66
0.4	0.125664	52680.37	1	6620.026
0.5	0.19635	41030.76	1	8056.39
0.6	0.282744	33452.35	4	37833.8
0.7	0.384846	28147.91	1	10832.61
0.8	0.502656	24237.91		0
0.9	0.636174	21242.44		0
1	0.7854	18878		0
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	94691.8

Table B-10: In-situ shear test data for rooted sample 5

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
1	0.001	0.0254	0.04	6	0.016	0.20
2	0.002	0.0508	0.0254	8	0.134	1.68
3	0.003	0.0762	0.0381	10	0.252	3.15
5	0.005	0.127	0.0635	12	0.37	4.63
9	0.009	0.2286	0.1143	14	0.488	6.10
10	0.01	0.254	0.127	16	0.606	7.58
14	0.014	0.3556	0.1778	18	0.724	9.05
17	0.017	0.4318	0.2159	20	0.842	10.53
22	0.022	0.5588	0.2794	22	0.96	12.00
29	0.029	0.7366	0.3683	24	1.078	13.48
38	0.038	0.9652	0.4826	26	1.196	14.95

45	0.045	1.143	0.5715	28	1.314	16.43
52	0.052	1.3208	0.6604	30	1.432	17.90
61	0.061	1.5494	0.7747	32	1.55	19.38
73	0.073	1.8542	0.9271	34	1.668	20.85
95	0.095	2.413	1.2065	36	1.786	22.33
130	0.13	3.302	1.651	38	1.904	23.80
190	0.19	4.826	2.413	40	2.022	25.28
320	0.32	8.128	4.064	42	2.14	26.75
540	0.54	13.716	6.858	44	2.258	28.23
990	0.99	25.146	12.573	46	2.376	29.70
1250	1.25	31.75	15.875	46	2.376	29.70

Table B-11: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 5

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	T_i*a_i*n_i
0.1	0.007854	248860.5	2	3909.101
0.2	0.031416	114499.2	5	17985.53
0.3	0.070686	72707.66	3	15418.24
0.4	0.125664	52680.37	5	33100.13
0.5	0.19635	41030.76	1	8056.39
0.6	0.282744	33452.35		0
0.7	0.384846	28147.91	4	43330.44
0.8	0.502656	24237.91	3	36550
0.9	0.636174	21242.44	2	27027.77
1	0.7854	18878	4	59307.12
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	244684.7

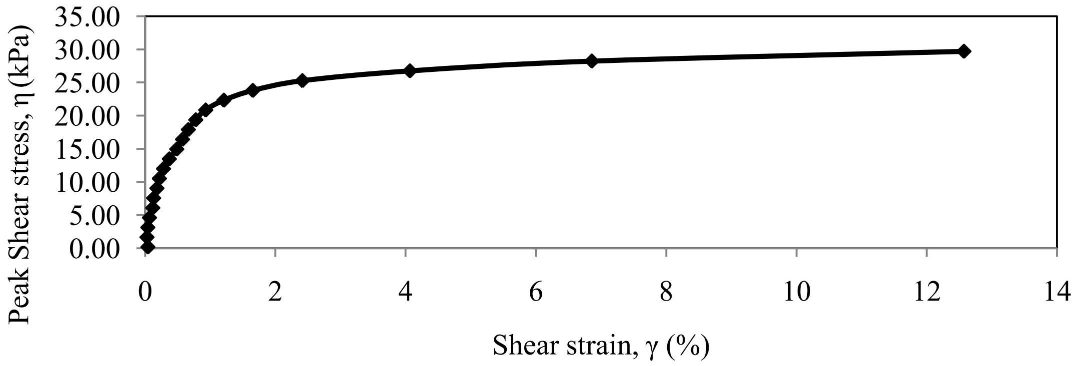


Figure B-6: Shear stress vs shear strain curve for rooted sample 5

Table B-12: In-situ shear test data for rooted sample 6

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
2	0.002	0.0508	0.08	6	0.016	0.20
4	0.004	0.1016	0.0508	8	0.134	1.68
6	0.006	0.1524	0.0762	10	0.252	3.15
10	0.01	0.254	0.127	12	0.37	4.63
14	0.014	0.3556	0.1778	14	0.488	6.10
19	0.019	0.4826	0.2413	16	0.606	7.58
25	0.025	0.635	0.3175	18	0.724	9.05
35	0.035	0.889	0.4445	20	0.842	10.53
44	0.044	1.1176	0.5588	22	0.96	12.00
54	0.054	1.3716	0.6858	24	1.078	13.48
66	0.066	1.6764	0.8382	26	1.196	14.95
80	0.08	2.032	1.016	28	1.314	16.43
100	0.1	2.54	1.27	30	1.432	17.90
140	0.14	3.556	1.778	32	1.55	19.38
170	0.17	4.318	2.159	34	1.668	20.85
210	0.21	5.334	2.667	36	1.786	22.33
310	0.31	7.874	3.937	38	1.904	23.80
420	0.42	10.668	5.334	40	2.022	25.28
1030	1.03	26.162	13.081	42	2.14	26.75
1230	1.23	31.242	15.621	42	2.14	26.75

Table B-13: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 6

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2		0
0.3	0.070686	72707.66	3	15418.24
0.4	0.125664	52680.37	2	13240.05
0.5	0.19635	41030.76	3	24169.17
0.6	0.282744	33452.35	5	47292.25
0.7	0.384846	28147.91	4	43330.44
0.8	0.502656	24237.91		0
0.9	0.636174	21242.44	2	27027.77
1	0.7854	18878		0
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	170477.9

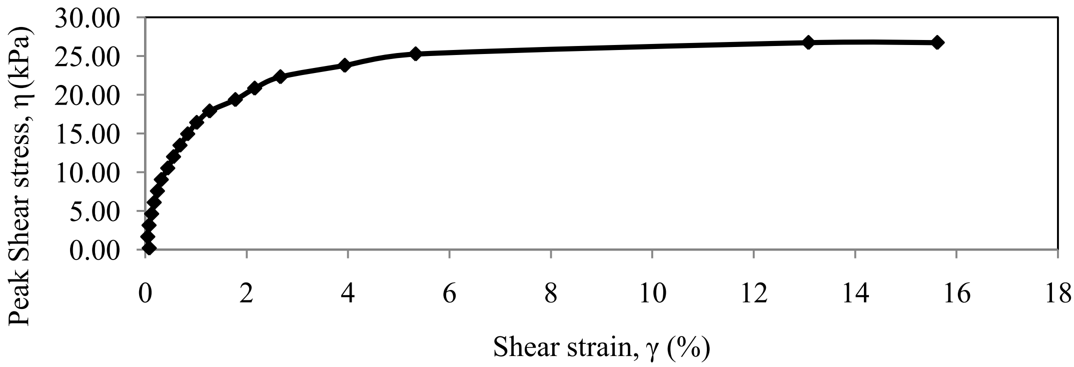


Figure B-7: Shear stress vs shear strain curve for rooted sample 6

Table B-14: In-situ shear test data for rooted sample 7

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
3	0.003	0.0762	0.12	6	0.016	0.20
6	0.006	0.1524	0.0762	8	0.134	1.68
10	0.01	0.254	0.127	10	0.252	3.15
15	0.015	0.381	0.1905	12	0.37	4.63
22	0.022	0.5588	0.2794	14	0.488	6.10
26	0.026	0.6604	0.3302	16	0.606	7.58
65	0.065	1.651	0.8255	18	0.724	9.05
120	0.12	3.048	1.524	20	0.842	10.53
260	0.26	6.604	3.302	22	0.96	12.00
320	0.32	8.128	4.064	24	1.078	13.48
440	0.44	11.176	5.588	26	1.196	14.95
560	0.56	14.224	7.112	28	1.314	16.43
780	0.78	19.812	9.906	30	1.432	17.90
940	0.94	23.876	11.938	32	1.55	19.38
1020	1.02	25.908	12.954	34	1.668	20.85
1340	1.34	34.036	17.018	34	1.668	20.85

Table B-15: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 7

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2		0
0.3	0.070686	72707.66	3	15418.24
0.4	0.125664	52680.37	1	6620.026
0.5	0.19635	41030.76	3	24169.17
0.6	0.282744	33452.35	2	18916.9
0.7	0.384846	28147.91	1	10832.61

0.8	0.502656	24237.91		0
0.9	0.636174	21242.44	2	27027.77
1	0.7854	18878		0
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i * n_i * a_i =$	102984.7

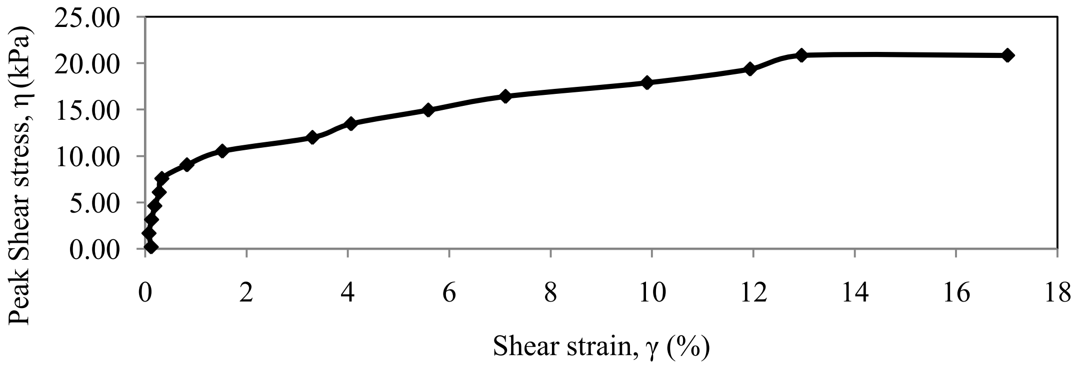


Figure B-8: Shear stress vs shear strain curve for rooted sample 7

Table B-16: In-situ shear test data for rooted sample 8

Shear Displacement Dial (divn)	Shear Displacement (inch)	Shear Displacement (mm)	shear strain (%)	Pressure gauge reading (psi)	Actual Load (kN)	Shear Stress (kPa)
2	0.002	0.0508	0.08	6	0.016	0.20
4	0.004	0.1016	0.0508	8	0.134	1.68
6	0.006	0.1524	0.0762	10	0.252	3.15
8	0.008	0.2032	0.1016	12	0.37	4.63
11	0.011	0.2794	0.1397	14	0.488	6.10
13	0.013	0.3302	0.1651	16	0.606	7.58
19	0.019	0.4826	0.2413	18	0.724	9.05
25	0.025	0.635	0.3175	20	0.842	10.53
40	0.04	1.016	0.508	22	0.96	12.00
50	0.05	1.27	0.635	24	1.078	13.48
65	0.065	1.651	0.8255	26	1.196	14.95

78	0.078	1.9812	0.9906	28	1.314	16.43
190	0.19	4.826	2.413	30	1.432	17.90
240	0.24	6.096	3.048	32	1.55	19.38
390	0.39	9.906	4.953	34	1.668	20.85
430	0.43	10.922	5.461	36	1.786	22.33
1290	1.29	32.766	16.383	36	1.786	22.33

Table B-17: Calculation of average mobilized tensile force in roots per unit area of soil (t_R) for rooted sample 8

Root Diameter (mm)	Mean cross sectional area of root, a_i (mm^2)	Root tensile strength, T_i (kPa)	Number of roots, n_i	$T_i*a_i*n_i$
0.1	0.007854	248860.5		0
0.2	0.031416	114499.2	3	10791.32
0.3	0.070686	72707.66	4	20557.66
0.4	0.125664	52680.37	1	6620.026
0.5	0.19635	41030.76	1	8056.39
0.6	0.282744	33452.35	2	18916.9
0.7	0.384846	28147.91	1	10832.61
0.8	0.502656	24237.91		0
0.9	0.636174	21242.44		0
1	0.7854	18878		0
1.1	0.950334	16966.65		0
1.2	1.130976	15391.22		0
1.3	1.327326	14071.47		0
			$\Sigma T_i*n_i*a_i$=	75774.9

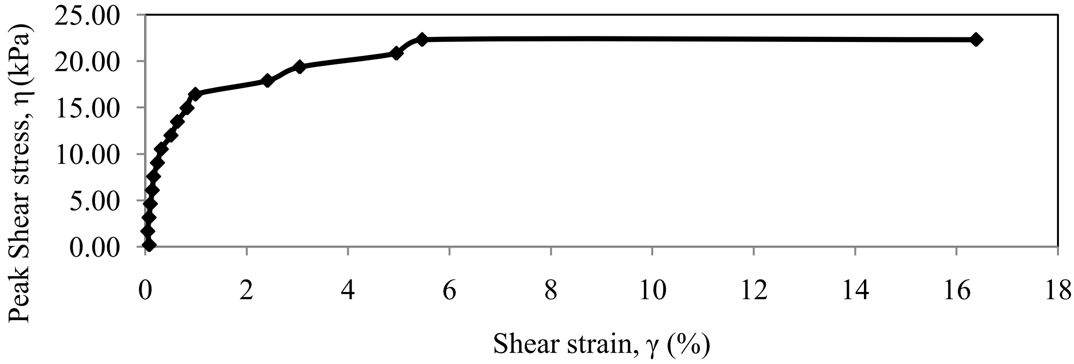


Figure B-9: Shear stress vs shear strain curve for rooted sample 8