EROSION CONTROL AND SLOPE STABILIZATION OF EMBANKMENTS USING VETIVER SYSTEM

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TO

MY PARENTS

The thesis titled **"Erosion Control and Slope Stabilization of Embankments using Vetiver System",** submitted by Shamima Nasrin, Roll No. 0409042245F, Session April 2009 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering on 30th September, 2013.

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DECLARATION

It is thereby declared that except for the contents where specific reference have been made to the work of others, the study contained in this thesis are the result of investigation carried out by the author under the supervision of Dr. Mohammad Shariful Islam, Associate Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology.

No part of this thesis has been submitted to any other university or other educational establishment for a degree, diploma or other qualification (except for publication).

Shamima Nasrin

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ABSTRACT

Embankment failures happen continuously throughout Bangladesh. Traditional practices for protection of embankment are to use cement concrete blocks, stone or wood revetments, geobags, geotextile and plantation etc. But these are expensive and sometimes not so effective for their design life. On the other hand, vetiver grass (*Vetiveria zizanioides*) is being used for slope protection in many countries efficiently. The main objective of this research is to determine the strength of vetiver grass rooted soil in protecting embankment slope's failure that happens mainly due to rain-cut erosion.

In-situ shear strength of vetiver rooted soil matrix and bared soil was determined for block samples. Block samples ($29 \times 15 \times 19$ cm^3) were sheared under different normal loads at the field to determine the in-situ shear strength. It is found that the shear strength, τ_{max} of vetiver rooted soil matrix is 1.8 times higher than that of the bared soil. Horizontal deformation at failure, δ_{hf} of vetiver rooted soil is about 5.5 times higher than that of bared soil.

Direct shear tests were conducted on reconstituted soil samples for varying root contents (0% to 12% of dry weight of soil having root length of 2.54 cm under different normal stresses (i.e., 10.96 to 19.98 kPa). Test results show that τ_{max} of vetiver rooted soil are about 1.4 times higher than that of bared soil depending on the percentage of root content. δ_{hf} of vetiver rooted soil increases about 2.2 times in comparison to that of bared soils with the increase of root content from 0.5% to 12%. Strength varies with the increase of root content. However, it is found that shear strength (τ_{max}) increases with the increase of root content up to 9% rooted soil. However, the strength decreases at higher root contents. On the contrary, δ_{hf} increases with the increase of root content.

Direct shear tests were also conducted on laboratory reconstituted soil samples prepared with different root lengths varying from 1.25 cm to 5.00 cm under different normal stresses (i.e., 10.96 to 19.98 kPa) having 6% root content. Test results show that the shear strength, τ_{max} of vetiver rooted soil is about 1.4 times higher than that of bared soil. Similarly, δ_{hf} of vetiver rooted soil increases 3.0 times in comparison to that of bared soils with the increase of root content from 1.25 cm to 5.00 cm.

To observe the growth rate in submerged condition, vetiver grass was planted in both silty sand and silty clay soil. It is found that vetiver can survive under submerged condition for 3 months. The shoot of vetiver grass planted in Pubail soil (silty clay) and Keraniganj soil (silty sand) grew up to 109 cm and 114 cm, respectively in 3 months. Root length grew 28 cm in Keranigang soil and 13 cm in Pubail soil during this period. In field condition, the shoot of vetiver grass grew up to 175 cm in 13 months while the root grew 25 cm during the same period. It is clear that growth rate of vetiver grass in silty sand is higher than that of in silty clay soil. It is found that vetiver can survive under pH levels varying from 4.6 to 7.7 and Electrical Conductivity (EC) ranging from 0 to 15.9 ds/m.

Using the cohesion and angle of internal friction obtained in the study, the stability of embankment slopes were estimated using 'infinite slope method of slope stability analysis'. From the analyses, it is found that vetiver grass plantation is able to increase the factor of safety of embankment slope by 1.50 times.

From the erosion test, it is observed that erosion can be reduced by vetiver grass plantation. Vetiver grass reduces the erosion by 71%. So, it can be said that vetiver grass plantation can protect the embankment from rain-cut erosion and shallow depth slope failure.

Keyword: Slope stabilization, shear strength, rain-cut erosion, vetiver grass

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NOTATIONS

Symbol	Description
θ	Angle between roots and slip plane
ϕ	Angle of internal friction
c	Cohesion
γ_{dry}	Dry density
ϕ'	Effective angle of internal friction of the soil
c'	Effective soil cohesion
c'_R	Enhanced effective soil cohesion due to soil reinforcement by roots
K	Erodibility
FS	Factor of safety
$_f$	Failure shear strain
H	Height of slope
LL	Liquid limit
CL	Inorganic clays of low to medium plasticity
D_{50}	Mean grain size
w_n	Natural moisture content
σ_n	Normal stress
τ_{max}	Peak shear stress
PL	Plastic limit
PI	Plasticity index
γ	Shear strain

τ	Shear stress
SM	Silty sand
β	Slope angle
G_s	Specific gravity
W	Surcharge due to weight of vegetation
T	Tensile root force acting at the base of the slip plane (kN/m)
C_u	Uniformity coefficient
γ	Unit weight of soil
γ_w	Unit weight of water
h_w	Vertical height of ground water table above slip plane
h_v	Vertical height of groundwater table above the slip plane with the vegetation
z	Vertical height of soil above slip plane
D	Wind loading force parallel to the slope

Chapter One

INTRODUCTION

1.1 General

Bangladesh is situated in the low-lying Ganges Delta. Lands are exceedingly flat, low-lying, and subject to annual flooding. The coastal flooding twinned with the bursting of Bangladesh's river banks is common and severely affects the landscape and Bangladeshi society. Seventy five percent of Bangladesh is less than 10m above mean sea level and 80% is flood plain (Wikipedia), therefore rendering Bangladesh a nation very much at risk of further widespread damage despite its development.

Since 1960, 13,000 km of embankments have been constructed to safeguard against inundation, intrusion of saline water and devastation (Islam, 2000). Embankment a ridge built with earth or rock to contain flood water or to construct a road, railway, canal. Embankments vary in nature and function under a variety of situations. Designed to control or prevent flooding, flood control embankment is one of several types of embankments on the floodplains. A system of routine maintenance could not be established, mainly due to institutional shortcomings and the lack of an appropriate system of erosion control. Maintenance has been restricted to major repairs only when embankments were close to failure or had completely failed and caused serious losses. Soil thus eroded, including from other constructions, terraces and slopes and accumulated in water bodies (more than 2,700 million m^3/year) disrupting the transportation system, affecting productivity and deteriorating the environment.

Soil erosion physical removal of topsoil by various agents, including falling raindrops, water flowing over and through the soil profile, wind velocity and gravitational pull. Geological and accelerated erosion represent contrasting types of soil removal. Soil erosion is a naturally occurring process on all land. The agents of soil erosion are water and wind, each contributing a significant amount of soil loss each year. Soil erosion can be a slow process that continues relatively unnoticed or can occur at an alarming rate, causing serious loss of topsoil. Soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinisation and soil acidity problems are other serious soil degradation conditions that can accelerate the soil erosion process.

Water erosion is the most widespread form of degradation affecting 25% of agricultural land of Bangladesh. Various kinds of soil erosion such as sheet, rill and gully erosion, landslide, riverbank erosion and coastal erosion are occurring in Bangladesh. Accelerated soil erosion has been encountered in the hilly regions of the country, which occupy about 1.7 million hectares. In a study at the Ramgati station of the Bangladesh agricultural research institute (BARI), total soil loss of 2.0 to 4.7 ton/ha per year was observed.

An estimated soil loss is 4.2 tons/ha/yr and 7-120 tons/ha/yr on 30-40% and 40-80% slopes, respectively due to shifting cultivation. Besides soil loss, significant quantities of plant nutrients are also depleted from top layer causing tremendous soil degradation. In addition, the country is losing its forest area at the rate of about 3% annually due to deforestation. The deforested area is also becoming susceptible to severe water erosion, which is about 102 tons/ha/yr. In Bangladesh, bank erosion is caused due mainly to strong river current during the rainy season.

About 1.7 million hectares of floodplain areas are prone to riverbank erosion. Some areas of Bangladesh are also affected by wind erosion, particularly in the Rajshahi and Dinajpur regions during the dry months of the year. The soils eroded from the hills are deposited somewhere in the downstream. Burial of agricultural land by sandy over wash is a common feature in areas adjoining the active river channels and hill streams. The entire northern and eastern piedmont alluvium and the Chittagong hill tracts are adversely affected by the deposition of course materials brought down by runoff water (http://www.banglapedia.org/HT/S_0459.HTM).

Flooding normally occurs during the monsoon season from June to September during the monsoon. The convectional rainfall of the monsoon is added to by relief rainfall caused by the Himalayas. Melt-water from the Himalayas is also a significant input and flood every year.

To combat this disaster, erosion control is necessary for river bank, road embankment, hill slope and coastal embankments. For that technically suitable, cost-effective, people-oriented, sustainable and environmental friendly solutions are necessary.

1.2 Background of the Study

The failure of embankments and riverbank erosion are common problem in Bangladesh. Devastating flood, excessive rainfall and tidal surge accelerates the failure process which results immense damage to agriculture and infrastructures every year (Islam, 2000). The traditional practices for protecting embankments are expensive and sometimes not effective due to improper design and construction fault for the designed life. Biotechnology is an alternative solution for embankment protection. Past researches indicated that use of vetiver grass is a successful biotechnical method to protect the slope. The Vetiver System is used in more than 100 countries for soil and water conservation, infrastructure stabilization, pollution control, waste water treatment, mitigation and rehabilitation, sediment control, prevention of storm damage, and many other environmental protection applications through bioengineering and phytoremediation (Wikipwdia).

Ke et al. (2003) tested vetiver as a bank protection measure on several test sites (in Australia, China, Philippines and Vietnam). Their tests showed promising results for the use of vetiver grass as a bank protection measure. 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 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.

Verhagen et al. (2008) conducted different laboratory and model tests on vetiver grass to realize the use of it in coastal engineering and showed that vetiver grass is able to establish a full-stop of bank erosion caused by rapid draw down.

Dudai et al. (2006) described the growth rate of vetiver in different types of soil, in different seasons, and in different temperatures under Mediterranean condition.

Truong et al. (2010) explained the differences between different species of vetiver, showed different techniques of propagation of vetiver by using different parts of the grass and the applications of vetiver.

Recently, in Bangladesh a few research works have been conducted to understand the performance of vetiver grass in erosion control and slope protection against natural disasters.

Arifuzzaman (2011) studied the performance of vetiver grass in protecting coastal embankment in Bangladesh. Islam and Arifuzzaman (2010) and Islam et al. (2010) presented the in-situ shear strength of vetiver rooted soil matrix and bare soil.

Islam et al. (2012) compared the cost of vetiver with other traditional practices used for slope protection and analyzed the factor of safety for bare soil and vetiver rooted soil.

Islam (2013) used vegetation and geo-jute for slope protection in different regions in Bangladesh. It was showed that this method is effective in protecting slope.

Islam et al. (2013a) 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.

Generally, the slope of earthen embankment is kept 2 in horizontal with 1 in vertical when it is constructed. However, due to erosion and washing of soil particles from the embankment surface, the slope becomes steeper and steeper. In this way it becomes vulnerable to rainfall, flood and tidal surge. It is necessary to reduce the rain-cut erosion and shallow depth slope protection for their long term stability.

1.3 Objectives of the Research

Based on the above-mentioned background the main objective of this research was proposed to investigate the suitable propagation method of vetiver grass and the effect of vetiver grass on erosion control and slope protection.

The objectives of the present study are as follows:

a) To determine the in-situ shear strength of vetiver rooted soil matrix and bare soil. Again, to determine the shear strength of vetiver root mixed composite soil by conducting direct shear test on reconstituted samples and to compare the shear strength of vetiver rooted soil determined in the field with that determined in the laboratory.
b) To study the propagation (growth of both root and grass) of vetiver grass (*Vetiveria zizanioides*) in different soil and climatic conditions of Bangladesh. To study the effect of fertilizer and submergence on the growth of vetiver.
c) To determine the erosion protection of slopes and thus to estimate the stability of the vetiver grass protected slope.

It is expected that from this research the following outcome(s) will be obtained:

a) A correlation may be obtained between the shear strength of vetiver rooted soil determined from element test and in-situ test will be obtained. This correlation will be useful to determine the factor of safety (i.e. stability) of the slopes/embankment protected with vetiver grass. From the test result of reconstitute soil samples, the effect of root content and root length will be clarified.
b) The growth of vetiver grass and root increases with the increase of time. By plotting the time verses growth rate (for a particular depth) curve the stability of slope with respect to time (after application of vetiver) may be determined.
c) The effect of vetiver grass on top soil erosion will be determined and compare with the top soil erosion of bare soil.

1.4 Research Methodology

The whole research was conducted according to the following steps:

a) A device (Islam and Arifuzzaman, 2010) was used to determine the in-situ shear strength of the rooted soil and bare soil of clay soil in Pubail zone. Block samples (approx. 30 cm×15 cm×20 cm) have been tested at the field to know the in-situ strength of the rooted soil and bare soil. For this purpose, Linear Variable Displacement Transducer (LVDT) of 50 mm capacity was used to know the horizontal displacement. Calibrated hydraulic jack and pressure gauge (capacity: 5515 kPa) was used for measuring the in-situ strength.

b) Direct shear test was performed on laboratory reconstituted samples (composite rooted soil) and bare soil according to ASTM D 3080. The soil was collected from the same site where field test was conducted. Direct shear test was conducted at different root length and different root content.

c) Growth rate of vetiver grass was studied for two different soil conditions (silty sand and clay soil). Laboratory tests (i.e., grain size, specific gravity and Atterberg limits) have been conducted on the collected soils to characterize the soils.

d) The growth rate of vetiver grass in different conditions such as different types of soil, different submerged conditions and weather conditions have been measured in laboratory and open field by measuring the height of grass and depth of root at one month interval.

e) The soil loss was measured by creating artificial run-off in laboratory model. The soil was collected from both flood affected areas and coastal areas. Pubail was selected as flood-affected area and Kuakata was selected as coastal area. In a model (approx. 122 cm× 91 cm× 81.3 cm) a 1.5:1 (h: v) slope will be created. The test will be done after 4 months of the plantation of vetiver grass in order to be sure that its root already combined. Then artificial rainfall will be created and the run-off will be collected in a bucket of known volume. The amount of soil loss will also be measured. The same procedure will be applied on the bare soil model case.

f) A time versus growth rate of vetiver root curve was plotted. From this curve, time dependent stability curve of slopes was estimated and plotted.

1.5 Thesis Layout

The complete research work for achieving the stated objectives is divided in number of chapters so that it becomes easier to understand the chronological development of the work. Briefly the contents of each chapter are presented below:

Chapter One describe the background of this study, objectives and the methodology of the research. Finally the organization of the thesis is summarized in this chapter.

Chapter Two discusses the characteristics and properties of vetiver grass and availability of vetiver grass in Bangladesh, past researches related to this study, uses of vetiver grass, causes of soil erosion, salient characteristics of surficial erosion and mass movement, role of vegetation in the stability of slopes, root morphology and strength.

Selection of study areas for the research has been discussed in Chapter Three. Experimental program discussed in this chapter. Model analysis of Vetiver grass to know the growth rate and the reduction rate has been also discussed in this chapter.

In-situ shear strength test results of vetiver rooted soil matrix and bare soil are broadly described in this chapter four. Stability of embankment slopes is estimated here. The compare between field test and laboratory test are also shown here. The growth rate of vetiver at different soil and moisture conditions and the reduction of soil erosion by using vetiver grass are also described here.

Chapter Five includes the conclusions of the in-situ shear strength test and laboratory results of the rooted soil sample and bare soil, the factor of safety of the vetiver grass protective embankment slopes and the un-protective embankment slope, the strength of the vetiver root, the growth rate of vetiver grass at different soil and moisture conditions and the reduction of soil erosion by using vetiver grass. Recommendations for future studies have also been listed in this chapter on the basis of present study.

Chapter Two

LITERATURE REVIEW

2.1 General

In Bangladesh embankment failure and river bank erosion has been a major issue in the past and will become an even greater issue in the future as population growth continues to expand and land resources are more intensively used, often to a point of destruction. Increased soil erosion means loss of land, reduced soil fertility, greater rainfall runoff, lower groundwater recharge, more sediment flows in river, higher contaminants in diminishing water supplies, lowered quality of drinking water, increased flooding, and diminished economic benefits and increased hardships to both rural and urban populations.

Devastating flood, excessive rainfall, cyclonic and tidal surge accelerates the process which results in immense damage to agriculture and infrastructures every year. Embankments, riverbanks and other hydraulic structures are the first defense and should be protected against flood and cyclonic storm surge to minimize the losses. The country has over 4,000 km of coastal embankments, nearly 13,000 km of flood and river embankments and 24,000 km of rivers situated on alluvial plain easily eroded by rainfall, river currents and wave action etc (BWDB, 1998). Again the country has 3,478.42 km of national highway, 4221.52 km of regional highway and 13,247.79 km of zilla roads which are also vulnerable different forms of erosion.

Different methods like aar badh, gravity walls, RCC-walls, sand bags as revetment or sand-cement mixed bags, CC blocks are used to protect the embankments, riverbanks and other hydraulic structures. But those methods are expensive, not effective and not environmental friendly.

The cause of embankment failure and soil erosion of Bangladesh, past researches related to soil erosion and performance of vetiver grass, characteristics and properties of vetiver grass, effect of root for increasing the strength of soil and the performance of vetiver grass in embankments is discussed in this chapter.

2.2 Past Researches

Vetiver grass is used for many purposes like slope stability, soil erosion, agriculture improvement, disaster mitigation, prevention and treatment of contaminated water and land etc. 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. A few research papers relevant to this thesis are presented here.

2.2.1 Researches Conducted in Abroad

The Vetiver Network International (TVNI) is an international NGO, with members in over 100 countries promoting the worldwide use of the Vetiver System (VS) for a sustainable environment particularly in relation to land and water. This network tries to establish the vetiver as a biotechnical solution for slope stability, soil erosion, agriculture improvement, disaster mitigation, prevention and treatment of contaminated water and land etc.

Hengchaovanich et al. (1996) 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.

Carey (2000) and Chomchalow (2000) showed the different techniques of vetiver propagation by using different parts, ground preparation and given planting and maintenance tips. They suggested cutting back the tops of the vetiver slips to 200 mm length and the roots to 50 mm and fertilize by sprinkling each pot with approximately 5 g of DAP (di-ammonium phosphate). They also suggested plant well-rooted slips or bare root plants 150 to 200 mm apart to ensure a close hedge within 12 months of planting.

Ke et al. (2003) tested vetiver as a bank protection measure on several test sites (in Australia, China, Philippines and Vietnam). Their tests showed promising results for the use of vetiver grass as a bank protection measure.

Dudai et al. (2006) studied the growth management of vetiver grass under Mediterranean condition. They found that the plant height and the number of sprout per plant in clay soil under long day conditions were significantly higher than under short day. They also found that the heights of irrigated vetiver plant in open fields were higher than those of rain-fed plants. They suggested that in order to obtain fast growth of vetiver and to increase the possibility of using the rainwater for their growth, the plants should be planted during winter (i.e., February to March).

Truong et al. (2007) explained the differences between different species of vetiver, four common ways (splitting mature tillers from vetiver clump or mother plants, using various parts of a mother vetiver plant, bud multiplication and tissue culture) to propagate vetiver and applications of vetiver.

Verhagen et al. (2008) conducted different laboratory and model tests on vetiver grass to realize the use of it in coastal engineering and showed that vetiver grass is able to establish a full-stop of bank erosion caused by rapid draw down.

James et al. (2011) evaluated the method to mitigate erosion due to plunging water by strengthening the soil with ground modification. They used vetiver plant and Polyhedral Oligomeric Silsesquioxanes (POSS) as ground modifiers used in this test and showed that both POSS and the vetiver were effective in reducing erosion. But vetiver showed higher resistance to erosion by plunging water, but required time to achieve a well established root/stem system.

2.2.2 Researches Conducted in Bangladesh

Few researches have also been conducted in Bangladesh on vetiver in last 10 years. Recently some research works are conducted at BUET.

Rahman et al. (1996) survey on vetiver grass in Bangladesh. The survey records information on the ecological distribution, morphological variation and the uses of vetiver grass. They collected vetiver grass from many districts of Bangladesh and found mainly one species of vetiver that is *Vetiveria zizanioides* by microscopically analysis of flowering material and DNA fingerprinting. They found that it is able to survive in submerge condition for 3 to 4 months a year during monsoon and it could be spread from seeds. They also found that vetiver grass is not survived in saline areas. They showed various socio-economic, cultural and many other uses of vetiver grass in Bangladesh like forage, thatch and roofing materials, fire wood, raw materials in cottage industry, an ingredient of medicine, soil stabilizer etc. They suggested to use that vetiver grass could be used as protection of roads, irrigation channels, water dams, to stabilize waste land and to use as an ingredient of paper and perfume manufactured.

The plant's environmental limits are surprisingly broad. It can grow on sites where annual rainfall ranges from 200 to 5,000 mm. It can withstand adverse climatic change. It grows on both highly acidic (pH: 4) and alkaline (pH: 8) soil (Rahman et al., 1996).

Bangladesh Water Development Board (BWDB) (2000) showed available places and the uses of vetiver in Bangladesh for erosion control in cultivated land. They found vetiver grass is very common about 40% (in the division of Chittagong, Dhaka and Rajshahi) of the total land area of Bangladesh and common in the Khulna, Sylhet division and other parts of Bangladesh which is about 45% of the total land area of Bangladesh. There are some districts of Bangladesh like Barguna, Bagerhat, Bhola, Jamalpur, Pirojpur and Shatkhira where vetiver is rare and about 15% of the total land area of Bangladesh.

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 interferences, 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.

Moula et al. (2008) studied on the nursery performance of vetiver grass from June 2000 to June 2001 with different number of tillers. He investigated the optimum number of tillers per clump for the proper propagation of vetiver grass. He observed that the percentage survivability (mean ± SD) of the clump was found as 73.08 ± 1.57, 96.79 ± 0.91 and 91.67 ± 1.26 for single, double and triple tillers, respectively. On the other hand, net tiller increment per clump (mean ± SD) was found as 10.21 ± 0.81, 16.99 ± 1.06 and 14.02 ± 2.27 for the single, double and triple tillers, respectively. The maximum number of tillers per clump was found with the double tillers. According to his observation, it is revealed that propagation of vetiver clump with double tillers is better than single or triple tillers.

Huq (2010) studied on types of vetiver grass in Bangladesh and their propagation in different soil and climatic condition. According to his observation, five types of vetiver grass like Bennashoba (*vetiver*), KhusKhus (*Vetiveria zizanioides*), Gondhabena (*vetiver*), Ecorban (*vetiver*), Vetiveria zizanioides (*dwarf ecotype*) are available in Bangladesh and able to propagate in our soil and climatic condition.

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. 29×15×19 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 costal region in Bangladesh, in-situ strength of vetiver rooted soil and un-rooted soil, and its effectiveness for protecting the embankments against erosion and surge.

Islam et al. (2011) studied availability and sustainability of vetiver grass in the climatic and soil condition of Bangladesh. They also determined the factor of safety of slopes by using the vetiver grass in the basis of in-situ shear strength of vetiver rooted soil matrix and found that for a particular soil the factor of safety of vetiver rooted soil slope is 1.8 to 2.1 times higher than the bared soil and compared the cost of vetiver with other traditional methods.

Islam (2013) used vegetation and geo-jute for slope protection in different region in Bangladesh. Islam et al. (2013a) 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. Laboratory results are also compared with that of the 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 others methods.

2.3 Causes of Erosion and Embankment Failure

Surface runoff and erosion contribute widely to land degradation in many parts of the world, because of their contributions to losses of water and soil fertility, on the one hand, and their intensification of flooding and surface water pollution risks, on the other hand. Top soil erosion of natural slopes become more vulnerable in bare soil where top surface is not covered with significant vegetation since vegetation acts as a natural reinforcement of soil. Two fold mechanisms may be involved with top soil erosion.

a) Raindrop impact energy loosens the top soil: After a rainfall over significant time raindrop impact energy may loosens the bond among the soil particles and becomes vulnerable to sheet erosion.
b) Surface runoff carries it downwards: the loosened soil mass is subjected to an additional hydraulic push by the surface runoff, carries it downwards and induces a failure surface (Khan and Rahman, 2009).

Runoff occurs when the rainfall intensity exceeds the soil infiltration rate and the soil surface water holding capacity, therefore, a decrease in the infiltration rate could increase the runoff. The main factor that decreases soil infiltration under rainfall in arid and semi-arid regions is seal formation at the soil surface (Morin et al., 1981; Ben-Hur and Letey, 1989). A surface seal is thin and is characterized by greater density and lower saturated hydraulic conductivity than the underlying soil (Wakindiki and Ben-Hur, 2002). Soil erosion processes comprise rill and interrill processes: runoff from a soil surface may concentrate into small, erodible channels known as rills or gullies, and thereby damage earth embankments and infrastructures.

Centre for Environment and Geographic Information Services- CEGIS in Bangladesh shows in a recent research that 0.1 million people become homeless every year in the country due to river erosion. In the last 34 years submerging of river side lands are 219286 acres in Jamuna, 69135 acres in Ganges and 95119 acres in Padma. To be concerned that, erosion in the Jamuna would cause 3408 acres of land, 543 localities, 3360 metres of embankment, 5160 metres of roads, 4 educational institutions, and 2 market place to be submerged by 2007. In the mean time, the Ganges would cause 1778 acres of lands, 136 acres of localities and 570 meters of roads while the Padma would cause 1600 acres of lands, 370 acres of localities, 3930 m of roads, 9 educational institutions, 5 market places and 1 Union Council office to be submerged in the river by recent rate of erosion. Main areas of erosion in Bangladesh are presented in Table 2.1.

Geography and Environmental Science Department of the Jahangirnagar University presented a chart of the losses of river erosion between 1996 to 2000. The chart is presented in Table 2.2.

Table 2.1: Main areas of erosion in Bangladesh (Zaman, 1998)

River	No. of location of bank/embankment erosion	Length of erosion (km)
Brahmaputra-Jamuna	41	162.60
Ganges-Padma	26	94.50
Meghna	8	72.00
Teesta	11	34.90
Minor river	112	92.30
Flashy river	75	23.00
Tidal river	32	85.80
Total	305	565.10

Table 2.2: Losses of river erosion between 1996 to 2000 (Chowdhury et al., 2007)

Year	Affected areas (Acres)	Affected population
1996	71680.4	10103635
1997	7756	173090
1998	41519	321000
1999	227755	899275
2000	219310	415870

From the field survey and past studies it was observed that, the most common causes of embankment and river bank failure can be broadly classified into two major groups (Arifuzzaman, 2011):

a) Natural forces (such as; rainfall impact, wave action, wind action etc)

b) Human interference (such as; travel paths for men and cattle, cattle grazing, unplanned forestation of embankment slopes etc).

(a)

(b)

(c)

Figure 2.1: Failure (a) road embankment; (b) river bank and (c) and hill slope (Dr-drave, 2012)

2.3.1 Natural Forces

The natural forces which are responsible for embankment erosion or damage are discussed in this section.

a) Rainfall impact

Mean annual rainfall varies from 1500 mm in the northwest (Khulna district) to over 3750 mm in the south (Cox's Bazar). The heaviest rainfall occurs in July and ranges from 350 mm to over 875 mm accordingly. The slope erosion caused by rain runoff is enormous and its speed/force grows exponentially towards the toe. Toe erosion is the combined effect of runoff and wave action. The main features of rainfall impact are:

i) The embankment crest is mainly affected with the formation of holes and initiation of piping action leading to collapses in combination with either.
ii) Surface runoff caused by rainfall results in sheet erosion and the formation of gullies and rills on poorly protected embankment shoulders, slopes and toes.
iii) Flooding (monsoon/periodic floods and those created by storms/cyclones).
iv) The high head of water on the river side induces piping across the embankment, which may lead to breaching and collapse of the polder system.
v) Monsoon flooding often gives rise to serious erosion of embankments by undermining due to current, vortex and wave forces; the entire embankment gets affected, beginning with the damage of shoulders and crest due to undermining, and gradually the overtopping causes a complete wash down.

b) Wave action

Tidal waves cause damage to the embankments located too near to the sea (the earthen embankments in the coastal zones should have adequate setback not allowing its exposure to wave actions). A severe hydraulic load is steadily exerted on the toes and slopes and causes erosion. Cyclonic storms in the coastal zone (occurring repeatedly) act upon the water surface, causing it to advance towards the shore with enormous hydraulic loads. The waves thus formed eventually hit the embankment toe and slopes. The high hydraulic loads exerted on the embankment cause erosion and if there is overtopping, the physical structure of the embankment is destroyed.

Figure 2.2a and 2.2b shows failure of an embankment slope due to wave and tidal action, where no protective measures and no vegetation at the slope of embankment are used. From the Figure, it is seen that due to wave and tidal action the slopes of the embankment change its original shape and becomes steeper.

(a)

(b)

Figure 2.2: Photograph showing damages of embankments: (a) failure due to wave action, no protective measures and no vegetation at the slope (Islam and Arifuzzaman, 2010) and (b) embankment washed away by cyclonic storm surge

Figure 2.3: Photograph showing failure of embankments due to turbulent water currents (Wikimedia Commons, 2010)

c) Turbulent water currents

The high velocity flow of water associated with vortex motion in rivers and estuaries often causes erosion of the banks by undermining, and the eventual collapse of the embankment threatens unless protective measures are taken. At the mouth of a branch river or canal, especially in the surroundings of sluice gates, the turbulent water current erodes the banks and subsequently the embankments. Figure 2.3 shows failure of an embankment slope due to turbulent water currents.

The presence of continuous borrow-pits on a river or seaside induces undercutting of the embankment toes and slopes due to complete inundation of the riverbank or seashore during the monsoon. The borrow-pits and adjoining lowlands thus inundated induce a parallel water current to flow along very near the embankment toes and slopes, thereby eroding the surfaces rapidly.

d) Wind action

The slow and steady action of wind in the relatively sparse fields and coastlines blows away the topsoil of the embankments where it is sandy or a mixture of silt and sand. But wind with the high velocity during cyclone may lead overturning or uprooting of trees on the embankment slope. This may cause severe injury of the coastal embankment.

Figure 2.4: Failure of embankment due to overturning or uprooting of trees during cyclone (Mohammad Shariful Islam, BUET)

Therefore, the factor of safety of embankment becomes lower and lower and the vulnerability of embankment increases. Figure 2.2b shows that the unprotected embankment washed away by cyclonic storm surge. But, if it was protected by vegetation or other measure it will give higher stability in the long run. Figure 2.4 shows the failure of embankment slope due to overturning or uprooting of trees during cyclone. It indicates that only plantation can not protect the embankment and also cause problem to transfer relief material and communication during disaster. Therefore, it is essential to select long rooted trees with suitable vegetation for environment friendly solution and the best performance of embankments.

2.3.2 Human Interference

The human interference responsible for major embankment erosion is quite diverse in nature and often varies according to the lifestyle and manner of using the embankments of the inhabitants of different areas. The most commonly observed erosion problems out of the varied human uses are presented below:

a) Travel paths for men and cattle

The people living around use the embankments as the main travel paths. The crests thus serve as a rural communication road between villages. Besides plying rickshaws, vans, bicycles and bullock carts, in many areas motorized vehicles also move regularly on these earthen embankments in the dry season. Movement of bullock carts in the rainy season inscribes deep path marks along the track which induce further decaying of the embankment crest by trapping of the rainwater inside.

The people and their cattle, while moving along the damaged crest, often tend to take a better alternative route along the shoulders, slopes and even toes. Gradually the shoulders and slopes are also affected.

b) Cattle grazing

Cattle, mainly belonging to people living on the embankment, cause erosion by uncontrolled browsing of natural grasses. When the embankment is overgrazed, plant species and the vegetative cover, especially the grasses, show retarded growth, weaken and cannot continue to ensure adequate protection of the embankment. The squatters, most of whom are poor and landless, prefer to keep goats as pet animals with their limited scope at the embankment homesteads. The grazing of goats is particularly harmful to the vegetative cover.

Slopes grazed by heavy cattle, mainly cows and buffaloes, often show a typical pattern of browsing tracks running more or less along the contours. These paths form unstable micro-terraces, where the upslope soil material is deposited at the lower side of the track and finally reaches the embankment toe in successive down-slope movements. The uncontrolled grazing of heavy cattle destroys the foreshore gardens and shrubs or bushes growing on the riverbanks, resulting in direct exposure of the embankment surfaces to wave action and water currents. The community people rarely feel it necessary to prevent their grazing animals from destroying the embankment slope vegetation because of their lack of knowledge on the importance of stable embankment as well as unscrupulous attitude of profiteering through grazing.

c) Unplanned forestation of embankment slopes

Forestation without appropriate planning and management techniques destroys the undergrowth grass cover and becomes ineffective for erosion protection. On the other hand, trees on the embankment slopes may lead overturning or uprooting during cyclone. Such cases, forestation results in the weakening of the embankment without any substantial contribution to its stability.

d) Improper design and construction technique

In many cases the embankments are designed with insufficient setback, resulting in increased exposure to waves and current action. This may be due to the high costs involved in land acquisition. Sometimes the setback area is also eroded.

Furthermore, insufficient supervision during construction results in poor-quality earthworks with the use of inappropriate soil materials, insufficient or no clod breaking, inadequate compaction and no or insufficient laying of topsoil layers. Scouring holes and rills appear in no time after completion of the construction. Therefore, to improve the embankment stability proper supervision and proper selection of embankment materials is very essential.

2.4 Surface Erosion

2.4.1 Mechanics of Erosion

Prevention and control of erosion depends on understanding of the mechanics of the erosion process. Erosion is basically a twofold process that involves: (1) particle detachment and (2) particle transportation. Drag or tractive forces exerted by the flowing fluid are resisted by inertial or cohesive forces between particles. Erosion is caused by drag or tractive forces which are the function of velocity, discharge, shape of particles and roughness of particles. On the other hand, erosion is resisted by inertial, friction and cohesive forces which are the function of basic soil properties, soil structure and physicochemical interactions.

Erosion protection essentially consists of: (1) decreasing drag or tractive forces by decreasing the velocity of water flowing over the surface or by dissipating the energy of the water in a defended area, and (2) increasing resistance to erosion by protecting/reinforcing the surface with a suitable cover or by increasing interparticle bond strength.

2.4.2 Principal Determinants of Erosion

i) Rainfall Erosion

Rainfall erosion is controlled by four basic factors, namely, climate, soil type, topography, and vegetative cover. The most important climatic parameters controlling rainfall erosion are intensity and duration of precipitation. Wischmeier and Smith (1978) have shown that the most important 'single' measure of the erosion-producing. The mechanism of top soil erosion is shown in Figure 2.5.

ii) Wind Erosion

Wind erosion is controlled by the same basic factors that control rainfall erosion. The dependence of wind erosion on these factors is expressed schematically in Figure 2.6. The climatic factors that most affect soil moisture are amount and distribution of rainfall, temperature, and humidity. Only relatively dry soils are susceptible to wind erosion. The most important characteristics of the wind are its velocity, duration, direction, and degree of turbulence. Wind can only pick up and carry in suspension dry soil particles primarily less than 0.1 mm, that is fine silt size materials.

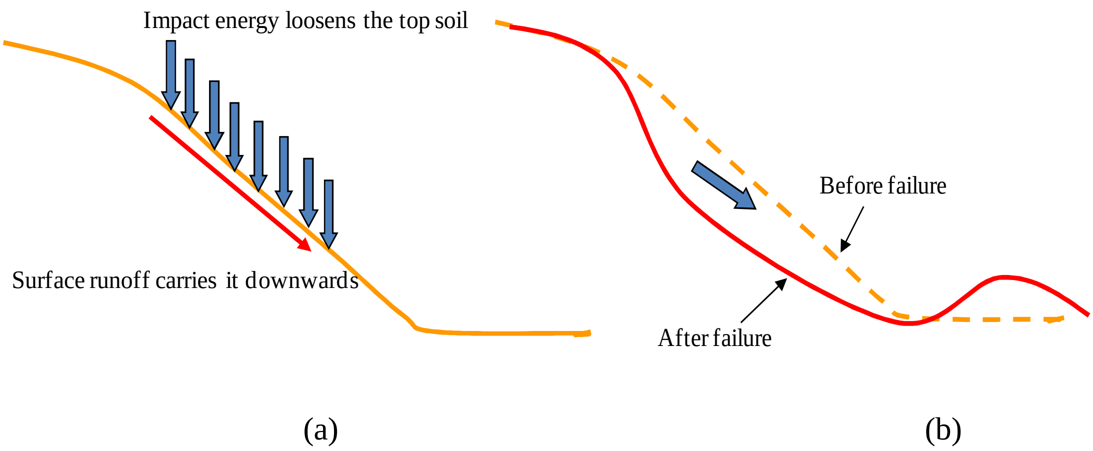


Figure 2.5: Mechanism of top soil erosion: (a) impact of rain fall on slope and (b) after slope failure due to rain fall

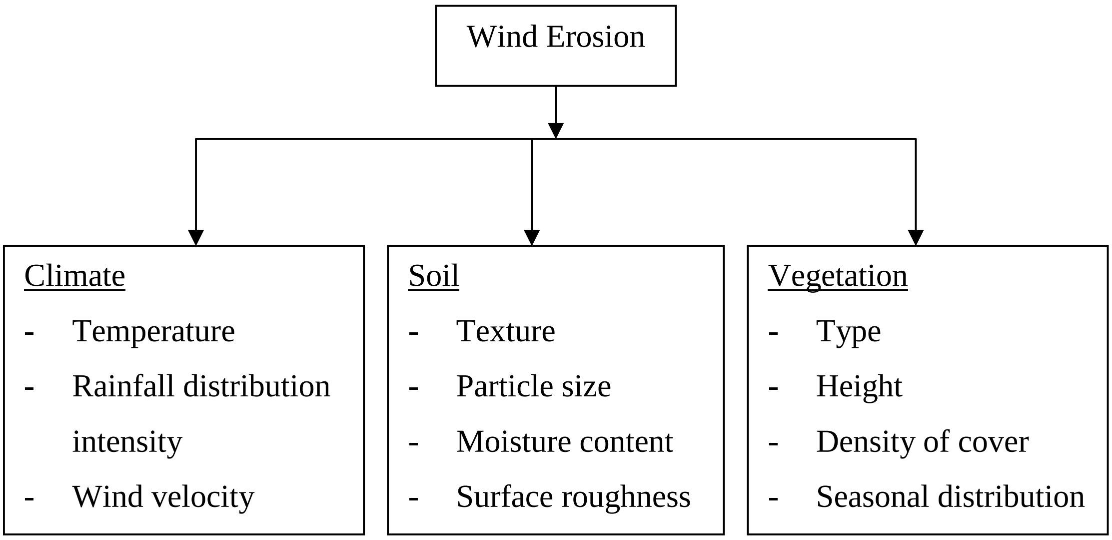


Figure 2.6: Schematic diagram showing factors of wind erosion (after Gray and Sotir, 1996)

Wind erosion consists of three distinct phases: initiation of movement (detachment), transport, and deposition. Soil movement by wind is initiated as a result of turbulence and velocity. The velocity required to start movement increases as the weight of particles increases. Laboratory studies by Chepil (1945) established that soil particles are transported by wind in the manner. The major portion of soil particles transported by the wind occurs near the ground surface at heights under 1 m. Approximately 62 to 97 percent of the total wind-eroded soil is transported in this zone near the surface, a fact that suggests the utility of installing relatively low barriers or windbreaks to filter and impede the movement of windborne soil. Vegetation readily serves this purpose in addition to its other control functions such as increasing surface roughness, slowing and deflecting the wind, and binding soil particles together. Because of these properties vegetation can be used very effectively in combination with fencing to trap drifting sand and build up dunes along beaches.

2.5 Salient Characteristics of Surficial Erosion and Mass Movement

Most common types of erosion are rainfall and wind erosion. Rainfall erosion starts with falling raindrops themselves. When these drops impact on bare or fallow ground, they can dislodge and move soil particles a surprising distance. Bare or unprotected earth surfaces are the most vulnerable to all forms of surficial erosion. Unlike erosion, mass movement involves the sliding, toppling, falling, or spreading of fairly large and sometimes relatively intact masses. A slide is a relatively slow slope movement in which a shear failure occurs along a specific surface or combination of surfaces in the failure mass. Slides are amenable to quantitative stability analysis by techniques of limiting force equilibrium and limit analysis.

Many of the same factors e.g., slope, soil, hydrology etc. that control surficial erosion also control mass movement. The salient characteristics of surficial erosion on the one hand and mass movement on the other are contrasted in Table 2.3.

Table 2.3: Salient Characteristics of Surficial Erosion versus Mass Movement (after Gray and Sotir, 1996)

	Slope Degradation	
	Surficial Erosion	Mass Movement
Process	Detachment and transport of individual particles	Movement of large soil mass along discrete failure surface
Predictive or Physical Model	Universal soil loss equation $A = R * K * LS * CP$ A= Annual average soil loss, R = Rainfall erosivity factor, K = Soil erodibility factor, LS = Topographic factors, CP = Cropping management factor	'Infinite Slope' or Circular arc analysis $F.S. = A \frac{\tan ¤'}{\tan} + B \frac{c'}{¥H}$
Important soil property	Erodibility $K = f(D_{50}, C_u, \% org)$	Shear strength $² = c + ± \tan ¤$
Protective role of vegetation:	Interception Restraint Retardation Infiltration	Reinforcement Moisture extraction Buttressing Arching
Most effective vegetation	Herbaceous Grasses and forbs, near surface root mat and good surface cover by foliage.	Woody Shrubs and trees – deep vertical sinker and tap root system. High root/shoot ratio.

Precipitation, a key factor directly affecting rainfall erosion, only affects mass movement indirectly via its influence on the groundwater regime at a site. In contrast, geologic conditions such as orientation of joints and bedding planes in a slope can have a profound influence on mass stability but not on surficial erosion. Vegetation has an important influence on both erosion and shallow mass movement. Different predictive techniques or models have been developed to determine soil losses from surficial erosion or the likelihood of catastrophic slope failure in the case of mass movement. Rainfall and wind erosion, for example, are controlled by a number of soil, climatic, and topographic factors, including intensity and duration of precipitation, ground roughness, length and steepness of slope, inherent erodibility, and type or extent of cover.

2.6 Available Practice to Protect Slope Failure

The methods to protection slopes and embankments can generally be classified as: (a) indigenous methods, (b) gravity walls, (c) RC-walls, (d) sand bags as revetment or sand cement mixed bags and (e) CC-blocks.

a) Indigenous methods: grass, water hyacinths etc.

Grass

There is no hard and first rule for this type of protection work. The tradition practice is to use chailla grass. The straw of chailla grass is spread over the slope at a certain thickness and is held back to the slope surface with the help of a split up bamboo woven net. This bamboo net is anchored to the slope with pegs. Technically known as soft protection, it is called the aar bandh. It needs to construct every year at the beginning of monsoon and dismantled at the end of monsoon, otherwise it disintegrates during the dry season. It cannot withstand the force of the erosive waves when the wave height exceeds 0.6 m for a sustained period of time (CIDA, 2002).

Water hyacinths

The water hyacinth is a floating plant that grows in water abundance and is sustainable on land and in dry conditions. When the water level goes up the plants also float and encased around the mound with help of bamboo poles and fencing. As a result, waves cannot directly attack the slope. Theck as well method is only effective if the wave height is in the form of ripples.

b) Gravity walls

Masonry walls are designed as gravity walls with a view to protecting against wave attack as well as retaining the earth at the back. It saves land which otherwise should be required for providing slopes. But it is not environment friendly and attractive to the eye. It is also very costly due to poor soil condition.

c) RC walls

RCC-walls are used as wave barrier. But RCC-walls are not environment friendly. These are costly in comparison with other methods.

d) Sand bags and sand-cement mixed bags

This is a cheap and temporary type of protection work. For this type of protection work gunny or polyethylene bags of about 1.25 cft capacity are used for filling with low FM sand. The sand-filled bags are placed over the slopes in a rip-rap way. Polyethylene bags are better than gunny bags as they more sustainable. This item of work is best suited for emergency and repair work with minimum time and cost implications.

Figure 2.6: Poor performance of sand bags against cyclonic storm surge (Islam and Arifuzzaman, 2010)

Figure 2.7 shows that sand bags were washed away from some portion of the embankment slope due to wave action. Thus it made the embankment slope unprotected and vulnerable at this portion and this weak portion may lead the embankment failure.

e) CC-block

Placed cement-concrete blocks with geotextile have come into use recently in slope protection. But it is not environment friendly and also very costly.

Figure 2.8 shows that protected embankment slopes by cement concrete (CC) blocks were failed at Keraniganj. The reasons of this failure may be the lack of proper compaction of embankment slope, existing soft layer(s) below the embankment, lack of proper placement of CC blocks on the embankment slope or high tidal surge make the embankment toe weak and wash away the soil particles below the CC blocks, etc. But all the above practices are expensive and not eco-friendly.

Figure 2.7: Poor performance of CC blocks at Keraniganj Beribadh site (Source: Prothom Alo, dt: 04.04.2011)

2.7 Low-Cost Solutions to Protect Slope Failure

As the available practices which is available used in Bangladesh to protect the embankment is expensive and not eco-friendly that’s why some low-cost methods are also used for this purpose. The available low-cost solutions to protect slope failure are (Arifuzzaman, 2011):

a) Vegetation by grass seeding

b) Compaction of embankments soil by layers.

c) Vegetation and plantation.

2.8 Effects of Vegetation in the Stability of Slopes

Plants growing on slopes can control runoff and erosion through three main mechanisms: (i) the plant canopy can protect the soil surface from raindrop impact, thus, in turn, preventing seal formation, infiltration reduction, and soil detachment (Ben-Hur et al., 1989; Agassi and Ben-Hur, 1992); (ii) Plant roots can act as an anchor that holds the soil particles together, so limiting the risk of landslides along the slope and (iii) Rows of plants oriented perpendicularly to the slope direction can be used as semi-permeable barriers that reduce the surface runoff velocity so that the amount of infiltrated water increases and the runoff and soil loss amounts decrease (Wakindiki and Ben-Hur, 2002).

Vegetation helps stabilize forested slopes by providing root strength and by modifying the saturated soil water regime. Plant roots can anchor through the soil mass into fractures in bedrock, can cross zones of weakness to more stable soil, and can provide interlocking long fibrous binders within a weak soil mass.

The right choice plant material is critical. A tight, dense cover of grass or herbaceous vegetation, e.g., 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.

a) Influence on Surficial Erosion

Vegetation plays an extremely important role in controlling rainfall erosion. Soil losses due to rainfall erosion can be described a hundredfold (USDA Soil

Conservation Service, 1978) by maintaining a dense cover of sod, grasses, or herbaceous vegetation. The beneficial effects of herbaceous vegetation or grasses in preventing rainfall erosion are tabulated below:

i) Interception

Erosion occurs when rainfall dislodges soil particles and carries them off a slope, forming rills and gullies that can trigger landslides. Raindrops hitting the soil surface can also seal the soil particles and make a crust that prevents infiltration and creates runoff. Trees and shrubs intercept precipitation before it hits the soil surface. Most of the intercepted precipitation evaporates back into the atmosphere, and the moisture that drips off the plants causes little soil damage because it has less force. It's a good idea to include evergreen trees in slope plantings because conifers intercept more moisture than deciduous trees, especially in the rainy season when deciduous plants have lost their leaves. Leaves and branches that fall from the plants shield the soil surface from rain drop impact, slow the movement of water across the soil surface, and encourage rainfall to soak into the soil.

ii) Dewatering

Soil saturation can trigger erosion and landslides. Plants improve slope stability by removing water from the soil. Plants use water, absorbed through their roots, to perform basic metabolic processes such as photosynthesis. Plants release absorbed water to the atmosphere, by transpiring through pores on the leaves, much as a person sweats. Transpiration cools the plant and helps transport minerals up the stems. The rate of transpiration varies greatly, depending on the plant species, weather, and other factors. A single tree can transpire hundreds of gallons on a hot, dry day.

iii) Soil Reinforcement

Roots physically reinforce soils, resist erosion, and increase infiltration of water into the soil. Roots form physical pathways (little tunnels) that help water infiltrate the soil. Deep, woody roots lock the soil layers together, and lateral roots connect many plants into an interlocking grid. Fine feeder roots form a network through the upper soil layer, preventing surface erosion. Groundcovers and grasses have relatively shallow roots and low biomass, so they prevent surface erosion only, and do not stabilize deep soil. Trees possess deeper roots than shrubs and are essential for slope plantings. Puget Sound bluff soils often feature porous sandy, gravelly soil overtopping dense, clayey glacial till. Rainfall saturates the upper soils and then seeps laterally over the glacial till, causing slides. Deep tree roots penetrate into the compacted layer and help tie the layers together, preventing slides. Tree roots occurring at the crest and toe of a slope help to prevent wasting in these susceptible areas where larger slides often start.

iv) Ecologically Healthier Overall

Vegetation actively decompacts soil through the expansion of the root systems and the addition of organic matter to the site. Water absorbs more readily into uncompacted soil. Vegetation also encourages soil fauna to thrive. Soil fauna, such as microorganisms, insects and worms, condition the soil as well. The cumulative impacts of these organisms result in healthier soil that is more resilient during storm events.

b) Influence on Mass Wasting

The protective role of vegetation on the stability of slopes has gained increasing recognition. The main beneficial effects of woody vegetation on the mass stability of slopes are listed below:

i) Root Reinforcement: Roots mechanically reinforce a soil by transfer of shear stress in the soil to tensile resistance in the roots.
ii) Soil Moisture Depletion: Evapotranspiration and interception in the foliage can limit build-up of positive pore water pressure.
iii) Buttressing and Arching: Anchored and embedded stems can act as buttress piles or arch abutments to counteract down slope shear forces.
iv) Surcharge: Weight of vegetation can, in certain instances, increase stability via increased confining (normal) stress on the failure surface.

The most obvious way in which woody vegetation enhances mass stability is via root reinforcement. Extensive laboratory studies (Maher and Gray, 1990) on fibre-reinforced sands indicate that small amounts of fibre can provide substantial increases in shear strength. The soil buttressing and arching action associated with roots and the stems/trunks of woody vegetation are also important components of slope stabilization. In addition, evapotranspiration by vegetation can reduce pore water pressures within the soil mantle on natural slopes, promoting stability (Brenner, 1973). The primary detrimental influence on mass stability associated with woody vegetation appears to be the concern loading and the danger of overturning or uprooting in high winds or currents (Tschantz and Weaver, 1988). This problem is likely to be critical for large trees growing on relatively small dams, levees, or stream banks.

c) Analysis for the Role of Vegetation in Slope Stability

The stability of a slope against failure is evaluated by the factor of safety (FS), which is defined as the ratio of resistance of the soil mass to shear along a potential slip plane to the shear force acting on that plane. Soil failure occurs when the ratio falls to unity. The simple case of a transitional failure along a sliding surface parallel to the ground over a relatively long uniform slope can be analyzed by infinite slope analysis.

2.9 Root Morphology, Effect and Strength

Plant root systems play a major role in the mechanical properties of soil by increasing soil strength and stability, and by increasing the porosity. The value of the root system in this regard will depend upon the strength and interface properties of the roots themselves and on the concentration, branching characteristics, and spatial distribution of roots in the ground. Root strength and architecture in turn are governed by the type of plant and by local soil conditions.

2.9.1 Root Architecture

a) Main Component

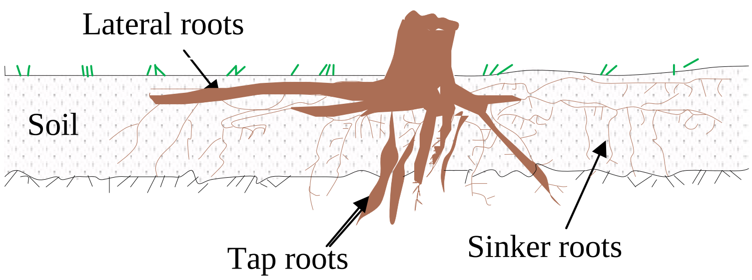


Figure 2.8: Main components of woody root system (Reproduce from Gray and Sotir, 1996)

The nature of the balance and, therefore, the engineering function which individual plants perform will depend upon their structure or architecture. Specific terms have been adopted to describe the various parts of a tree root system, as noted in Figure 2.9. Taproot refer to the main vertical root directly below the bale 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 a horizontal orientation. The overall shape or morphology of a tree root system can also be categorized. Plants with strong tap and sinker roots will help stabilize a slope through arching and buttressing, whereas plants with a dense lateral rooting system will increase the strength of top layer of the soil by adding to cohesion.

b) Pattern of Roots

i) H-type: Maximum root development occurs at moderate depth, with more than 80% of the root matrix found in top 60 cm. Most roots extend horizontally and their lateral extent is wide.

ii) R-type: Maximum root development is deep, with only 20% of the root matrix found in top 60 cm. Most of the main roots extend obliquely or at right angles of the slope and their lateral extent is wide.

iii) VH-type: Maximum root development occurs at moderate depth, with more than 80% of the root matrix found in top 60 cm. Most root extend horizontally and their lateral extent is wide.

iv) V-type: Maximum root development is moderate to deep. There is a strong tap root but lateral roots are sparse and narrow in extent.

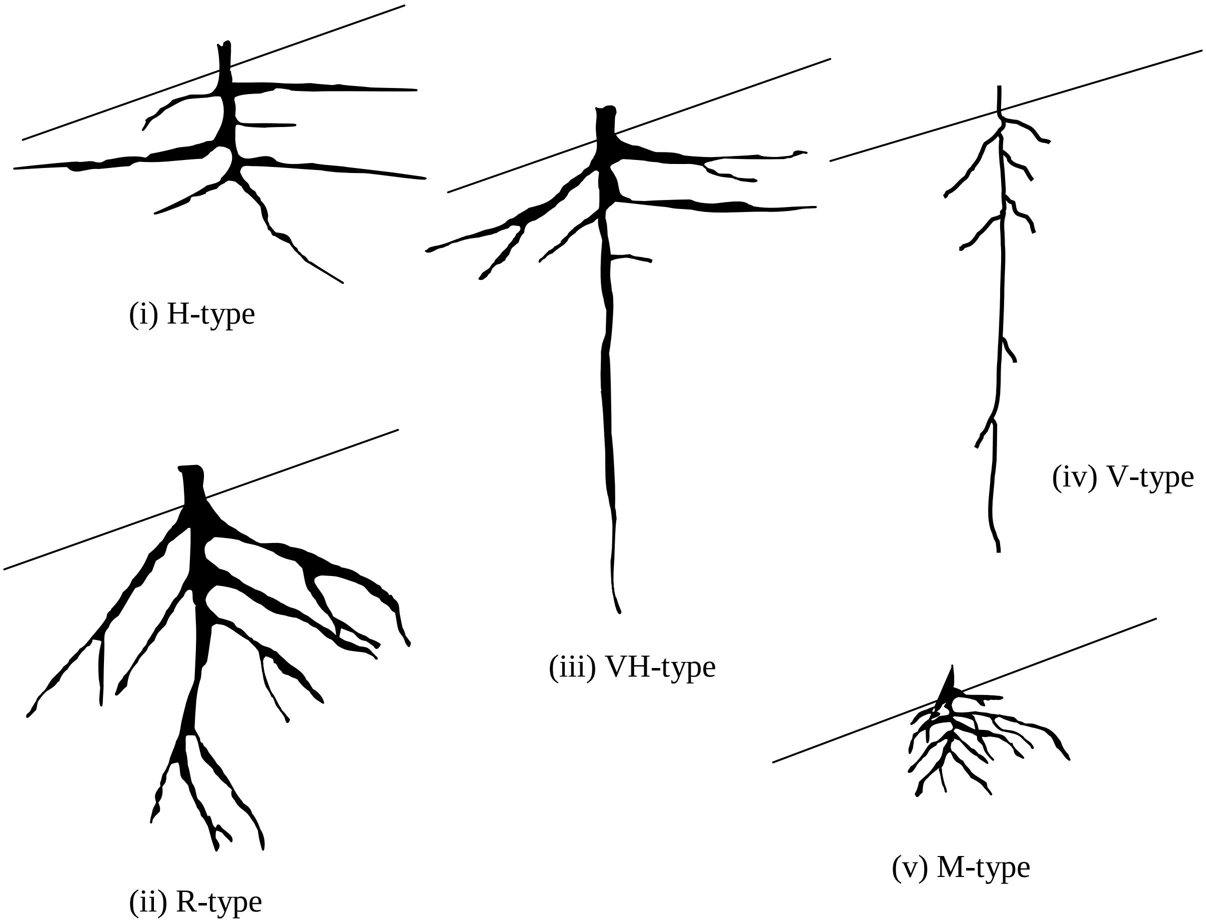


Figure 2.9: Patterns of root growth (after Yen, 1987)

v) M-type: Maximum root development is deep but 80% of the root matrix occurs within top 30 cm. The main roots grow profusely ans massively under stump and have a narrow lateral extent.

H and VH- types are considered beneficial for slope stabilization and wind resistance. H and M-types are considered beneficial for soil reinforcement. The V-type is wind resistance.

2.9.2 Effects of Roots

Morphology is controlled both genetically and by environmental conditions. The development of 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 few large-diameter roots for increasing the shear strength of a root-penetrated soil mass. Deeply penetrating vertical taproots and sinker roots provide the main contribution to the stability of slopes vis-à-vis resistance to shallow sliding.

Mechanical restraints against sliding only extend as far as the depth of root penetration. In addition, the roots must penetrate across the failure surface to have a significant effect.

2.9.3 Root Strength

Root tensile strength has 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 2.4 for selected shrub and 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 2.4 should be considered only as rough or approximate averages. Nevertheless, some interesting trends can be observed in the tabulated strength values. Tensile strengths can approach 70 MPa but appears 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. It is important to recognize that root tensile strength is affected as much by difference in size (diameter) as by species.

Table 2.4: Nominal Tensile Strength of Selected Grass Species (after Schiechtl, 1980)

Grass	Avg Dia. Of roots (mm)	Avg tensile strength (MPa)
Late Juncellus	0.38±0.43	24.50±4.2
Dallis grass	0.92±0.28	19.74±3.00
White Clove	0.91±0.11	24.64±3.36
Vetiver grass	0.66±0.32	85.10±31.2
Common Centipede grass	0.66±0.05	27.30±1.74
Bahia grass	0.73±0.07	19.23±3.59
Manila grass	0.77±0.67	17.55±2.85
Bermuda grass	0.99±0.17	13.45±2.18

For the determination of tensile root strength of (Abe and Iwamoto, 1986; Nilware, 1994 and Burroughs and Thomas, 1977), the power regression analysis of the relationship between the ultimate root tensile force and the root diameter provides the best fit with the following equation:

$F_1 = 46.93\ d^{1.4217}$……………………(1)

where,

F_1 = ultimate tensile root force (kN)

d = the root diameter (mm)

This power regression function can be used to predict the ultimate tensile force of a vetiver root with known diameter.

The tensile root strength, Ts (MPa) decreases with the increasing root diameter d (mm) following the power regression relationship.

$Ts = 59.80\ d^{-0.5785}$…………………… (2)

From the table 2.5, the tensile strength of vetiver roots varies from 150 to 35 MPa for the range of root diameter of 0.2-2.5 mm. From Figure 2.11, it is shown that the mean tensile strength is about 75 MPa at 0.7-0.8 mm root diameter which is the most common diameter class for vetiver roots.

Table 2.5: Ultimate Tensile Force and Tensile Strength of Vetiver Root at Different Diameter (Abe and Iwamoto, 1986; Nilware, 1994 and Burroughs and Thomas, 1977)

Diameter, d (mm)	Ultimate tensile force, F_1 (kN)	Tensile root strength, Ts (MPa)
0.2	4.76	151.72
0.5	17.52	89.29
0.7	28.26	73.50
1.0	46.93	59.80
1.5	83.52	47.30
2.0	125.73	40.00
2.5	172.66	35.20

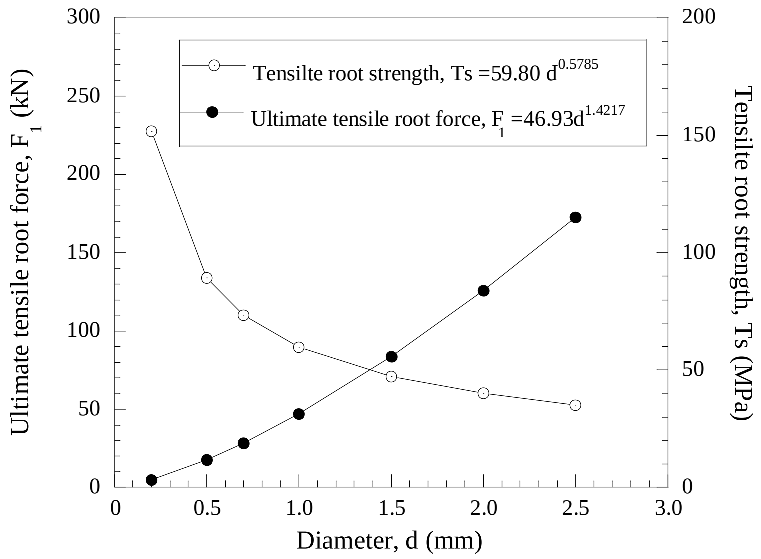


Figure 2.10 Relationship of tensile root strength and ultimate tensile root force with different root diameters (Abe and Iwamoto, 1986; Nilware, 1994 and Burroughs and Thomas, 1977)

Several investigators (Turmanina, 1965; Wu, 1976; Burroughs and Thomas, 1977; Nilaweera, 1994) have reported a decrease in root tensile strength with increasing size (diameter). 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 wind throwing. This could be an important consideration, for example, in stream bank or levee slope stabilization.

Finer roots have the advantage of not only higher tensile strengths but also superior pullout resistance because they have higher specific areas than larger roots at equivalent area ratios.

2.10 Mechanism of Soil Reinforcement by Root

The roots and rhizomes of the vegetation interact with the soil to produce a composite material in which the roots material are fibres of relatively high tensile strength and adhesion embedded in the matrix of lower tensile strength. The shear strength of the soil is therefore enhanced by the root matrix.

Since shear strength affects the resistance of the soil to detachment by raindrop impact (Cruse and Larson, 1977; Al-durrah and Bradford**,** 1982), and the susceptibility of the soil to rill erosion (Laflen, 1987 and Rauws and Grovers, 1988) as well as the likelihood of mass 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. Root failure occurs when their tensile strength exceeded.

2.11 Selection of Vegetation

Most developed and developing countries like Australia, China, India, Malaysia, Spain, Thailand and Zimbabwe use vetiver for different erosion protection works. It creates a simple vegetative barrier of rigid, dense and deeply rooted clump grass, which slows runoff and retains sediment on site. Binna or vetiver grass (*Vetiveria zizanioides*) is used in more than 100 countries of the world (Truong, 2000). The special attributes of vetiver is that it can grow on sites where annual rainfall ranges from 200 mm to 5,000 mm (Rahman et al., 1996). It can survive in temperature ranging from 0˚C to 50˚C. It grows on highly acidic soil types (pH ranges from 3.0 to 10.5). It is also high tolerant to Al, Mn, As, Cd, Cr, Ni, Pb, Hg, Se and Zn in the soil (Truong and Baker, 1998). Even in the soil with ECse values 7.8 dSm^{-1}, the relative yield of vetiver grass is found to be 100%. But in soil with ECse values of 10 and 20 dSm^{-1} yield of vetiver is reduced by 10% and 50%, respectively (Truong et al., 2002). Its roots are very strong with high tensile strength of 75 MPa (Hengchaovanich, 1998). Vetiver hedges can survive even for more than 100 years (Verhagen et al., 2008).

2.12 Vetiver Ecotypes

Vetiver belongs to the same part of the grass family as maize, sorghum, sugarcane, lemon grass and Cymbopogon. According to the results from a systematic plant taxonomy study being conducted on Vetiveria in Thailand, the ecotypes which are commonly found are *Vetiveria zizanioides* (belongs to the family Gramineae) and

Vetiveria nemoralis. Both species naturally grow in a wide range of areas from lowlands to highlands, from the altitude close to mean sea level to as high as 800 m above mean sea level. The *Vetiveria zizanioides* occurs in Bangladesh. *Vetiveria zizanioides* is a kind of plant that can suitably and rapidly adapt to the environment. The leaf of *Vetiveria zizanioides* is 45-90 (100) cm. long and 0.6-0.9 (1.2) cm. wide. The upper surface of the blade is curved and the apex is flat and dark green. The texture is smooth and waxy. The lower surface of the blade is pale white. When holding the leaf against the sunlight, we can see a septum clearly, especially at the base and middle of the blade. The midrib which is hidden in the blade is not big or clearly seen.

Vetiveria zizanioides at one year of age can produce the roots penetrating more than 1 meter deep. This somehow, depends on the conditions of the soil and health of the grass. The roots will be longest if the grass is grown in loose clay soil with good water drainage potential.

2.13 Characteristics and Properties of Vetiver Grass

a) Morphological Characteristics

i) Vetiver grass has no stolons, very short rhizomes and a massive finely structured root system that can grow very fast, in some applications rooting depth can reach 3-4m in the first year. This deep root system makes vetiver plant extremely drought tolerant and difficult to dislodge by strong current.

ii) Stiff and erect stems, which can stand up to relatively deep water flow.

iii) Highly resistance to pests, diseases and fire.

iv) A dense hedge is formed when planted close together acting as a very effective sediment filter and water spreader. New shoots develop from the underground crown making vetiver resistant to fire, frosts, traffic and heavy grazing pressure.

v) New roots grow from nodes when buried by trapped sediment. Vetiver will continue to grow up with the deposited silt eventually forming terraces, if trapped sediment is not removed.

Figure 2.11: Root system of vetiver grass

b) Physiological Characteristics

i) Tolerance to extreme climatic variation such as prolonged drought, flood, submergence and extreme temperature from -22^{o}C to 60^{o}C.

ii) Ability to regrow very quickly after being affected by drought, frosts, salinity and adverse conditions after the weather improves or soil ameliorants added.

iii) Tolerance to wide range of soil pH (3.0 to 10.5).

iv) High level of tolerance to herbicides and pesticides.

v) Highly efficient in absorbing dissolved nutrients and heavy metals in polluted water.

vi) Highly tolerant to growing medium high in acidity, alkalinity, salinity, sodicity and magnesium.

vii) Highly tolerant to Al, Mn and heavy metals such as As, Cd, Cr, Ni, Pb, Hg, Se and Zn in the soils.

c) Ecological Characteristics

i) Although vetiver is very tolerant to some extreme soil and climatic conditions, it is intolerant to shading. Shading will reduce its growth and in extreme cases, may even eliminate the grass. Therefore vetiver produces best growth in the open and weed control may be needed during establishment phase.

ii) Vetiver grass can be eliminated easily either by spraying with glyphosate or uprooting and drying out.

d) Mechanical Characteristics

i) Tensile and Shear Strength of Vetiver Roots:

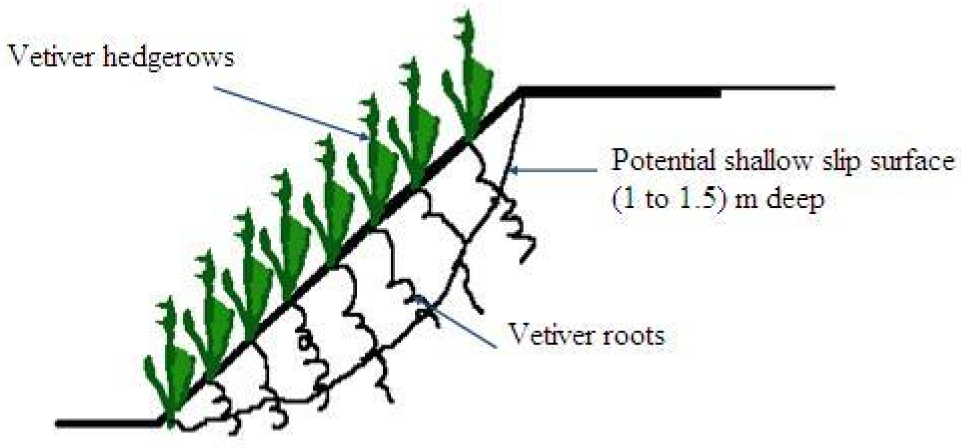


Figure 2.12: Shallow slip surface protected by vetiver root

In a soil block shear test, Hengchaovanich and Nilaweera (1996) also found that root penetration of a two year old Vetiver hedge with 15cm plant spacing can increase the shear strength of soil in adjacent 50 cm wide strip by 90% at 0.25 m depth. The increase was 39% at 0.50 m depth and gradually reduced to 12.5% at 1.0 m depth. Moreover, because of its dense and massive root system it offers better shear strength increase per unit fiber concentration (6-10 kPa/kg of root per cubic meter of soil) compared to 3.2-3.7 kPa/kg for tree roots.

In our study, the root diameter was found in the range 0.5 and 1.0 mm. From the Table 2.5, it is seen that in this range the tensile force is varying from 18 to 50 kN and root strength varying from 89 to 60 MPa. That means within these range of vetiver root has higher strength. This data will be useful for FE Modeling, DEM or any other methods for stability analysis.

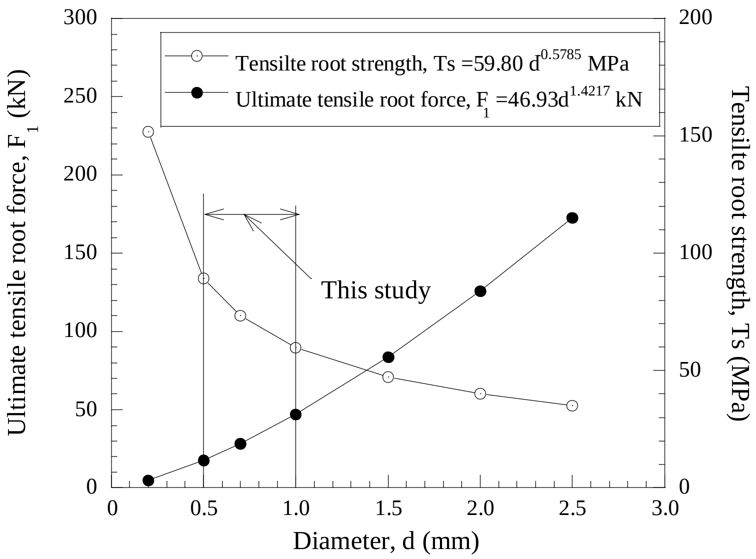


Figure 2.13 Relationship of tensile root strength and ultimate tensile root force with different root diameters (Abe and Iwamoto, 1986; Nilware, 1994 and Burroughs and Thomas, 1977)

ii) Pore Water Pressure:

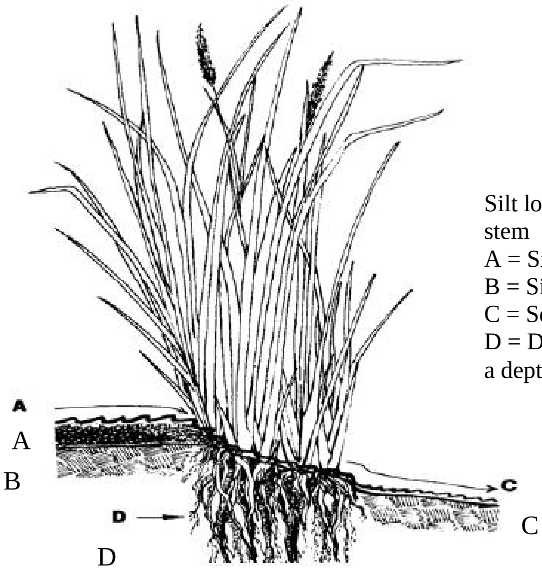
Increase in water infiltration is one of the major effects of vegetation cover on sloping lands and there has been concern that the extra water will increase the pore water pressure in the soil which could lead to slope instability. However, field observations show much better counter-effects. First, planted on contour lines or modified patterns of lines which would trap and spread runoff water on the slope, the extensive root system of vetiver grass helps prevent localized accumulation of surplus water and distribute it more evenly and gradually. Second, the possible increased infiltration is also balanced by a higher, and again, gradually rate of soil water depletion by the grass.

2.14 Uses of Vetiver Grass

The vetiver system provides significant economic, environmental and social benefits. Vetiver system is now used in most tropical and semi-tropical countries. Vetiver system has expanded from a technology primarily for farm soil and water conservation to include major applications for:

i) Soil Erosion Control: The Vetiver System is the premier soil erosion method outside of temperate zones. Narrow hedgerows of Vetiver grass will spread out rainfall runoff across the slope, act as a filter to trap erosion sediment, create natural terraces and reduces the velocity of rainfall runoff. It has application for on farm soil and water conservation, rehabilitation of eroded lands, and prevention of erosion on sloping lands. Figure 2.14 shows the mechanism of soil erosion reduces by vetiver grass.

ii) Agriculture Improvement: The Vetiver System has many agricultural uses for: soil and water conservation, soil moisture improvement, groundwater recharge, recycling soil nutrients, pest control, mulch, forage, clean up of agricultural contaminated waste water, protection of farm infrastructure (canals, drains, roads, and building sites).



Silt loaded runoff water is slowed down by the plant dense stem
A = Silt-loaded runoff being slowed down by the plant
B = Silt dropping out of the water behind the plant
C = Sediment free water continuing on down the slope
D = Dense spongy root system that binds the soil together to a depth up to 3m

Figure 2.14: Mechanism of reduce runoff (Carlin et al., 2003)

iii) Slope Protection: The combination of deep roots with tensile strength of 75 MPa that improve the shear strength of soil by as much as 40% makes vetiver grass an ideal plant for stabilizing steep and unstable slopes. The Vetiver System when applied to such slopes significantly reduces the probability of land slippage and reduces the need for “hard solutions”. Applications include highway, railway, riverbanks, public utility right of ways, canal, dikes, and levee slopes.

iv) Disaster Mitigation: The Vetiver System can be used to reduce potential disasters caused by extreme rainfall events. Stabilization of levees and sea dikes reduces the chance of breaching and subsequent devastating flooding. Steep slope protection by vetiver grass reduces potential land slippage caused by high rainfall events.

v) Community Quality of Life and Poverty Reduction: In most developing countries many of the Vetiver System applications can be applied at minimum cost to poor rural communities to enhance quality of life through protection of water supplies, improving soils and increasing farm benefits, cleaning up waste water and reduction of diseases, protection of rural infrastructure, and providing byproducts for handicrafts, forage, mulch, thatch, medicines, and vetiver plant material for sale to other users.

vi) Landscaping: The Vetiver System can be applied for urban landscaping including beautification, slope stabilization, traffic dividers, demarcation of walkways, prevention of urban erosion etc.

vii) Handicrafts: Vetiver grass provides a source of excellent material for handicrafts, particularly if the leaves are properly processed first. Sometimes, as in the case of Venezuela, a handicraft program for women and girls led to the Vetiver System being used for other applications. Thus adding to the quality of communities and community effort.

2.15 Summary

Past researches related to propagation and performance of vetiver to erosion and slope protection, characteristics of surficial erosion and mass movement, role of vegetation in the stability of slopes, root morphology and strength and its performance all over the world and the recent trials on vetiver in Bangladesh is discussed in this chapter. These can be summarized in the following:

a) Most common types of erosion are rainfall and wind erosion. Rainfall erosion starts with falling raindrops themselves. When these drops impact on bare or fallow ground, they can dislodge and move soil particles a surprising distance. Unlike erosion, mass movement involves the sliding, toppling, falling, or spreading of fairly large and sometimes relatively intact masses. A slide is a relatively slow slope movement in which a shear failure occurs along a specific surface or combination of surfaces in the failure mass. 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.

b) Many researchers have been conducted in home and abroad to know the performance of vetiver grass against climatic change, slope protection, coastal embankment protection and so on. Hengchaovanich et al. (1996) studied the strength properties of vetiver grass roots in relation to slope stabilization. Ke et al. (2003) tested vetiver as a bank protection measure on several test sites (in Australia, China, Philippines and Vietnam). Verhagen et al. (2008) conducted different laboratory and model tests on vetiver grass to realize the use of it in coastal engineering. Islam (2003) studied the performance of vetiver grass on eighteen coastal polders over eighty- seven kilometers of earthen coastal embankment of Bangladesh.

c) Available low-cost solutions to protect slope failure are vegetation by grass seeding or trees, compaction of embankments soil by layers or vegetation and plantation with geo-jute. There might be so many alternatives, among these the vegetation with vetiver grass (*Vetiveria zizanioides*) is considered potentially all over the world.

d) Introduction to vetiver grass, the special attributes and the performance of vetiver grass in different slope protection works, treatment of contaminated water and agricultural improvement is discussed in this chapter.

Chapter Three

EXPERIMENTAL PROGRAM

3.1 General

The objective of this chapter is to describe the experimental program that has been carried out to conduct the research. Here, the location of the tests for the research has been shown. Then all the field and laboratory test procedures has been discussed. During field investigation disturbed samples were collected. Laboratory tests and all model tests were performed on the collected samples at the Geotechnical Laboratory of Civil Engineering Department of Bangladesh University of Engineering and Technology (BUET).

3.2 Study Areas

Riverbank erosion and submerging of the coastal lands are the national phenomenon being one of the main natural disasters. An estimated soil loss is 4.2 tons/ha/yr and 7-120 tons/ha/yr on 30-40% and 40-80% slopes (Banglapedia). About 1.7 million hectares of floodplain areas are prone to riverbank erosion. Some areas of Bangladesh are also affected by wind erosion, particularly in the Rajshahi and Dinajpur regions during the dry months of the year. The soils eroded from the hills are deposited somewhere in the downstream. Efforts have been made at times to protect the embankments from erosion. Protection of slopes using vegetation is being used efficiently all over the world. Vetiver grass (*Vetiveria zizanioides*) is commonly found in different districts of Bangladesh. The performances of vetiver grass in coastal region already done but in flood plain region not done yet. Pubail is selected as a flood plain region. Figure 3.1 shows the location of the study area (Pubail, Gazipur).

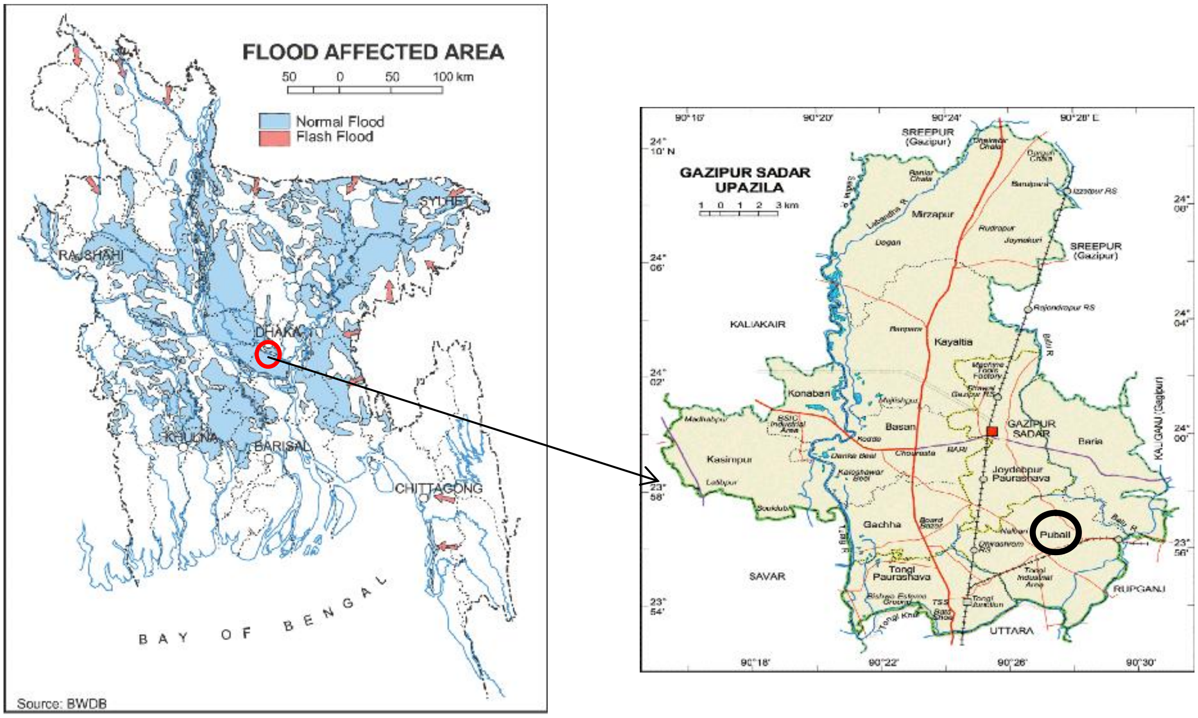


Figure 3.1: Location map of the study area for field test

3.3 Experimental Program

Field tests were conducted to determine the in-situ shear strength and failure strain of vetiver rooted soil matrix and soil without root at Pubail. Soil samples were also collected during the field test for laboratory investigations and model tests.

3.3.1 In-Situ Shear Strength of Block Samples

In-situ shear strength test was conducted in the field on six block samples. Tests were conducted under different normal stresses. Normal stresses for the in-situ tests were arbitrarily selected in the range between 10.96 kPa and 19.98 kPa.

a) Test Set-up

A device developed by Islam and Arifuzzaman (2010) was used in this study to determine the in-situ shear strength of the vetiver rooted soil and soil without root. The apparatus used for the in-situ shear strength tests were hydraulic jack, pressure gauge, wooden plate, metal plate, metal box (approx. 29×15×19 cm^3), normal load and Linear

Variable Displacement Transducer (LVDT). Photograph of Figure 3.2c shows the apparatus used in the field to determine the in-situ shear strength of vetiver rooted soil matrix and soil without root. The capacity of the pressure gauge used for this in-situ shear strength test was 800 psi and the capacity of LVDT was 50 mm. Both the pressure gauge and LVTD were calibrated (Appindix-A) before using them in the test.

b) Preparation of Block Sample

Clump of vetiver grass was cut at the ground level with a sharp knife. Keeping the root position undisturbed a trench of the size (1 m × 1m) was made up to the desired depth. Initially the rooted area was greater than desired block sample size. After that the rooted area was made in desired block sample shape by sharp knife. Photograph of Figure 3.2 shows the preparation of block soil sample for in-situ shear strength test.

c) Test Set-up

Block samples (approx. 29×15×19 cm^3) were tested under different normal stresses at the field to know the in-situ strength of the rooted soil and soil without root. After preparing the block sample in the desired shape the metal box (having bottom face open) was smoothly pushed from the top of the block sample. Then normal load was placed on the metal box. It was carefully ensured that, the bottom edge of the metal box could not touch the ground level. Wooden plate was placed between the metal box and the hydraulic jack. The back sides of the hydraulic jack was made hard and smooth enough by placing brick and wooden plate between the jack and edge of the prepared hole. Then horizontal force was applied to the box from one side by hydraulic jack. Calibrated pressure gauge was used to measure the horizontal force. The block sample was failed at the bottom and the deflection of sample was measured by Linear Variable Displacement Transducer (LVDT) which was fixed to the ground surface by metal plate. For this purpose, Linear Variable Displacement Transducer (LVDT) having capacity of 50 mm was used to determine the horizontal deformation. LVDT was placed on a metal box and fixed it with the metal plate by magnetic stand. The metal plate is placed on the ground and the metal was fixed with the ground by metal clamp.

(a)

(b)

(c)

Figure 3.2: Preparation of block soil sample: (a) trench of the size (1 m × 1m); (b) desired block sample shape and (c) prepared block sample for in-situ shear test

3.3.2 Laboratory Tests

In-situ direct shear tests were conducted in consolidated un-drained (CU) condition. Hence, the laboratory direct shear tests were also conducted in similar condition so that the laboratory test results can be compared with that of the in-situ test results. Direct shear tests were conducted on reconstituted soil samples. Tests were conducted on both bare and root mixed composite soil samples collected from the Pubail region of Bangladesh. The test was performed in both different root content (0.5%, 6%, 9% and 12%) with same root length (2.54 cm) and different root length (1.25 cm, 2.54 cm and 5 cm) with same root content (6% of dry weight of soil).

a) Preparation of Reconstituted Soil Samples

At first the collected soil samples were air dried. Then the air dried soil samples were crushed to powder form by a wooden hammer. After that water (equal to natural moisture content, 25%) was added with 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, to attain a density similar to that of field density. The compaction was done in three layers where 25 blows were applied in each layer. The wet density of the prepared soil samples varied from 17.45 to 17.50 kN/m^3 which is very close to the field density of the block soil sample (17.48 kN/m^3). 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. Figures 3.3a~3.3d show the photographs of different stages of reconstituted soil sample preparation.

b) Test Set-up

The remolded soil sample was placed carefully in the shear box from the ring. Then the desired normal load was applied. Vertical displacement dial gauge was attached to record the vertical deformation with respect to time. Enough time (about 2 hours) was allowed for complete dissipation of the pore water pressure before applying the shear force.

(a)

(b)

(c)

(d)

Figure 3.3: (a) powdered air dry soil sample; (b) 25.4 mm pitches of vetiver roots; (c) The pitches of vetiver roots were randomly mixed with the wet soil and (d) Prepared soil sample inside a probing ring of diameter 7.62 mm

When the vertical deformation dial reading was substantially ceased the shear 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.

3.3.3 Growth Rate of Vetiver Grass

Vetiver is adaptable to a wide range of soil and climatic conditions. It can survive in extreme climatic variation such as prolonged drought, flood, submergence and extreme temperature from -22^{o}C to 60^{o}C.

a) Natural Condition

Vetiver grass was planted in BUET Ladies Hall. Grass was collected from Pubail site. Growth of vetiver plant was measure one month interval. Some pictures of growth of vetiver plants and roots are shown in Figure 3.4. The growth rate of vetiver roots measured only planted time and after 1 year of plantation.

(a)

(b)

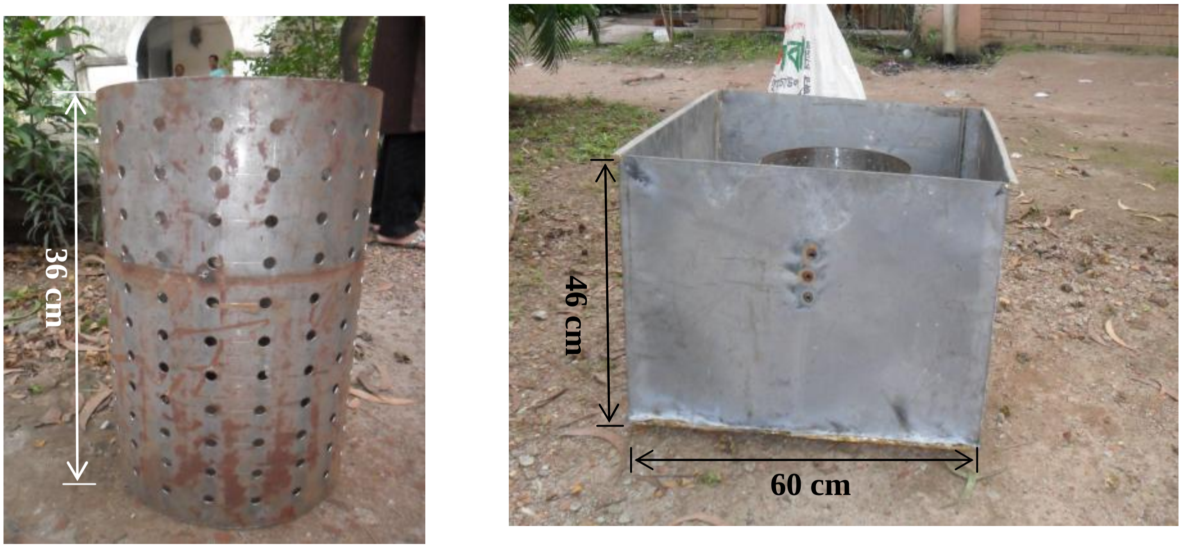
Figure 3.4: Growth of vetiver grass leaves: (a) after 3 weeks of plantation and (b) after 8 weeks of plantation

b) Model Study

Two models were made to know the growth rate of vetiver. The models had two basic parts:

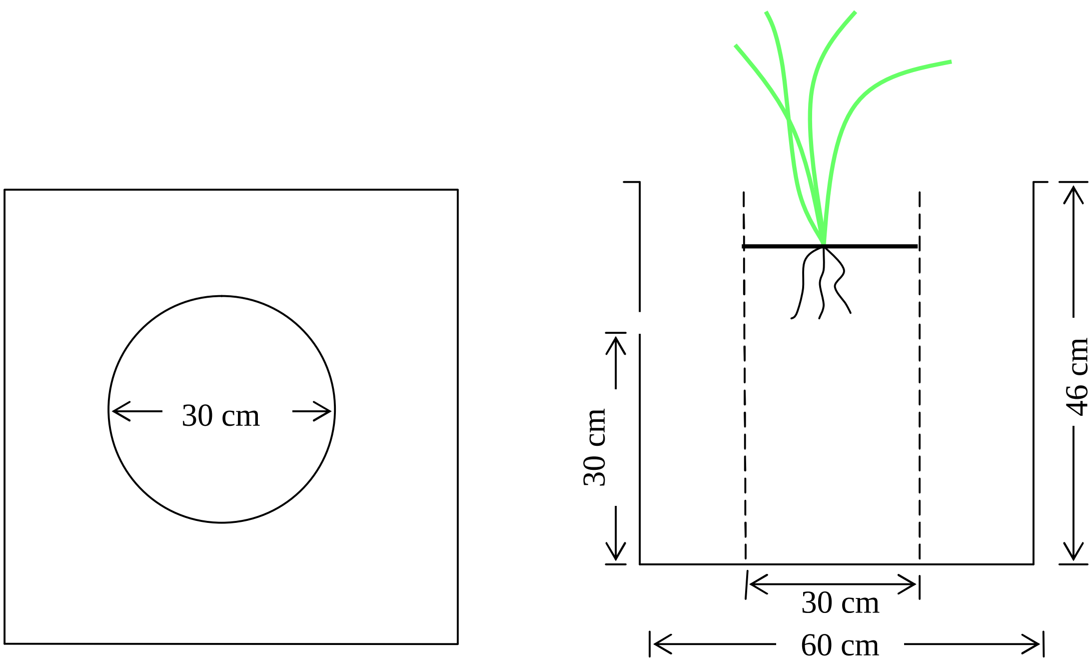
i) 30 cm dia round shape perforated steel container.
ii) 46 cm × 60 cm × 60 cm cube steel container with three holes (5cm dia) at 30 cm high from bottom so that excess water can flow through the holes.

Round shape perforated container was placed in the middle of the cube container and filled with soil and cow dung. One perforated container was filled with silty sandy soil (Keraniganj) and another one was clay soil (Pubail). The stems of the Vetiver grass were cut off at a length of around 12 cm, while the roots were cut off at a length of 8 cm, both measured from the surface level. After one month of application water was added up to 30cm. Then the growth rates of leaves were measured in one week interval.



(a) (b)

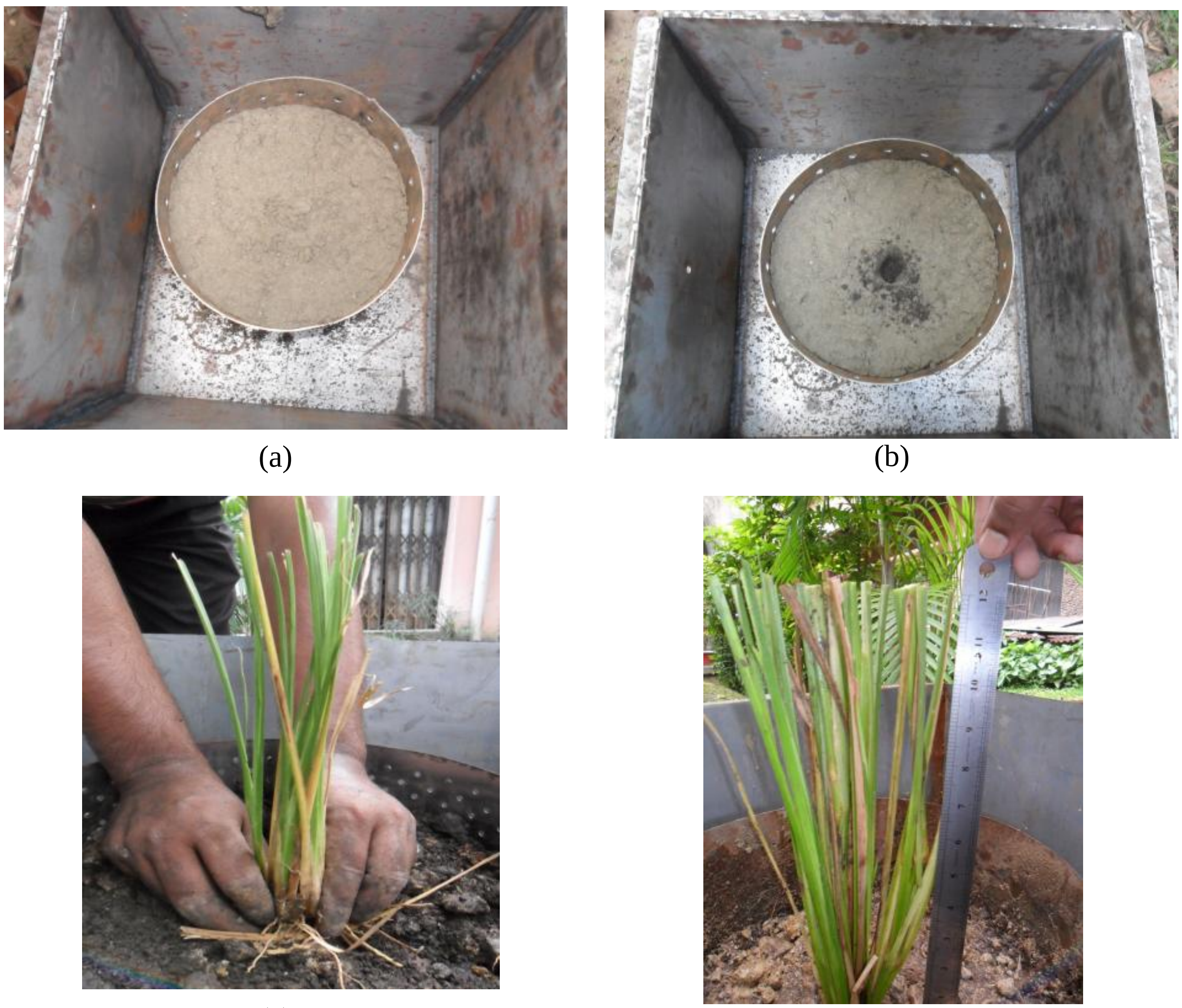
Figure 3.5: Container for growth rate measurement: (a) perforated steel container with 30cm diameter and (b) cube steel container (46 cm × 60 cm × 60 cm)



(a) (b)

Figure 3.6: Schematic set up of the model (a) Plan of the model (b) section of the model

Figure 3.7: Top view of the model



(a) (b)

(c) (d)

Figure 3.8: Propagation of vetiver in a model: (a) round shape container filled with cow dung mix soil; (b) make a hole in the soil; (c) plant the vetiver grass and (d) length of grass after plantation

c) Nutrient Analysis

Soil sample was collected from 5 different sites named Pubail, Kuakata, Keraniganj, Sirajganj and Dhaka where vetiver is available. Nutrient analysis was done from Soil Resource Development Institute (SRDI).

3.4 Model Analysis to Measure the Reduction of Soil Erosion by using Vetiver Grass

Erosion model was developed to simulate the details of the soil erosion process on river or hill slopes. Generally when the rain fall intensity exceeds soil infiltration capacity, the excess rain flows down and first forms a sheet flow on the slope. The process of sheet flow with water and sediment can be simulated in detail which may possibly render or truthful results for soil erosion.

The model had two basic parts:

a) Container for preparing soil slope
b) Rainfall distribution system.

a) Container for preparing soil slope

The soil slope was prepared in a 3.8 mm thick 1.22 m×0.91 m×0.91m wooden container. 8 wooden stick was attach to the container to make a frame. Then 1.22 m long, 0.91 m wide and 0.81 m high soil slope was prepared the container. Tests were carried out on 1:1.5 slope of compacted silty sand which was collected from Keraniganj with 0.15 m horizontal support of same sand on toe side of the slope. Length of slope used was 1.22 m including 0.15 m on toe side.

A schematic diagram of slope is shown in Fig 3.9. Approximately, 350 kg soil was compacted to obtain same volume and shape.

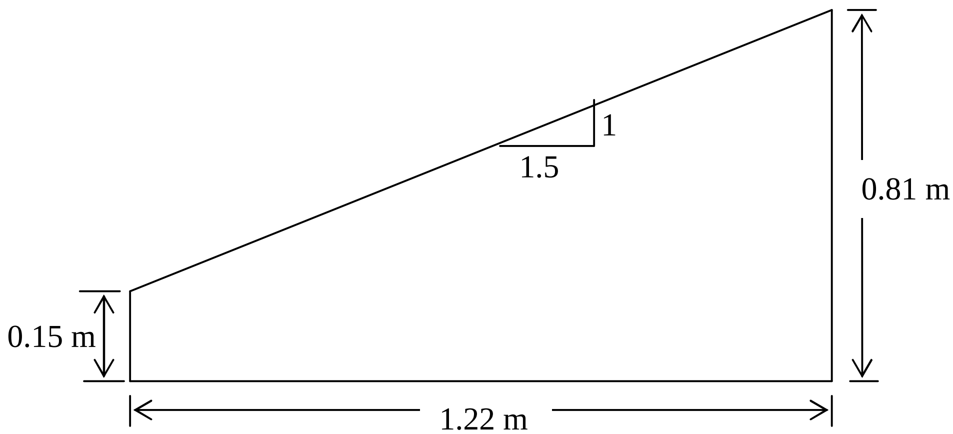


Figure 3.9: Schematic diagram of the slope

Figure 3.10: Preparation of the slope

Figure 3.11: Perforated GI sheet for rainfall distribution

b) Rainfall distribution system

A perforated GI sheet was used to make the water distribution uniform throughout the soil slope. This tray looks like a grating of 2 mm opening with 25.4 mm center to center spacing.

Average rainfall intensity of Bangladesh is 50-100 mm/hr. The rainfall intensity used in this model test was between 100 mm/hour to 125mm/hour to know the condition of soil at worst condition. Then rainfall was distributed uniformly over the soil surface from a constant height to maintain constant rainfall energy for all tests throughout the time. A plastic was added at the toe of the slope to minimize the water and soil loss.

The soil eroded with runoff water was collected in synthetic geo-textile. Geo-textile placed on a 0.91 m × 0.46 m × 0.61 m trench infront of the slope. Eroded soil mass were measured at ten minute interval and at last one hour. This process was repeated for vetiver covered slope. The test set-up is shown in Figure 3.12.

Figure 3.12: Test set-up for measuring top soil erosion

3.5 Slope Stability Analysis

The stability of a slope against failure is evaluated by the factor of safety (FS), which is defined as the ratio of resistance of the soil mass to shear along a potential slip plane to the shear force acting on that plane. Soil failure occurs when the ratio falls to unity. The simple case of a transitional failure along a sliding surface parallel to the ground over a relatively long uniform slope can be analyzed by infinite slope analysis. In this case, a single element or segment (Figure 3.13) of the slope can be considered as representative of the whole, and the head and top portions of the slope are ignored as being negligible in extent.

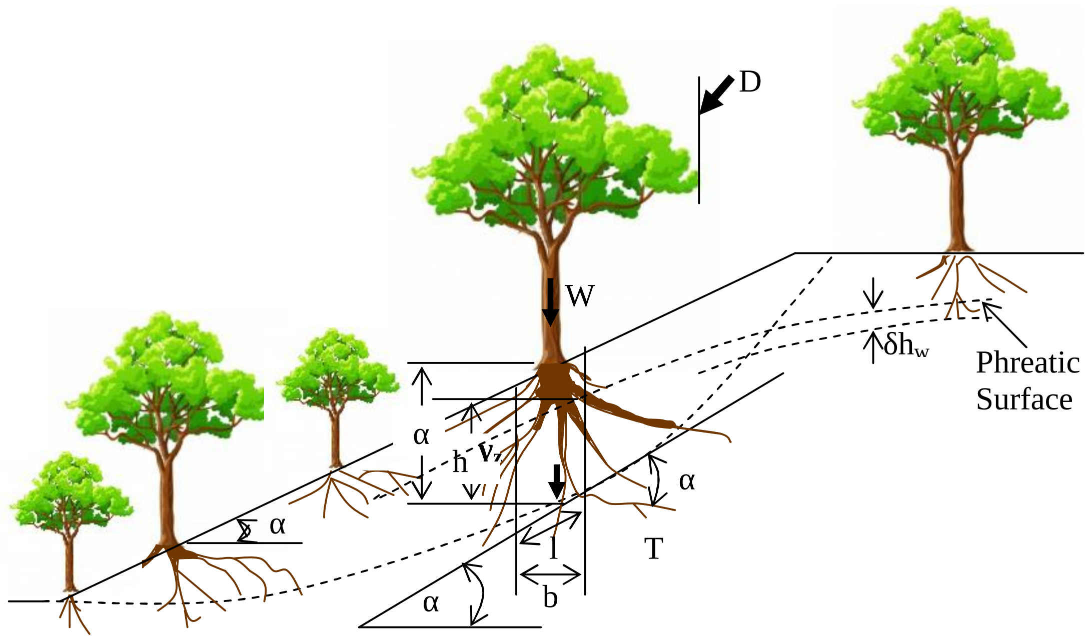


Figure 3.13: Main influences of vegetation on slope stability (reproduce from Coppin and Richards, 1990)

Using effective stress analysis, the factor of safety without vegetation can be defined by:

$$FS = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\beta \tan\phi'}{\gamma z \sin\beta \cos\beta} \tag{3.1}$$

Where,

c' = effective soil cohesion (kN/m^3)

γ = unit weight of soil (kN/m^3)

z = vertical height of soil above slip plane (m)

β = slope angle (degrees)

γ_w = unit weight of water (kN/m^3)

h_w = vertical height of ground water table above slip plane (m) and

ϕ' = effective angle of internal friction of the soil (degrees)

Based on Coppin and Richards (1990), shows the main influences of vegetation on the stability of slope segment. They can be included in the factor of safety as follows:

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2\beta + T\sin\theta]\tan\phi' + T\cos\theta}{\{(\gamma z + W)\sin\beta + D\}\cos\beta} \tag{3.2}$$

Where,

c'_R = enhanced effective soil cohesion due to soil reinforcement by roots (kN/m^3)

W = surcharge due to weight of vegetation (kN/m^2)

h_v = vertical height of groundwater table above the slip plane with the vegetation (m)

T = tensile root force acting at the base of the slip plane (kN/m)

θ = angle between roots and slip plane (degrees) and

D = wind loading force parallel to the slope (kN/m)

3.6 Summary

Study area for the experimental program is selected in the flood plain regions of Bangladesh. Both in-situ and laboratory tests were conducted to know the performance of vetiver grass in slope protection. Two models were established to know the growth rate of shots and roots of vetiver grass at different soil condition. Erosion test was done to compare the loss of soil both bare slope and vegetated slope.

a) A device which was developed by Islam and Arifuzzaman (2010) was used to determine the in-situ shear strength of vegetative soil matrix and soil without root. The apparatus used for the in-situ shear strength tests were Hydraulic jack, Wooden plate, Metal plate, Metal box (approx. 29×15×19 cm3), Normal load, Linear Variable Displacement Transducer (LVDT). A clear description of the developed device is presented here. Block soil sample were tested in the field under different normal stresses and different depths. Normal stresses were arbitrarily selected in the range between 10.96 kPa and 19.98 kPa. Block soil sample preparation and test set-up were described in this chapter.

b) Laboratory investigation was carried out on collected soil samples from the selected sites Pubail and Keraniganj. The laboratory-testing program consisted of carrying out specific gravity, moisture content and particle size analysis.

c) Direct shear test was done on the reconstitute soil sample of Pubail soil. The soil sample was collected from field test site. Normal stresses were tried to keep same as in-situ test done on Pubail block samples and root content was 0%, 0.5%, 6%, 9% and 12% and root length was fixed (2.54 cm). Again direct shear test was done on the reconstitute soil sample of Pubail soil and the root length was 1.25, 2.54 and 5.0 cm in a particular content (6% of dry weight of soil).A clear description was given in this chapter.

d) Model study for growth rate in submerge condition was done both silty sand (Keraniganj) and clay (Pubail) soil. After one month of application water was added up to 30 cm and growth rate of shoots measured leaves were measured in one week interval. The set up of the model was described here.

e) Erosion test was done on silty sand (Keraniganj) in a wooden container. The rainfall intensity used in this model test was between 100 mm/hour & 125mm/hour and the erosion of the soil from the slope was collected in a filter by 10 minutes interval. The test set-up and procedure of the test was briefly described in this chapter.

f) Theory of slope stability analysis (after Coppin and Richard, 1990) is also described in this chapter. According to the described method slope stability was estimated in the chapter four.

Chapter Four

RESULTS AND DISCUSSIONS

4.1 Introduction

The main objective of this chapter is to present detail test results of the field and laboratory investigations obtained in the study. In-situ shear strength of vetiver rooted block soil samples has been presented. In-situ shear strength of rooted soil has been compared with that of bared soil to show the effect of vetiver root on slope stability. Laboratory direct shear tests were conducted on reconstitute soil samples at different root content and root length. Growth rate of vetiver in different soil and climatic condition has been shown in this chapter. The effect of vegetation on slope erosion has been presented here. The erosion of the slope with vegetation has been compared with that of the slope without vegetation. Finally, stability of slopes has been estimated based on all the test results.

4.2 Selection of Study Areas

Coastal zone and flood plain zone are the most vulnerable to natural hazards. In-situ test in coastal region has already studied by Arifuzzaman (2011). For that region flood plain region has been selected as study area to find out the growth and strength of vetiver grass in flood prone areas. Pubail at Gazipur district has been selected as a representative of flood plain zone. Pubail region of Bangladesh has been selected for this study because most of the erosion, land slide is happened in flood plain region. Vetiver grass has been planted at BUET Ladies Hall, Pubail and Keraniganj to know the growth rate of vetiver and compare the growth rate between flood zone and coastal zone.

4.2.1 Metrological Condition of the Study Areas

Mean annual rainfall varies of Pubail is about 2376 mm and highest average temperature is 36°C and lowest average temperature is 12.7°C. In Dhaka nearly 80% of the annual average rainfall of 1,854 millimeters occurs during the monsoon which last from May to till the end of September and annual average temperature of 25 °C and monthly means varying between 18 °C in January and 32 °C in May.

4.2.2 Physical and Index Properties of Site Soil

a) Pubail Soil

The specific gravity (G_s) of the soil samples collected from Pubail region varies from 2.50 to 2.55. Natural moisture content (w_n) ranges from 24 to 25%. Dry unit weight of the soil samples varies from 13.92 to13.96 kN/m^3. Figure 4.1 shows the particle size distribution of the soil samples collected from Pubail region. Clay, silt and sand fractions of the soils have been determined according to ASTM D 422. Clay, silt and sand content of the soils vary between 20 to 30%, 60 to 65% and 2 to 5%, respectively. These soils are found to be plastic. The liquid limit varies from 41 to 44%, plastic limit varies from 22 to 24% and plasticity index varies from 18 to 20%. It is found that the soil samples collected from Pubail are silty clay and the designated group symbol according to ASTM D 2487 is CL (Inorganic clays of low to medium plasticity or silty clay). Summary of the soil properties collected from Pubail regions are presented in Table 4.1.

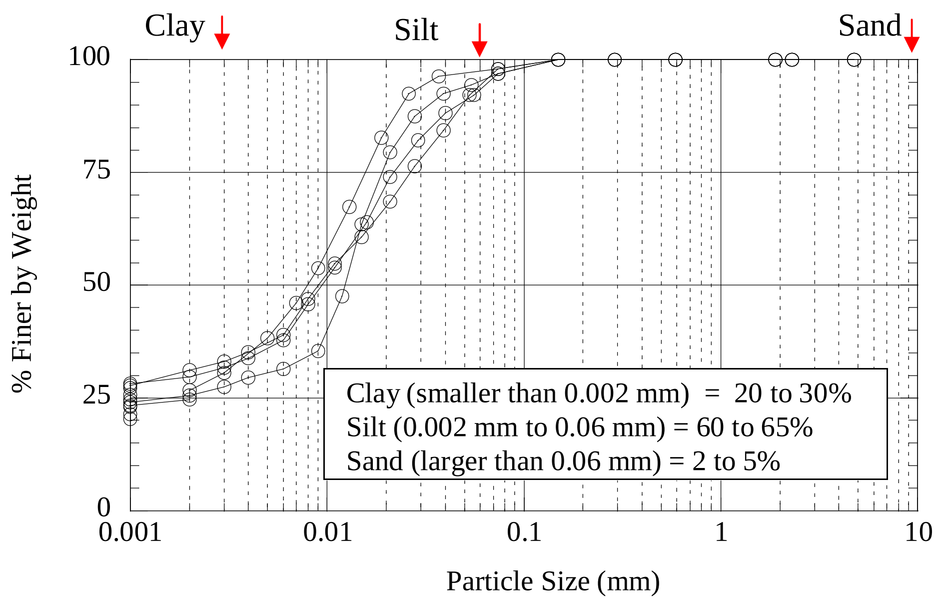


Figure 4.1: Particle size distribution of soil samples collected from Pubail region

Table 4.1: Physical properties of the soil samples collected from study area of Pubail

G_s	w_n (%)	Grain size			Atterburg Limits			Group (According to ASTM D 2487)
		Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI (%)	
2.50~2.55	24~25	2~5	60~65	20~30	41~44	22~24	18~20	CL

Note: Gs = specific gravity; w_n = natural moisture content; LL = liquid limit; PL = plastic limit; PI = plasticity index

b) BUET Ladies Hall

Figure 4.2 shows the particle size distribution of the soil samples collected from BUET Ladies Hall. Clay, silt and sand fractions of the soils have been determined according to ASTM D 422. Clay, silt and sand content of the soils is 27%, 63% and 10%, respectively. These soils are found to be plastic. The liquid limit 37%, plastic limit 19% and plasticity index 18 %. It is found that the soil samples collected from BUET Ladies Hall is silty clay and the designated group symbol according to ASTM D 2487 is CL (Inorganic clays of low to medium plasticity or silty clay).

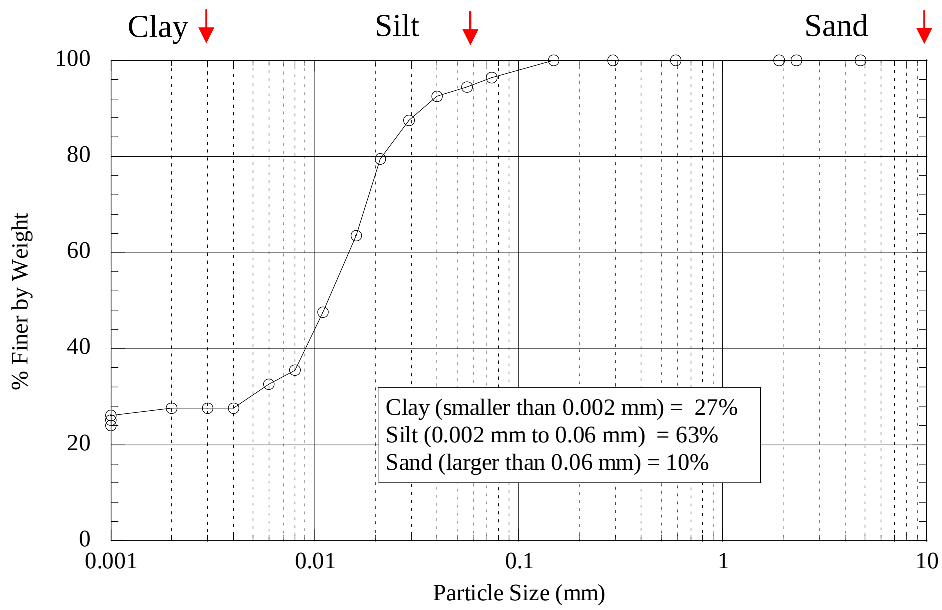


Figure 4.2: Particle size distribution of soil samples collected from BUET Ladies Hall

c) Keraniganj Soil

Specific gravity of the soil sample is 2.7. The grain size analysis of the said sample is presented in Figure 4.3. Sand, silt and clay content the soil is 10%, 80% and 10% respectively, According to the percentage of contents the soil is sandy silt. From the Figure, it is found that the mean grain size, D_{50} and co-efficient of uniformity, C_u is 0.048 mm and 7.5 respectively.

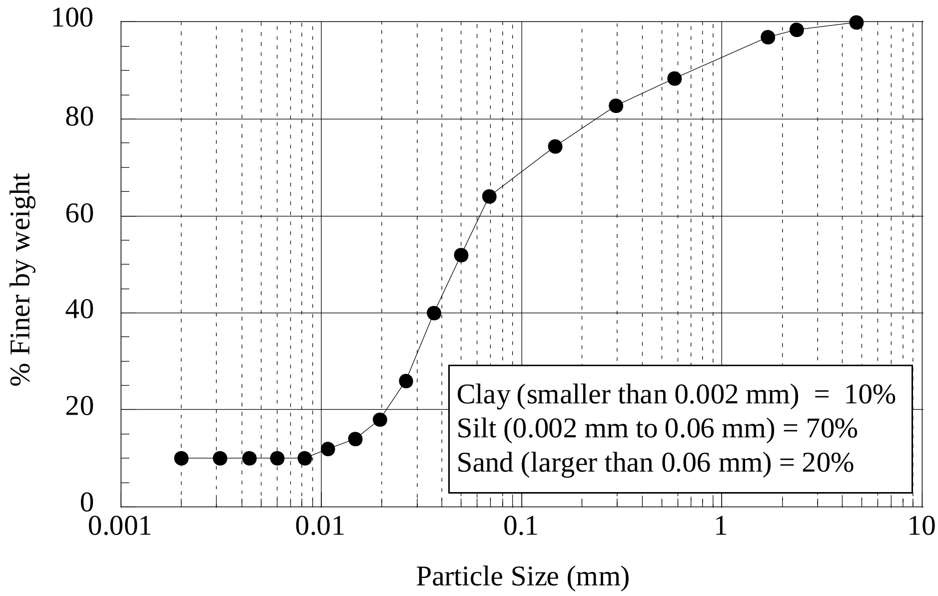


Figure 4.3: Particle size distribution of soil samples collected from Keraniganj

4.2.3 Effect of Nutrients

Nutrient test was conducted on different type of soil samples in different locations. From the Table 4.2 it is shown that in Pubail zone the pH is 4.60 which means the soil is acidic and in other zone pH value is 7.50 to 7.70 which means the soil is alkine. Other important factor for growth of plants is electrical conductivity. There is a direct and critical correlation between EC and plant growth performance. The response of plants to either low levels of fertilizer salts (EC <1) or high fertilizer salts (EC >1) will ultimately result in stunted growth and poor health. In addition, this accumulation of salts in the substrate and subsequent uptake by the plant roots can result in salt stress. Symptoms of salt stress include necrosis (death) of the roots and yellowing and wilting of the leaves. Thus, even though nutrient levels might be high the plant might show signs of nutrient deficiencies and drought stress.

Table 4.2: Nutrients of different type of soil at different zone

	Flood Zone		Coastal Zone	Flat Zone	
	Pubail	Taras, Sirajganj	Kuakata	Ladies Hall, BUET	Keraniganj
pH	4.60	7.50	7.70	7.50	7.80
OM (%)	1.66	3.17	1.30	2.89	0.38
Ec (ds/m)	–	0.52	15.9	0.59	0.32
Exch. Acidity	1.54	–	–	–	–
Ca (mg/100 gm soil)	1.0	2.82	9.7	8.30	2.83
Mg (mg/100 gm soil)	0.20	0.05	6.32	0.34	0.21
K (mg/100 gm soil)	0.16	0.34	0.35	0.24	0.14
Total N (%)	0.13	0.18	0.12	0.17	0.02
P (µgm/gm soil)	2.75	12.56	10	41.80	5.55
S (µgm/gm soil)	27.0	20.75	589	15.30	18.25
B (µgm/gm soil)	0.32	0.67	0.80	0.63	0.57
Cu (µgm/gm soil)	1.0	2.87	7.8	2.16	0.43
Fe (µgm/gm soil)	48	84.12	42	19.80	12.85
Mn (µgm/gm soil)	18.0	12.27	17.3	2.57	3.91
Zn (µgm/gm soil)	0.7	1.73	3.3	27.37	2.58

Depending on the type of plant, the salt concentration and the duration of exposure, a very high EC can quickly lead to plant death. But from the Table 4.2 it is also shown that vetiver can survive where EC range is 0 to 0.59 ds/m (Flood and Flat zone) and also in EC 15.9 ds/m.

4.3 Shear Strength of Soil Samples

In the field both vetiver rooted soil and bared soil samples are tested to determine the actual strength of vetiver rooted soil matrix and bared soil samples in the field condition because it is essential to determine the actual factor of safety of slopes.

4.3.1 In-situ Shear Strength of Block Samples

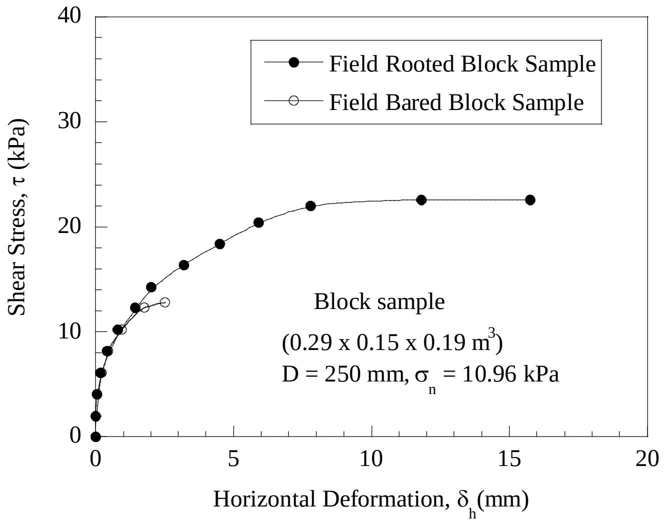
Tests were conducted at 250 mm depths from EGL for both rooted soil and soil without root. For each depth, tests were conducted under arbitrarily selected three different normal stresses (i.e., 10.96 kPa, 15.47 kPa and 19.98 kPa). Figure 3.2 in chapter 3 shows the detail test set-up for the in-situ direct shear test. Total 6 block samples were tested in the field under different normal stresses at same depths. Out of 6 samples, 3 samples were vetiver rooted and other 3 samples were bared soil.

Figure 4.4a–4.4c shows the typical shear stress and shear strain graph of block samples at 250 mm depth at three different normal stresses (i.e., 10.96 kPa, 15.47 kPa and 19.98 kPa). The test result of the samples at depth 250 is presented in Table 4.3. It is observed that the peak shear stress of vetiver rooted soil matrix is always higher than that of bared soil for a particular normal stress and peak shear stress increases with the increase of normal stress. It is also found that the strength of vetiver rooted soil matrix varies between 22.6 and 27.8. In this case the strength of vetiver rooted soil is about 1.8 times higher than that of bared soil. The failure behavior of the rooted soil is ductile and sustains to a higher strength and larger deformation before failure. It is seen that for normal stress of 10.96 kPa to 19.98 kPa, horizontal deformation of vetiver rooted soil is 5.42 time higher than that of the unreinforced soil.

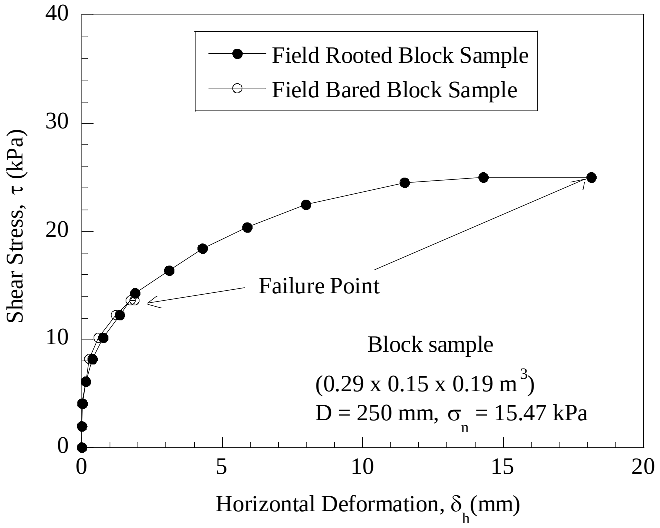
Table 4.3: Comparison of shear strength and horizontal failure deformation of rooted soil matrix and bared soil

Normal stress (kPa)	Peak shear stress τ_{max} (kPa)		Increase in peak shear stress of rooted soil τ_{max} (kPa)	Horizontal failure deformation, δ_{hf} (mm)		Increase in Horizontal failure deformation rooted soil, δ_{hf} (mm)
	Rooted Soil	Bared Soil		Rooted Soil	Bared Soil	
10.96	22.6	12.8	9.8	15.8	2.5	13.3
15.47	25.0	13.5	11.5	18.2	2.8	15.4
19.98	27.8	14.8	13.0	20.0	3.5	19.0

Note: natural moisture content, w_n = 25%



(a)



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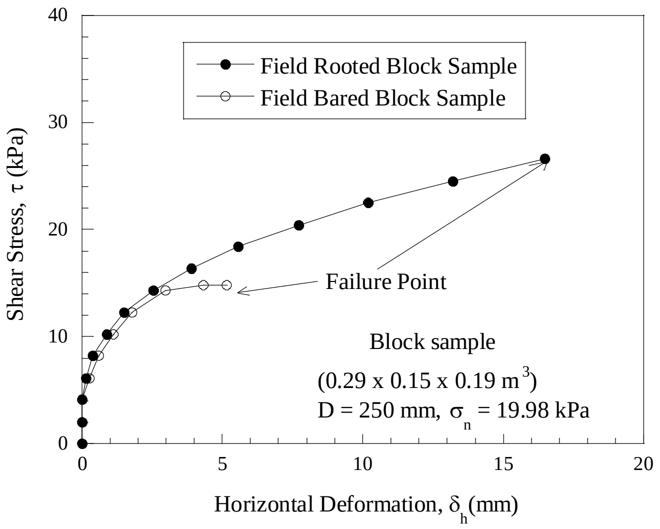


(c)

Figure 4.4: Shear stress versus horizontal deformation: (a) at normal stress, σ_n = 10.96 kPa; (b) at normal stress, σ_n = 15.47 kPa and (c) at normal stress, σ_n = 19.98 kPa. (Islam et al., 2013b)

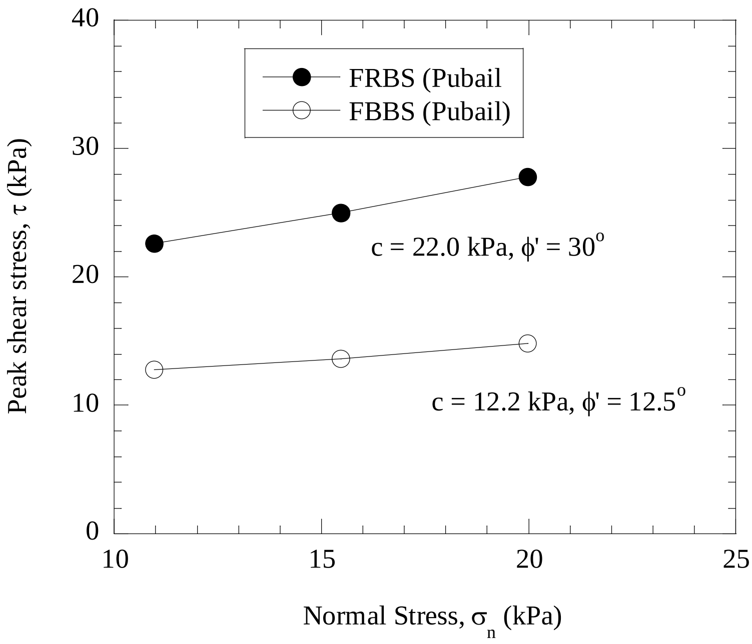


Figure 4.5: Peak shear stress versus normal stress, (Islam et al., 2013b)

4.3.2 Shear Strength Properties of Reconstituted Samples

Three reconstituted soil samples were tested under different normal stresses (i.e., 10.96 to 19.98 kPa) at the same soil sample which was collected from the field test site and natural moisture content, dry unit weight of the soil sample is tried to keep same as in the field condition. Natural moisture content (w_n) of the samples varied between 24 to 25%. Dry unit weight of the soil samples varies from 13.92 to 13.96 kN/m^3.

a) Different Root Content

Direct shear tests were conducted in different root content varies from 0% to 12% of the dry weight of soil sample. In this case the length of root is same (2.54 cm).

i) Effect of Root Content on Strength and Deformation:

Figure 4.6−4.10 shows the shear stress and shear deformation graphs of reconstituted soil samples. From the test results it is observed that the peak shear stress of vetiver rooted soil matrix varied 27.5 kPa to 45.7 kPa.

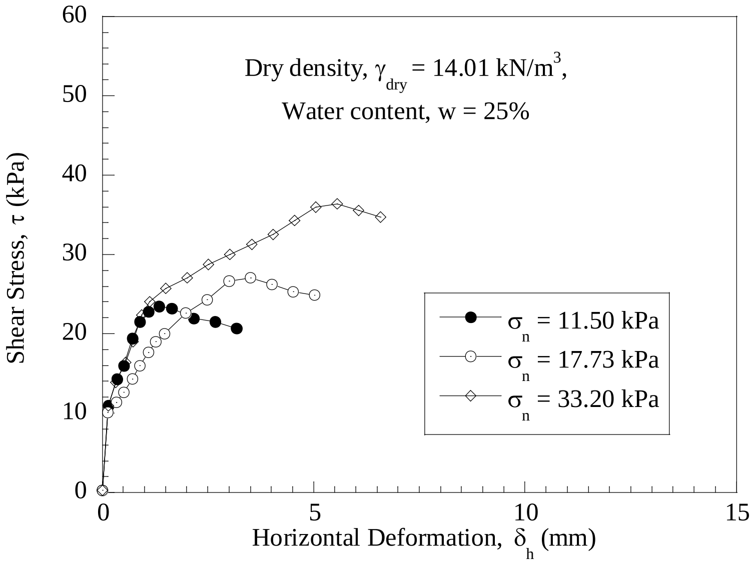


Figure 4.6: Shear stress vs horizontal deformation for bared soil

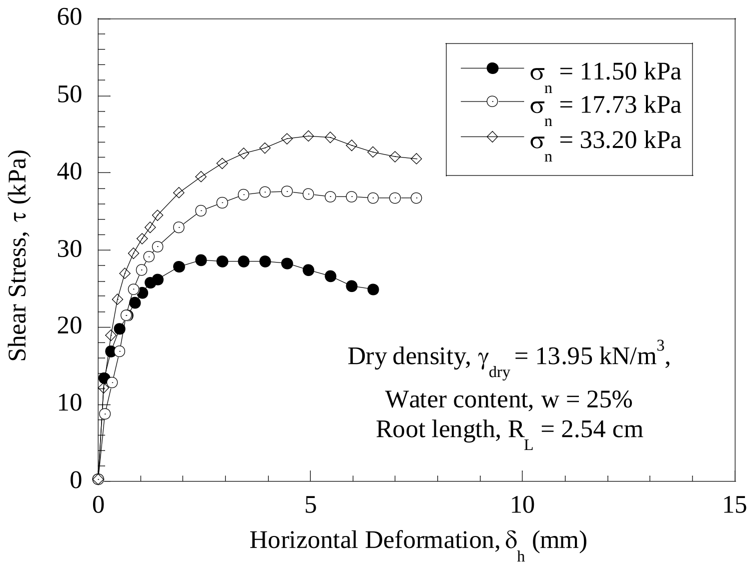


Figure 4.7: Shear stress vs horizontal deformation for 0.5% rooted soil

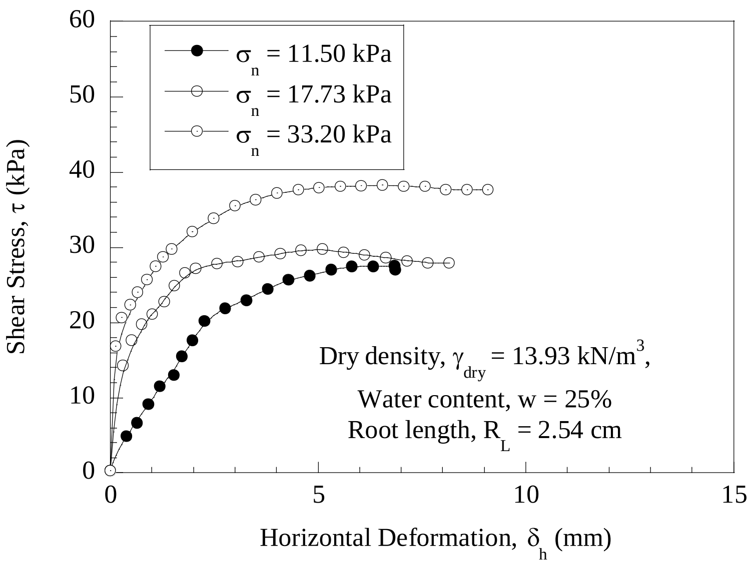


Figure 4.8: Shear stress vs horizontal deformation for 6% rooted soil (Islam et al., 2013b)

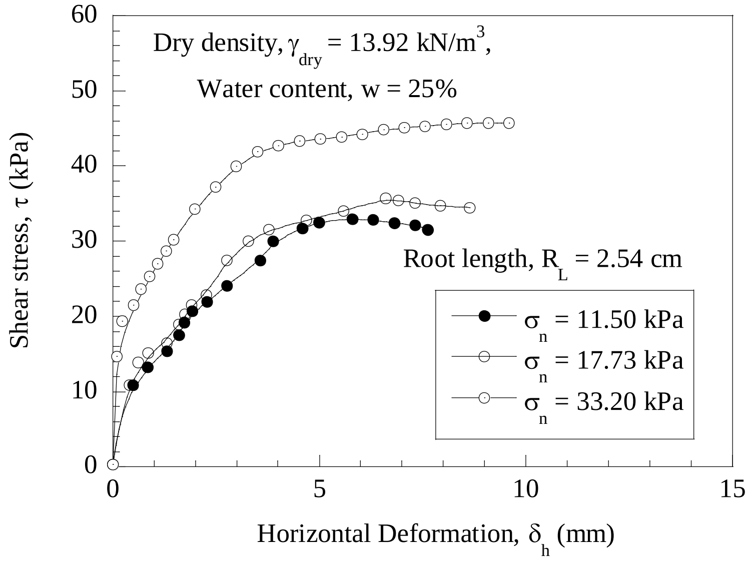


Figure 4.9: Shear stress vs horizontal deformation for 9% rooted soil (Islam et al., 2013b)

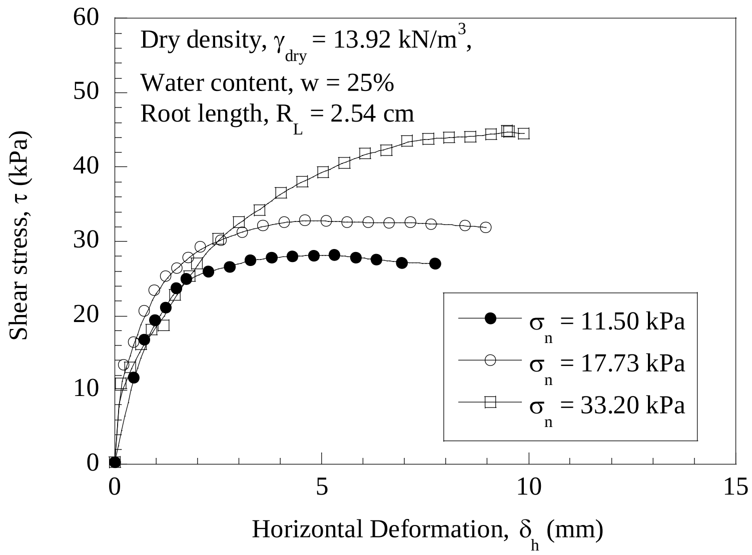


Figure 4.10: Shear stress vs shear deformation for 12% rooted soil (Islam et al., 2013b)

(a)

(b)

(c)

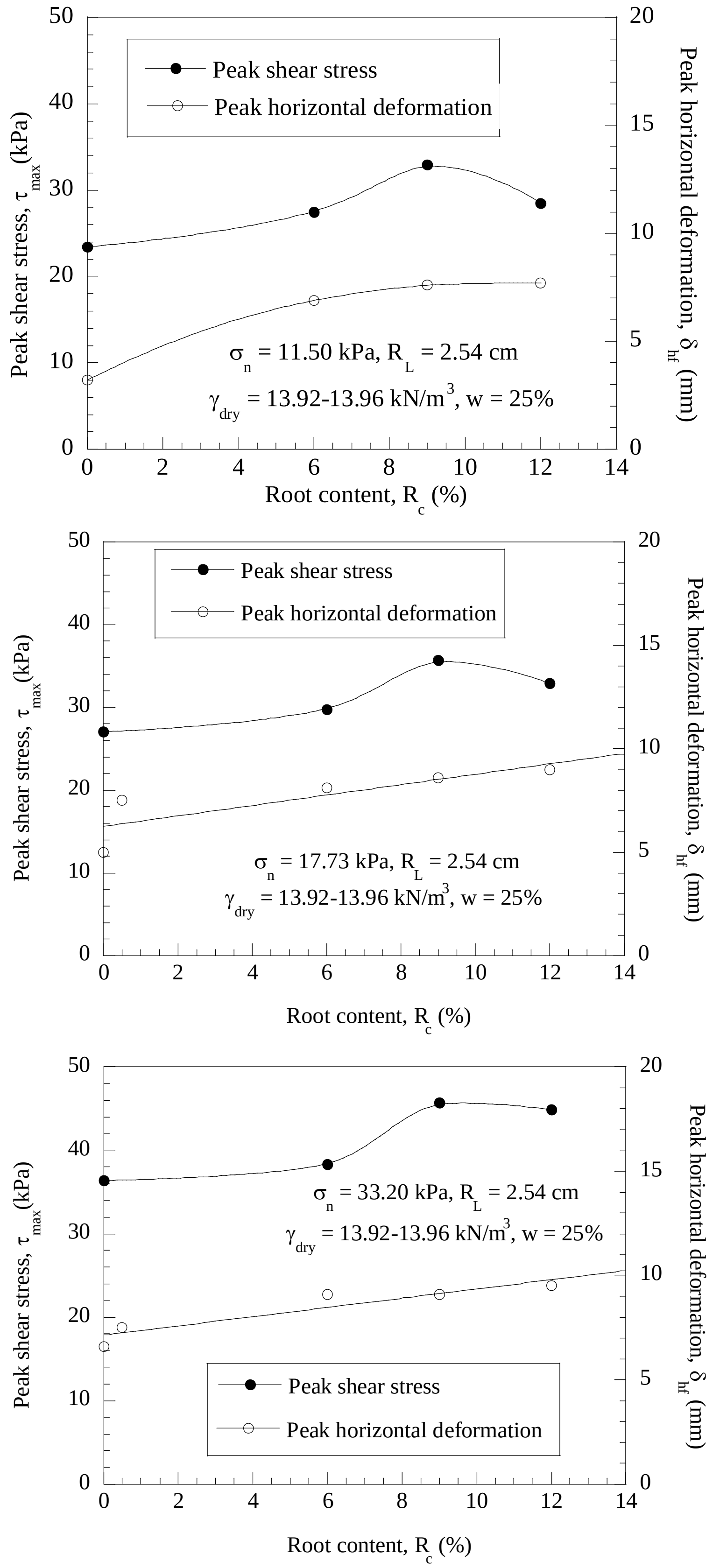


Figure 4.11: Comparison of peak shear stress vs peak horizontal deformation for different root content and normal stress: (a) at 11.50 kPa; (b) at 17.73 kPa and (c) at 33.20 kPa

It is also found that strength of vetiver rooted soil is 1.28 times higher in 0.5% root content, 1.10 times higher in 6% root content, 1.32 times higher in 9% root content and 1.22 times higher in 12% root content than that of the bared soil.

From the Figure 4.11a–4.11c, it is seen peak shear stress varies at different root content. The strength of 9% rooted soil sample is higher than 0, 0.5, 6 and 12% rooted sample. On the other hand deformation is increased as percentage of root content increased. Summary of the test results is listed in the Table 4.4.

ii) Effect of Root Content on Cohesion and Angle of Friction:

Figure 4.12−4.16 shows the average failure envelope of 0, 0.5, 6, 9 and 12% vetiver rooted mix soil samples respectively. From the test result, it is seen that both the average cohesion and average angle of internal friction of vetiver root mixed reconstitute soil samples are higher than those of the reconstitute bared soil.

From the Figure 4.17a–4.17b, it is seen that cohesion and angle of internal friction varies at different root content.

It means that percentage of roots in soil matrix has a major effect on the shear strength, cohesion and angle of internal friction of soil and there is an optimum combination of root and soil percentage. It follows the mechanism of fiber action. Summary of the test results is listed in the Table 4.5.

Table 4.4: Comparison of shear strength properties of the reconstituted bared and rooted soil at different root content

σ_n (kPa)	Bared soil		0.5% root mixed soil		6% root mixed soil		9% root mixed soil		12% root mixed soil	
	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)
11.5	23.42	3.2	28.73	6.5	27.5	6.9	32.97	7.6	28.5	7.7
17.73	27.03	5.0	37.64	7.5	29.79	8.1	35.69	8.6	32.89	9.0
33.2	36.37	6.6	44.77	7.5	38.28	9.1	45.7	9.1	44.86	9.5

σ_n = normal stress; τ_{max} = peak shear stress and δ_{hf} = horizontal failure deformation

Table 4.5: Comparison of strength and shear deformation of reconstituted bared and rooted soil at different root content

Bared soil				0.5% root mixed soil				6% root mixed soil				9% root mixed soil				12% root mixed soil			
c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°
18.0	27.0	16.0	31.0	27.5	45.6	30.5	32.0	24.0	20.0	20.0	28.8	28.0	23.6	24.0	32.9	28.0	31.2	26.0	37.7

Initial water content = 25%, Dry unit weight, γ_{dry}= 13.92 to13.96 kN/m^3

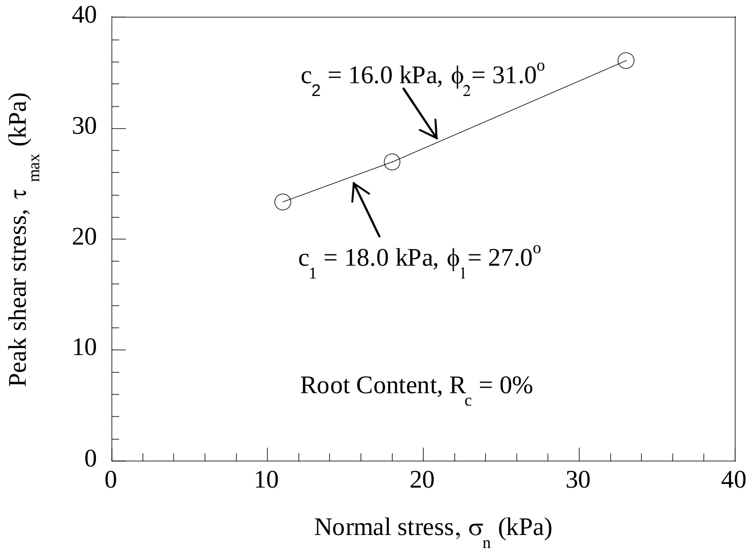


Figure 4.12: Shear stress vs normal stress for bared soil

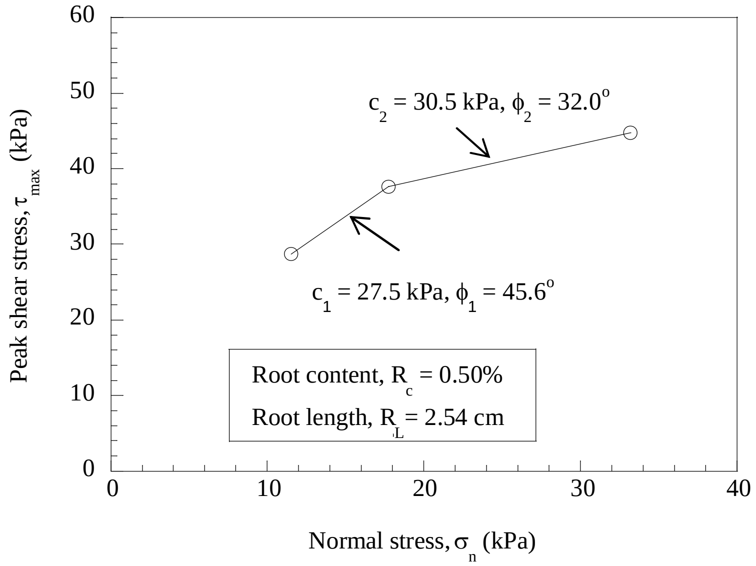


Figure 4.13: Shear stress vs normal stress for 0.5% rooted soil

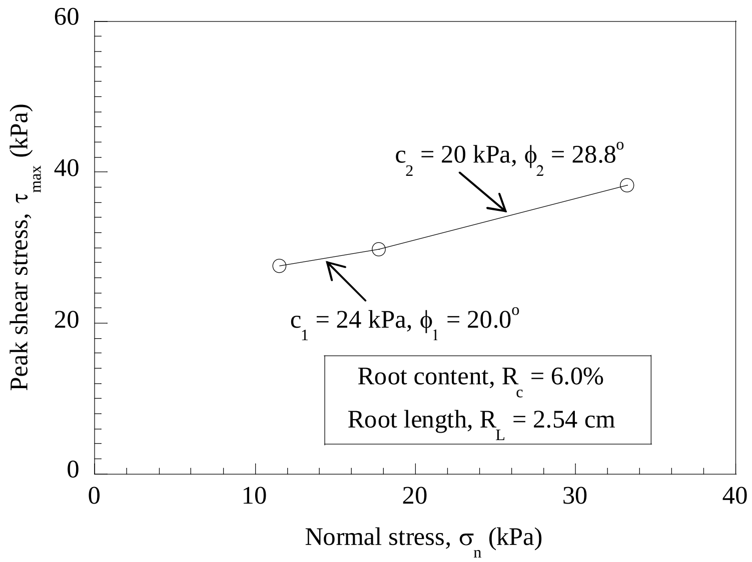


Figure 4.14: Shear stress vs normal stress for 6% rooted soil (Islam et al., 2013b)

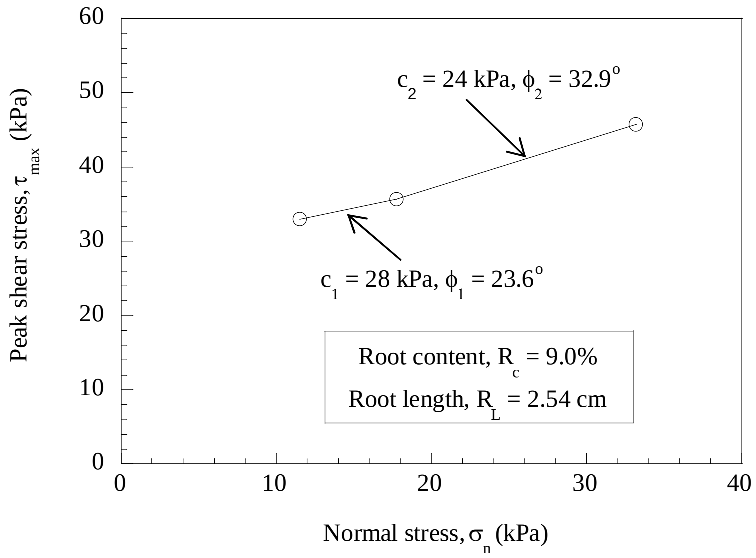


Figure 4.15: Shear stress vs normal stress for 9% rooted soil (Islam et al., 2013b)

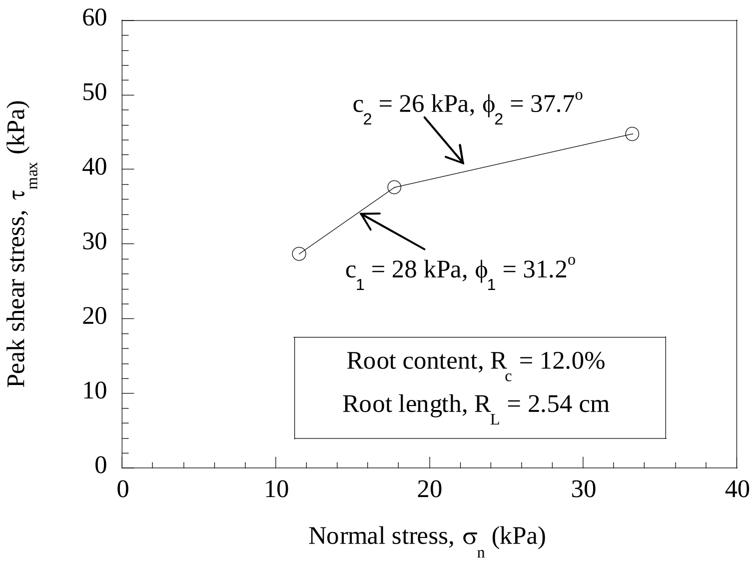
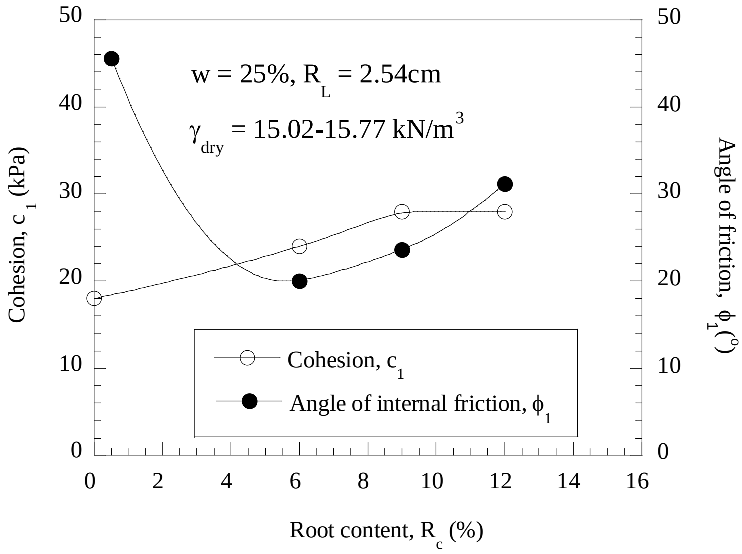
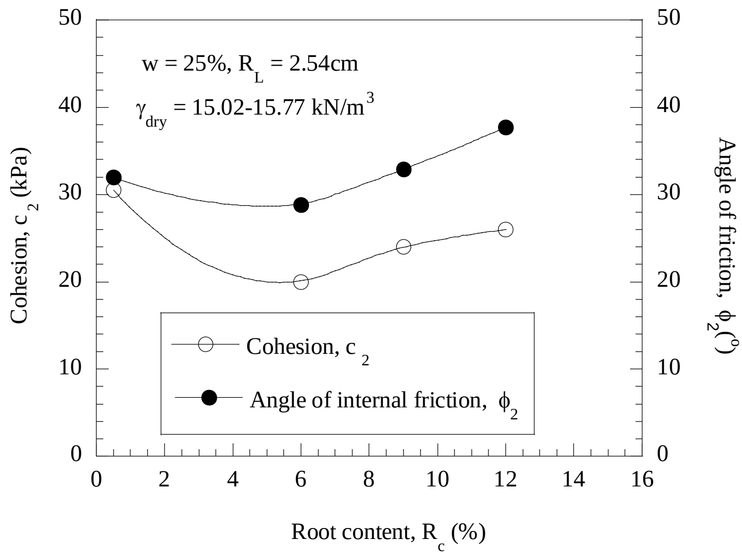


Figure 4.16: Shear stress vs normal stress for 12% rooted soil (Islam et al., 2013b)



(a)



(b)

Figure 4.17: Comparison of cohesion and angle of friction for different root content: (a) c_1 vs ϕ_1 and (b) c_2 vs ϕ_2

b) Different Root Length

Direct shear test was conducted in different root length varies from 1.25 cm to 5.0 cm of the dry weight of soil sample. In this case the root content is constant (6%).

i) Effect of Root Length on Strength and Deformation:

Figure 4.18−4.21 shows the shear stress and shear deformation graph of the reconstitute soil samples. The test result of the samples in different root content is presented in the Table 4.6. From the test results it is observed that the peak shear stress of vetiver rooted soil matrix varied 27.15 kPa to 45.28 kPa. From the figure 4.22a-4.22c, it is seen peak shear stress varies at different root content. The strength of 1.25 cm rooted soil sample is higher than 0, 2.54 and 5.0 cm rooted sample.

The deformation of the root mixed reconstitute soil sample with different length of roots is not uniformly increased like deformation of different root content. 1.25 cm root length shows higher deformation than 0, 2.54 and 5.0 cm root length.

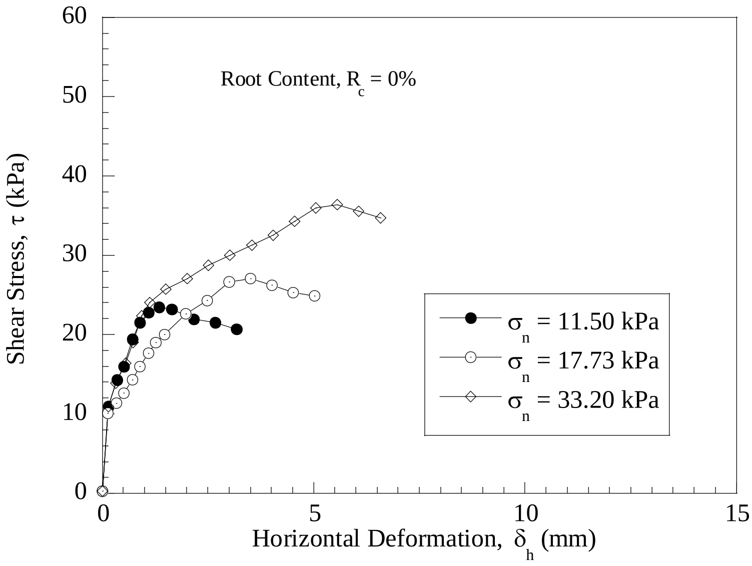


Figure 4.18: Shear stress vs shear deformation for bared soil

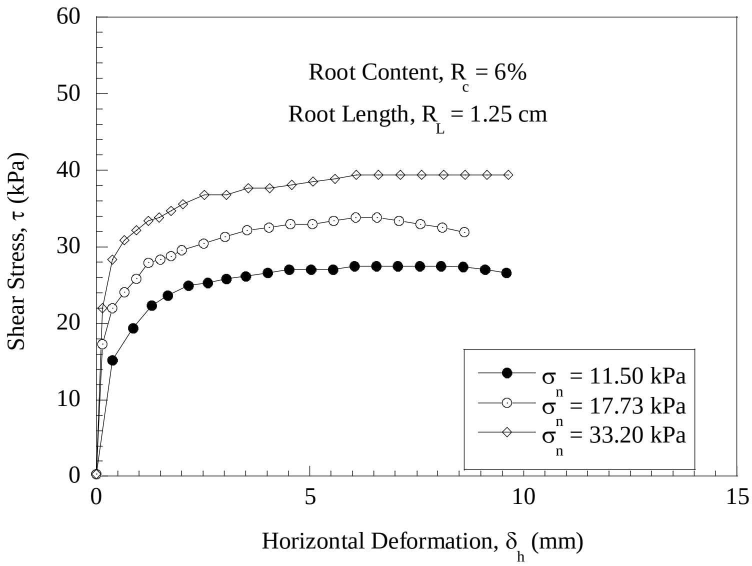


Figure 4.19: Shear stress vs shear deformation for 1.25 cm root length

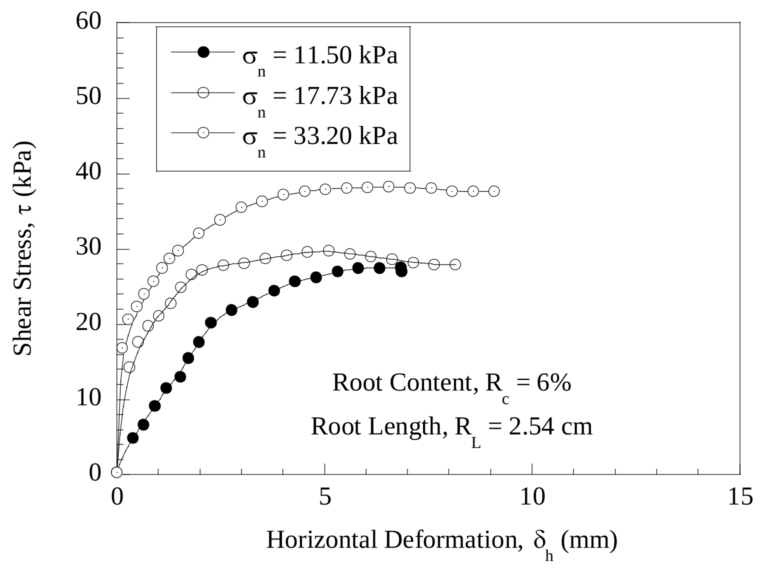


Figure 4.20: Shear stress vs shear deformation for 2.54 cm root length

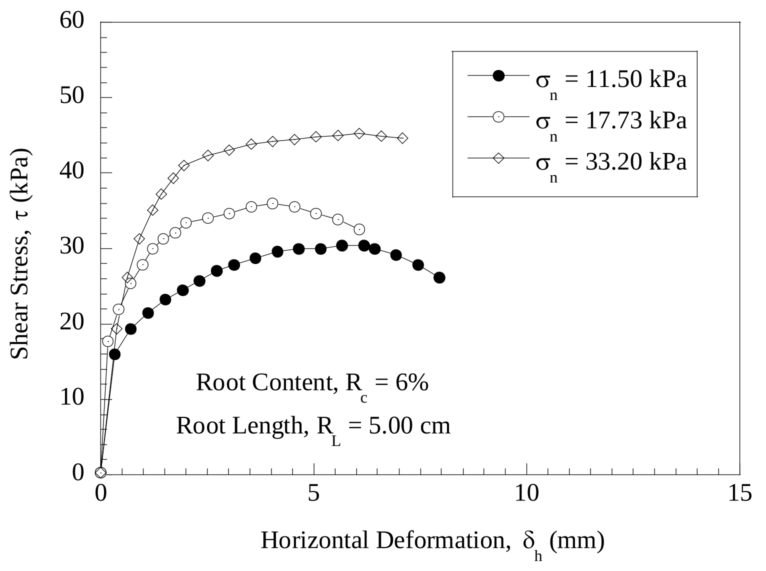


Figure 4.21: Shear stress vs shear deformation for 5 cm root length

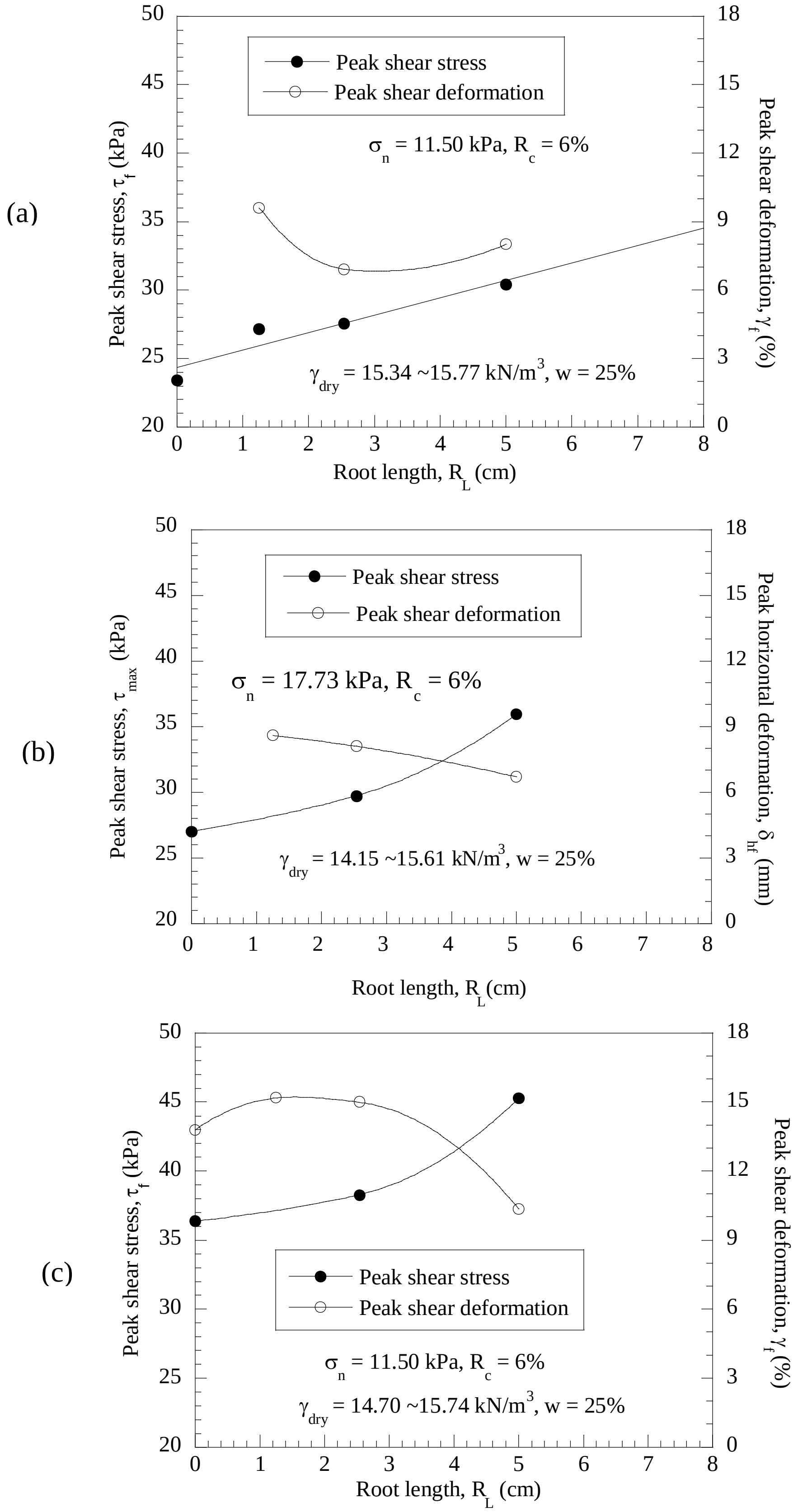


Figure 4.22: Compare of peak shear stress vs peak horizontal deformation for different root length and normal stress: (a) at 11.50 kPa; (b) at 17.73 kPa and (c) at 33.20 kPa

Table 4.6: Comparison of strength and shear deformation of reconstituted bared and rooted soil at different root length

	Bared soil		1.25 cm root length		2.54 cm root length		5 cm root length	
σ_n (kPa)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)	τ_{max} (kPa)	δ_{hf} (mm)
11.5	23.42	3.2	27.15	9.61	27.5	6.9	30.43	8.0
17.73	27.03	5.0	33.82	8.6	29.79	8.1	35.94	6.7
33.2	36.37	6.6	39.76	9.7	38.28	9.1	45.28	7.1

σ_n = normal stress; τ_{max} = peak shear stress and δ_{hf} = horizontal failure deformation

Table 4.7: Comparison of shear strength properties of the reconstituted bared and rooted soil at different root length

Bared soil				1.25 cm root length				2.54 cm root length				5 cm root length			
c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°	c_1 (kPa)	ϕ_1°	c_2 (kPa)	ϕ_2°
18.0	27.0	16.0	31.0	16.0	45.6	26.5	21.0	24.0	20.0	20.0	28.8	22.0	41.5	26.0	31.1

Water content = 25%, Dry unit weight, γ_{dry}= 13.92 to 13.96 kN/m^3

2) Effect of Root Content on Cohesion and Angle of Friction:

Figure 4.23−4.26 shows the average failure envelope of 0, 1.25, 2.54 and 5.0 cm long vetiver rooted mix soil samples respectively. From the test result, it is seen that both the average cohesion and average angle of internal friction of vetiver root mixed reconstitute soil samples are higher than those of the reconstitute bared soil.

From the Figure 4.17a–4.17b, it is seen that cohesion and angle of internal friction varies at different root content. Summary of the test results is listed in Table 4.7.

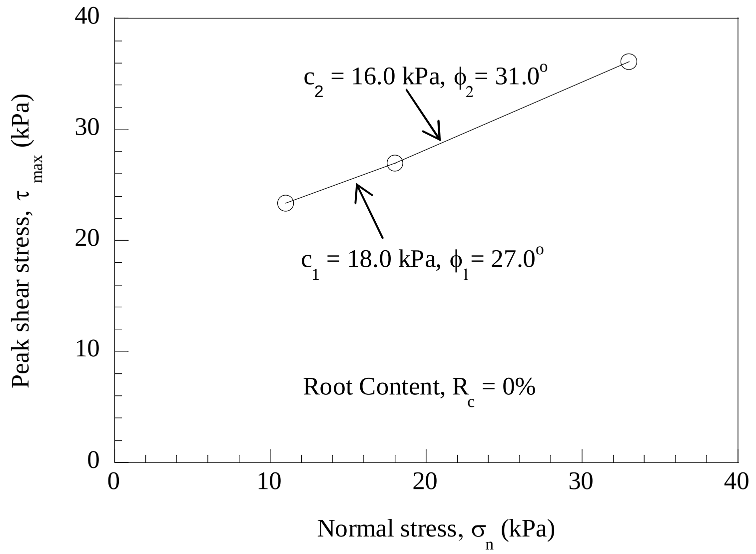


Figure 4.23: Shear stress vs Normal stress for bared soil

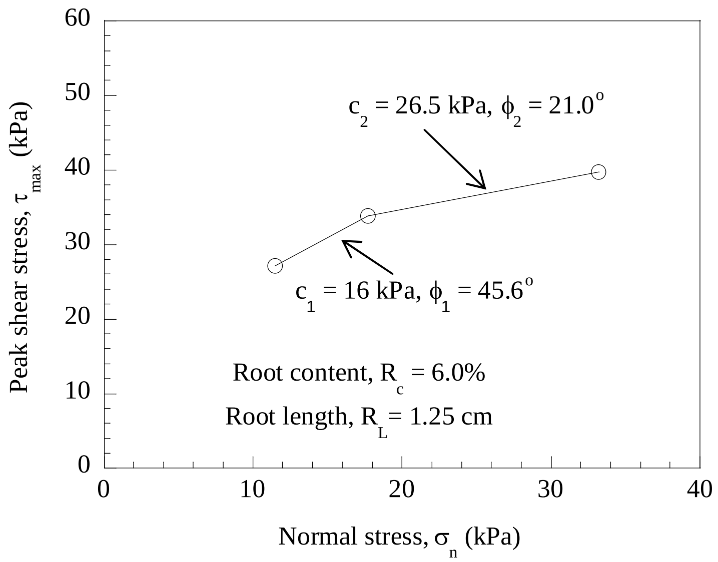


Figure 4.24: Shear stress vs Normal stress for 1.25 cm root length

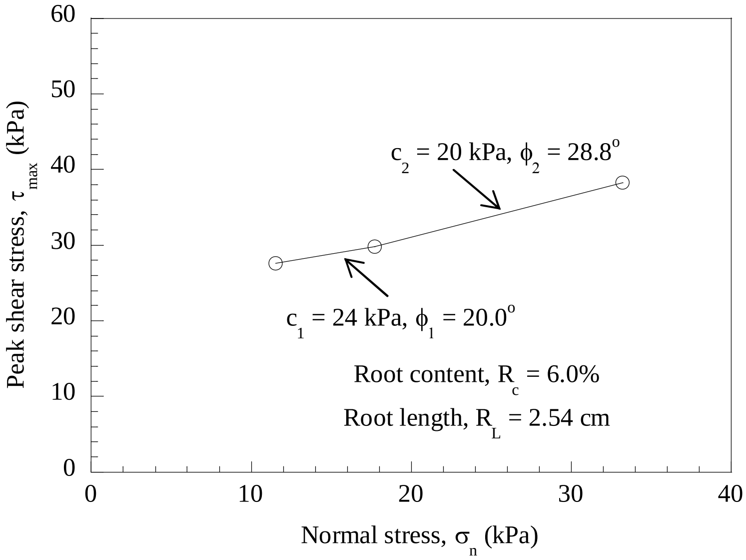


Figure 4.25: Shear stress vs Normal stress for 2.54 cm root length

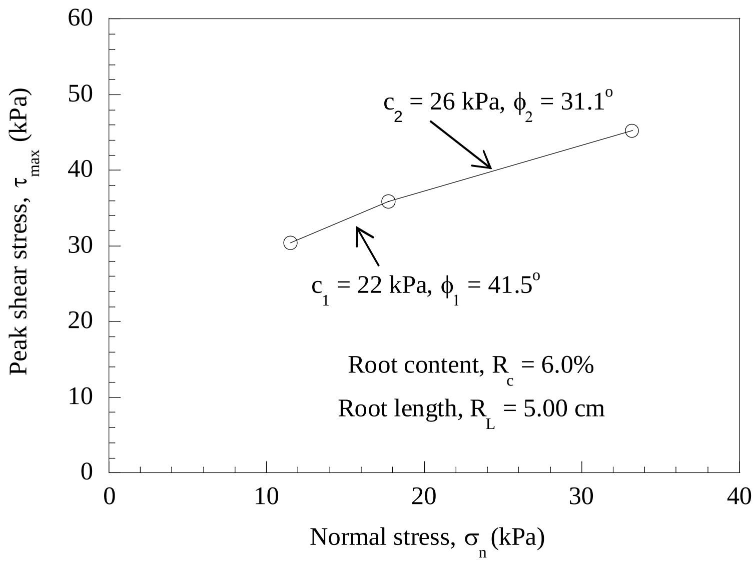


Figure 4.26: Shear stress vs Normal stress for 5 cm root length

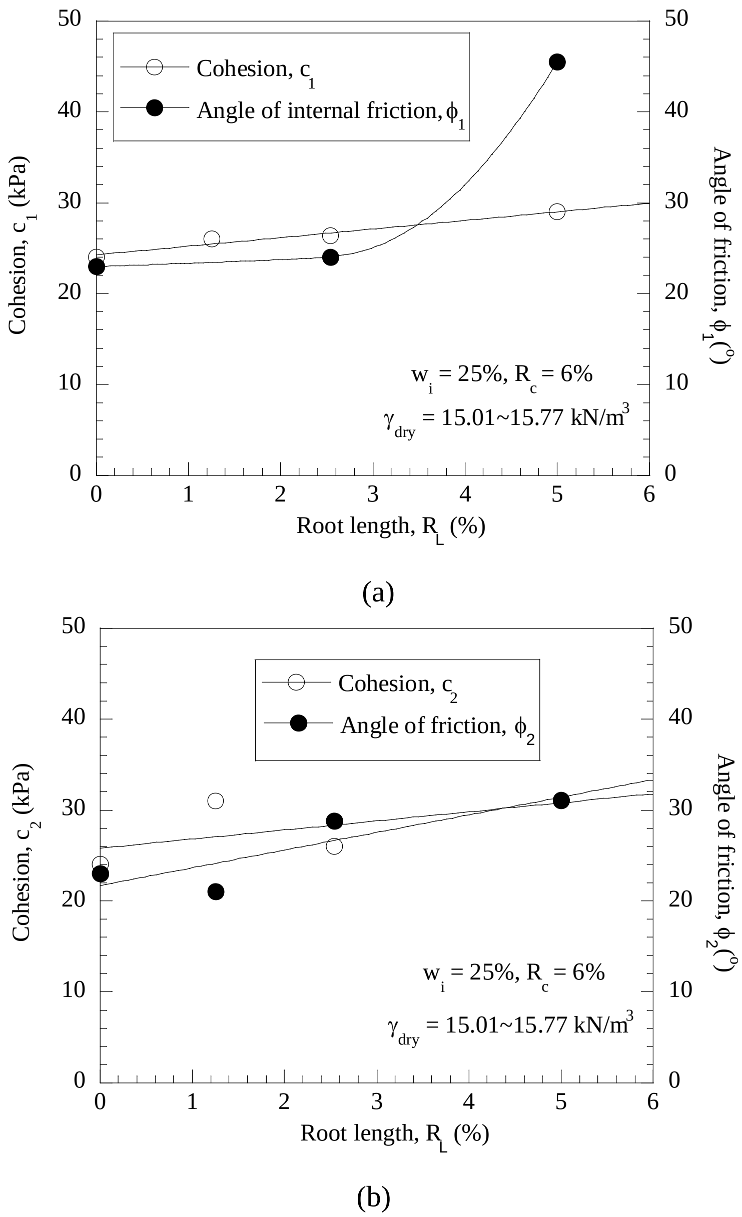


Figure 4.27: Comparison of cohesion and angle of friction for different root length: (a) c_1 vs ϕ_1 and (b) c_2 vs ϕ_2

From Figures 4.11, 4.17, 4.22 and 4.27, it is seen that shear stress, deformation, cohesion and angle of internal friction of a soil matrix continuously fluctuated with the increase in both root content and root length. It is due to the optimum combination of root in the soil matrix. The shear stress, deformation, cohesion and internal friction of a rooted soil matrix depends on the interaction between the soil and the roots and the distribution of roots on the soil matrix. The interaction between the soil particle and roots depends on the texture of soil and roughness and stiffness of roots. When a shear force comes at a certain plane in a rooted soil matrix the shear force is resist by both the soil and roots. The performance of the rooted soil matrix depends on the critical combination of soil and roots on the failure plane. The critical combination also fluctuates with root ratio and root content. That's why the shear stress, deformation, cohesion and angle of internal friction of a soil matrix continuously fluctuated. It means that the percentage and length of roots in the soil mix have a major effect on the shear strength of soil.

4.4 Growth Rate of Vetiver Grass

4.4.1 Field Condition

Figure 4.28 shows the growth rate of leaves with time. The growth rate of vetiver roots measured only planted time, 10 months of plantation and after 13 months of plantation. At the time of plantation leave height was 20 cm and after 11 months it was 175 cm. On the other hand root height of root at plantation was 10 cm and after 13 months it was 25 cm.

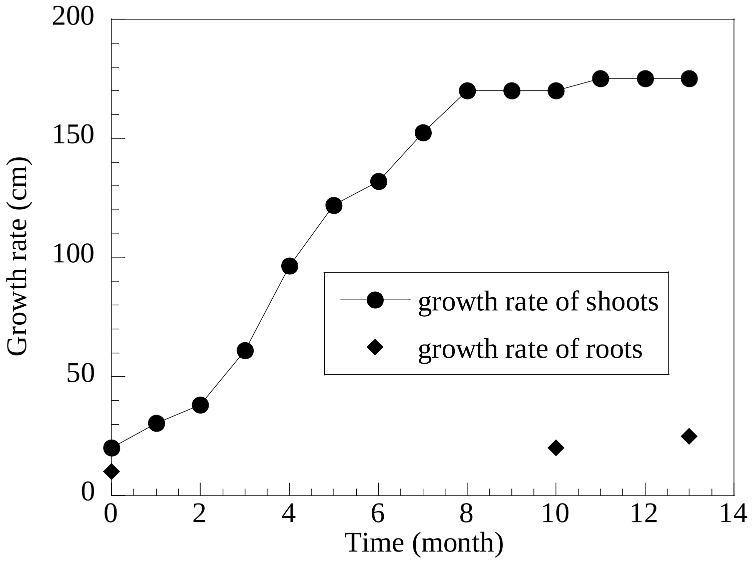


Figure 4.28: Growth rate of vetiver shoots and roots

4.4.2 Model Study

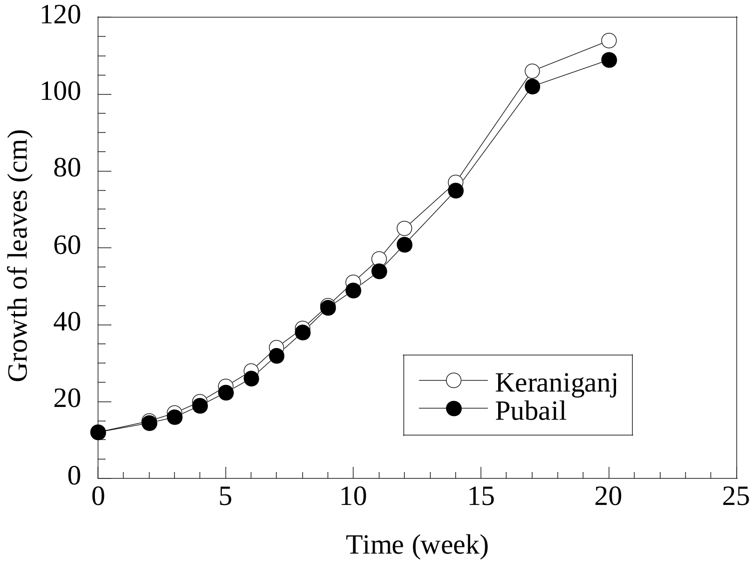
Figure 4.29 and 4.30 shows the growth of vetiver roots in submerge conditions. Growth of leaves is almost same in Pubail soil and Keraniganj soil. As the growth of root was not possible to measured every week it was measured only time of plantation and after 3 months of plantation. At plantation time root length was 9 cm and after 3 months it was 27.94 cm in Keranigang soil and in Pubail soil root length was 9 cm at plantion time and after 3 months it was 12.7 cm. Growth of root in Keraniganj soil (silty sand) is higher than that of Pubail soil (clay soil). But in both soil vetiver is survive in submerge condition.


(a) (b)

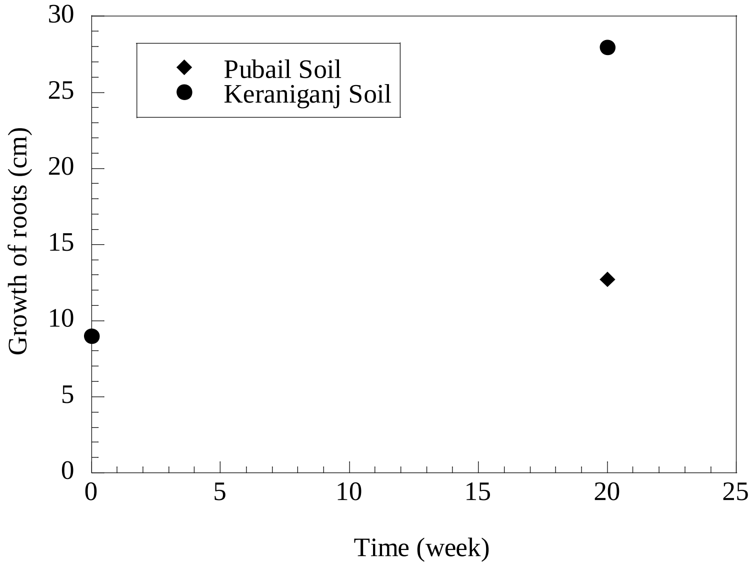
Figure 4.29: Growth of root in Keraniganj soil: (a) at plantation time and (b) after 3 months of plantation


(a) (b)

Figure 4.30: Growth of root in Pubail soil: (a) at plantation time and (b) after 3 months of plantation



(a)



(b)

Figure 4.31: Time vs growth rate of Pubail and Keraniganj soil in submerge condition: (a) shoots and (b) roots

4.5 Efficacy of Vetiver Grass in Top Soil Erosion Control

Figure 4.32 shows the condition of slope before and after test done. A comparative result of soil erosion without and with vegetated cover is presented in the Figure 4.33. Cumulative percentage of soil erosion for two hours for both bare soil and vegetated covered soil, It may be seen from the graph that cumulative erosion of bare soil is significantly high (3.4% of total soil mass used for the test) compared to that of (bellow 0.96% of total soil mass used for the test) vegetated covered soil. Hence total reduction of erosion is almost 71% of total erosion.

(a) (b)

Figure 4.32: Condition of slope: (a) before test and (b) after test

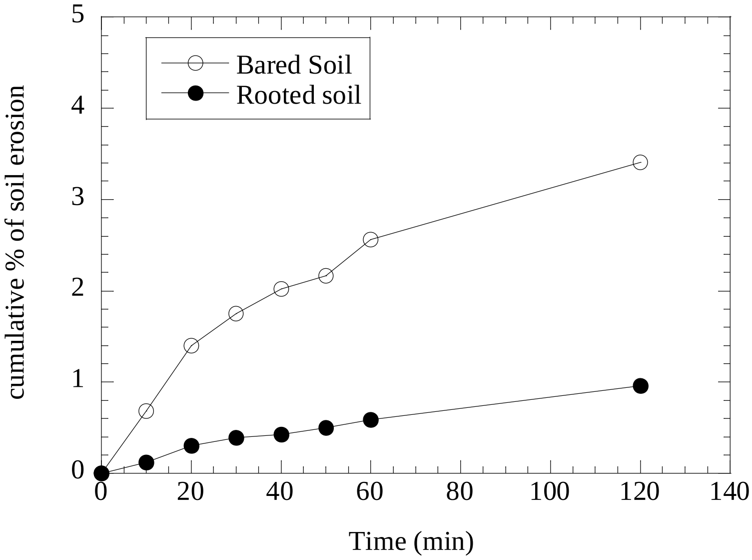


Figure 4.33: Cumulative percent soil erosion vs time graph

4.6 Stability of Slopes

From the field tests and laboratory test it is found that vetiver grass enhanced effective soil cohesion of the vetiver rooted roil matrix. Therefore, it is clear that vetiver grass is able to increase the stability of embankment slopes. Stability of slopes using infinite slope method is broadly discussed in the article 3.4 of Chapter 3.

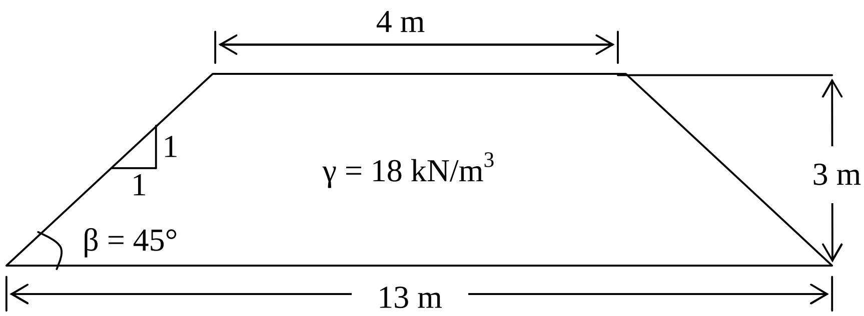


Figure 4.34: Typical embankment section of Bangladesh

The Parameters used for Stability analysis:

$$FS = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\beta \tan\phi'}{\gamma z \sin\beta \cos\beta}$$

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2\beta + T\sin\theta]\tan\phi' + T\cos\theta}{\{(\gamma z + W)\sin\beta + D\}\cos\beta}$$

The values of the parameters used for stability analyses and the Factor of Safety at different conditions are presented in Table 4.8, 4.9 and 4.10.

Table 4.8: Parameters used for stability analyses

Parameters	Bared Soil	Rooted soil
Unit weight of soil, γ (kN/m^3)	18	18
Vertical height of soil above slip plane (m)	1	1
Slope angle, β (deg.)	33.7	33.7
Unit weight of water, γ_w (kN/m^3)	9.8	9.8
Vertical height of ground water table above slip plane, h_w (m)	0	0
Surcharge due to weight of vegetation, W (kN/m^2)	5.51	5.51
Vertical height of groundwater table above the slip plane with the vegetation, h_v (m)	0	0
Tensile root force acting at the base of the slip plane, T (kN/m)	0.4	0.4
Angle between roots and slip plane, θ (deg.)	0	0
Wind loading force parallel to the slope, D (kN/m)	0.1	0.1

Table 4.9: Factor of Safety of Embankment Slope on the basis of in-situ test results

Parameters			Factor of Safety		Times Higher
c' (kPa)	c_R' (kPa)	ϕ ' (°)	Bared soil	Rooted soil	
12.2	9.8	12.5	1.6	2.5	1.5

c' = effective soil cohesion for bared soil, c_R' = enhance effective cohesion due to soil reinforcement by roots, ϕ' = effective angle of internal friction

Table 4.10: Factor of Safety of Embankment Slope on the Basis of Reconstitute Soil Samples Test Results at Different Root Content

Root content (%)	Parameters			Factor of Safety	Times Higher
	c' (kPa)	c_R' (kPa)	ϕ ' (°)		
Bared	18.0	-	31.0	2.6	-
0.5	18.0	12.5	31.0	3.6	1.4
6.0	18.0	6.0	31.0	3.1	1.2
9.0	18.0	10	31.0	3.4	1.3
12.0	18.0	10	31.0	3.4	1.3

c' = effective soil cohesion for bared soil, c_R' = enhance effective cohesion due to soil reinforcement by roots, ϕ' = effective angle of internal friction

Table 4.11: Factor of Safety of Embankment Slope on the Basis of Reconstitute Soil Samples Test Results at Different Root Length

Root length (cm)	Parameters			Factor of Safety	Times Higher
	c' (kPa)	c_R' (kPa)	ϕ ' (°)		
Bared	18.0	-	31.0	2.6	-
1.25	18.0	8.5	31.0	3.3	1.3
2.54	18.0	6.0	31.0	3.1	1.2
5.00	18.0	8.0	31.0	3.2	1.2

4.7 Summary

Both laboratory and field tests were conducted to determine the soil properties and strength of vetiver rooted soil matrix and bared soil. Growth rate of shoots and roots was measured for different soils under submerged condition. To determine the soil loss of bared slope and vegetated slope erosion tests were conducted on small scale models. Factor of safety of embankment slopes was determined for vetiver planted slope with different root lengths and contents. Main findings of this study are:

a) Field tests were conducted on vetiver rooted block soil samples and bared soil samples under different normal stresses (i.e., 10.96 kPa to 19.98 kPa) and different depths (250 mm). It is found that the shear strength and shear strain of vetiver rooted soil matrix is 1.83 times higher than that of bared soil.

b) Direct shear test was conducted on reconstituted samples prepared with different root contents varying from 0% to 12% of the dry weight of soil samples under different normal stresses (i.e., 10.96 to 19.98 kPa). In this case the length of root was constant (2.54 cm). From the test results, it is found that shear strength increases with increases of root content up to 9%. However, it is also found that shear strength of vetiver rooted soil is 1.1 to 1.32 times higher than that of the bared soil depending on the percentage of root content.

c) Direct shear test was conducted on samples prepared with different root lengths varying from 1.25 cm to 5.00 cm under different normal stresses (i.e., 10.96 to 19.98 kPa). In this case the root content was 6% of the dry weight of the soil samples. From the test results, it is found that shear strength increases with increases of root length. However, it is also found that shear strength of vetiver rooted soil is 1.1 to 1.29 times higher than that of the bared soil.

d) To observe the growth rate under submerged condition, vetiver grass planted in both silty sand and clay soil. It is found that vetiver can survive under submerge condition for three months. It is also found that growth rate of vetiver grass in silty sand is higher than that of in clay soil. From the nutrients test. it is found that vetiver grass can survive both in acidic (pH: 7.80) and saline soil (EC: 15.9).

e) Vetiver roots grew up to 25 cm in 13 months after plantation where as in USA the growth of vetiver roots is found to be 197 cm (Nix et al., 2006) and in Thailand the growth is found to be 400 cm in 9.6 months (Hengchaovanich and Nilaweera). The difference in growth rate of vetiver roots is due to nutrient and moisture content of the sites.

f) The results showed that cohesion and angle of internal friction of rooted soil is always higher than that of bared soil. From the obtained cohesion and angle of internal friction the stability of embankment slopes are estimated by using the infinite slope method of slope stability analysis. From the analyses, it is found that the vetiver grass is able to increase the factor of safety of embankment slope by 1.5 times.

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The main objective of the research was to determine the shear strength of rooted and bared soil by in-situ shear strength test and direct shear test on laboratory reconstituted samples. Besides, growth of vetiver grass was monitored in different soil and climatic conditions. Efficacy of the vetiver planted slope was studied using small scale models. Finally, slope stability analyses were conducted based on the properties obtained in the study. Results obtained from the study have been summarized in this chapter. Some recommendations for future study have also been listed.

5.2 Summary

The main findings of the study are as follows:

a) In-situ tests were conducted at 250 mm depths from EGL for both rooted soil and bared soil. For each depth, tests were conducted for arbitrarily selected three different normal stresses (i.e., 10.96 kPa, 15.47 kPa and 19.98 kPa). It is seen that the shear strength, τ_{max} of the vetiver rooted soil matrix vary between 22.6 to 27.8 kPa which is 1.1 to1.4 times higher than that of bared soil. Vetiver grass has strong and long finely structured root system which makes a heavy anchor with the soil particles. This anchor increases the shear strength and shear strain of rooted soil matrix. From the shear stress versus normal stress graph, it seen that the cohesion of bared soil and vetiver rooted soil matrix at 250 mm depth from EGL is 12.2 kPa and 22.0 kPa. On the other hand, the angle of internal friction of bared soil and vetiver rooted soil matrix is 12.5˚ and 30.0˚, respectively.

   Direct shear tests were conducted on reconstituted soil samples for varying root contents (0% to 12% of dry weight of soil having root length of 2.54 cm under different normal stresses (i.e., 10.96 to 19.98 kPa). Test results showed that τ_{max}

of vetiver rooted soil are 1.1 to 1.4 times higher than that of bared soil depending on the percentage of root content. δ_{hf} of vetiver rooted soil increases from 1.1 to 2.2 times in comparison to that of bared soils with the increase of root content from 0.5% to 12%. It was found that shear strength (τ_{max}) increases with the increase of root content up to 9% rooted soil. However, the strength decreases at higher root contents. On the contrary, δ_{hf} increases with the increase of root content.

Direct shear tests were also conducted on laboratory reconstituted soil samples prepared with different root length varying from 1.25 cm to 5.00 cm under different normal stresses (i.e., 10.96 to 19.98 kPa) having 6% root content. Test results show that the shear strength, τ_{max} of vetiver rooted soil is 1.1 to 1.4 times higher than that of bared soil. Similarly, δ_{hf} of vetiver rooted soil increases from 1.1 to 3.0 times in comparison to that of bared soils for the increase of root content from 1.25 cm to 5.00 cm.

So, it can be said that both the root content and root length in the soil mix have significant effect on the shear strength and deformation of the soil matrix.

b) Model study was conducted to investigate the effect of submergence on the vetiver grass growth. It is found that vetiver grass can survive even under submerge condition in different types of soil condition. Vetiver grass was able to survive for 3 months of observation.

c) Vetiver grass was planted in different types of soil conditions. The shoot of vetiver grass planted in Pubail soil (silty clay) and Keraniganj soil (silty sand) grew up to 114 cm and 109 cm, respectively in 3 months. Root length grew 28 cm in Keranigang soil and 13 cm in Pubail soil, in that period. In field condition, the shoot of vetiver grass grew up to 175 cm in 13 months. On the other hand, root grew 25 cm in the same period of 13 months. It is clear that growth rate of vetiver grass in silty sand is higher than that of in silty clay soil.

d) It is found that vetiver grass can grow in the soil which contains pH from 4.60 to 7.7. Vetiver grass can also survive in the soil where EC ranges from 0 to 15.9 ds/m. It is clear that vetiver can survive in different soil conditions.

e) It is observed that vetiver grass planted on embankment slopes will be able to increase the factor of safety of embankment slope from 1.23 to 1.50 in comparison to bared soil. It may be difficult to protect from the deep slope failure but it shows significant improvement in case of shallow depth failure.

f) Erosion test was conducted on small scale models to determine the efficacy of vetiver grass in erosion control. Vetiver grass is effective in reducing erosion of the slope by 71%.

5.3 Conclusions

From this investigation, it can be said that the vetiver grass plantation is effective to protect the embankment slopes against top soil erosion and runoff. It may act better in wave action. It also works against shallow depth failure. Plantation of vetiver can be a cost-effective, sustainable and eco-friendly method for the erosion control as well as shallow depth slope failure in Bangladesh.

5.4 Recommendations for Future Studies

The main objectives of this research is to know the effectiveness of vetiver grass in protecting embankments on the basis of in-situ shear strength of vetiver rooted soil matrix of flood plain zone. During the study, it was felt that following studies may be conducted in future:

a) During the study, 0.5%, 6%, 9% and 12% root contents were used to determine the strength of soil on reconstituted soil samples. Tests may be done on samples prepared with other root contents and root lengths to understand the effect of root content and root length on slope protection.
b) Numerical analyses may be conducted to plot time versus slope stability graph. Numerical analyses using Finite Element Method may also be conducted to estimate the bearing capacity of rooted soil.
c) Tensile strength of vetiver roots and performance of vetiver rooted soil in laboratory model may be studied to compare the field results.

d) Field trials may be undertaken to study the performance of vetiver grass in coastal embankments, river bank protection and hill slope management in different geographic locations of Bangladesh.

e) Cost-benefit analyses are needed to compare the benefits of vetiver grass plantation over other conventional methods of slope protection.

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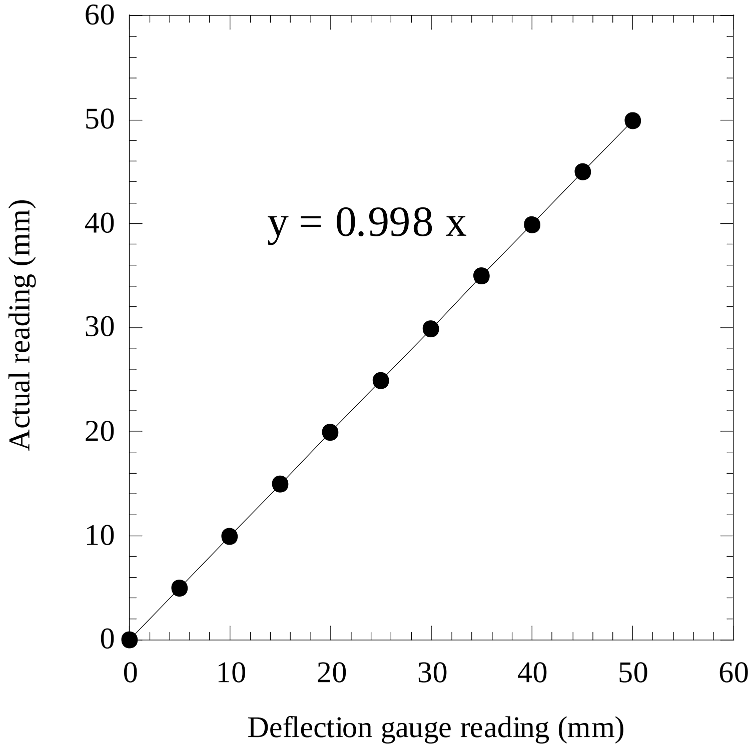
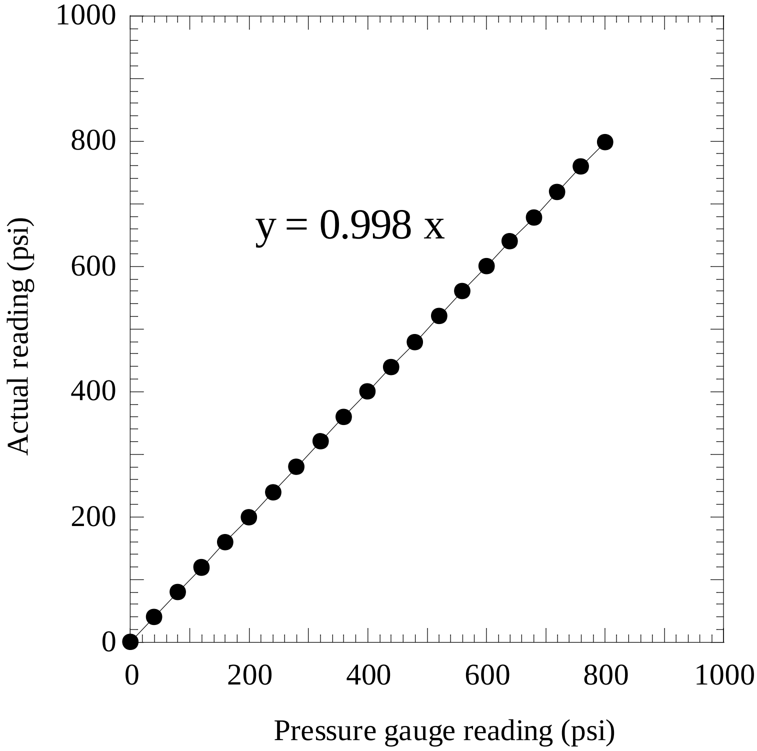
Appendix-A: Calibration Chart



LVDT Reading (mm)	Actual Reading (mm)
0	0.00
5	4.98
10	9.98
15	14.97
20	19.98
25	24.96
30	29.97
35	34.98
40	39.95
45	44.94
50	49.90

Figure 1: Calibration chart of Linier Variable Displacement Transducer (LVDT)



Gauge Reading (psi)	Actual Reading (psi)
0	0.0
40	39.8
80	79.5
120	119.5
160	160.0
200	199.0
240	239.0
280	280.0
320	320.0
360	360.0
400	400.0
440	439.0
480	479.0
520	520.0
560	560.0
600	600.0
640	640.0
680	678.0
720	718.0
760	758.0
800	798.0

Figure 2: Calibration chart of Pressure Gauge (800 psi)

Appendix-B: Factor of Safety Analysis

The Parameters used for Stability analysis:

Unit weight of soil, $\gamma = 18\ kN/m^3$

Vertical height of soil above slip plane = 1 m

Slope angle, $\beta = 45°$

Unit weight of water, $\gamma_w = 9.8\ kN/m^3$

Vertical height of ground water table above slip plane, $h_w = 0$ m

Surcharge due to weight of vegetation, $W = 0.1\ kN/m^2$

Vertical height of groundwater table above the slip plane with the vegetation, $h_v = 0$

Tensile root force acting at the base of the slip plane, T = 0.4 kN/m

Angle between roots and slip plane, $\theta = 0°$

Wind loading force parallel to the slope, D = 0.1 kN/m

i) Cohesion and angle of friction obtained from In-situ test:

Factor of Safety without Vegetation

Effective soil cohesion of bared soil, c' = 12.2 kPa

Effective angle of internal friction of bared soil, $\phi' = 12.5°$

$$FS = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\beta \tan\phi'}{\gamma z \sin\beta \cos\beta}$$

$$FS = \frac{12.2 + \{(18.0 \times 1.0) - (9.8 \times 0)\} \times \cos^2 45^o \times \tan 12.5^o}{18.0 \times 1.0 \times \sin 45^o \times \cos 45^o}$$

$$= 1.58$$

Factor of Safety with Vegetation

Effective soil cohesion of bared soil, c' = 12.2 kPa

Effective soil cohesion of rooted soil = 22 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, $c'_R = 9.8$

Effective angle of internal friction of bared soil, $\phi' = 12.5°$

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2\theta + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z + W)\sin\theta + D\}\cos\theta}$$

$$FS = \frac{(12.2 + 9.8) + [\{(18.0 \times 1.0 - 9.80 \times 0) + 0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 12.5^o + 0.4\cos 0^o}{\{(18.0 \times 1.0 + 0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$$= 2.5$$

ii) Cohesion and angle of friction obtained from Laboratory test:

Factor of Safety without Vegetation

Effective soil cohesion of bared soil, c' = 18 kPa

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\theta\tan\phi'}{\gamma z\sin\theta\cos\theta}$$

$$FS = \frac{18.0 + \{(18.0 \times 1.0) - (9.8 \times 0)\} \times \cos^2 45^o \times \tan 31^o}{18.0 \times 1.0 \times \sin 45^o \times \cos 45^o}$$

$$= 2.6$$

Factor of Safety with Vegetation

(a) For 0.5% root content

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 30.5 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 12.5

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2\theta + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z + W)\sin\theta + D\}\cos\theta}$$

$$FS = \frac{(18+12.5)+[\{(18.0\times 1.0 - 9.80\times 0)+0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times 1.0+0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$=3.6$

(b) For 6% root content

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 24 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 6.0

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c'+c'_R)+[\{(\gamma z-\gamma_w h_v)+W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z+W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+6.0)+[\{(18.0\times 1.0 - 9.80\times 0)+0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times 1.0+0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$=3.1$

(c) For 9% root content

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 28 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 10

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c'+c'_R)+[\{(\gamma z-\gamma_w h_v)+W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z+W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+10)+[\{(18.0\times 1.0 - 9.80\times 0)+0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times 1.0+0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$=3.4$

(d) For 12% root content

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 28. kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 10

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z + W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+10) + [\{(18.0\times 1.0 - 9.80\times 0) + 0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times 1.0 + 0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$=3.4$

(e) For 1.25 cm root length

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 26.5 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 8.5

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z + W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+8.5) + [\{(18.0\times 1.0 - 9.80\times 0) + 0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times 1.0 + 0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$=3.3$

(f) For 2.54 cm root length

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 24 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 6.0

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c' + c'_R) + [\{(\gamma z - \gamma_w h_v) + W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z + W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+6.0)+[\{(18.0\times1.0 - 9.80\times0)+0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times1.0+0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$$=3.1$$

(g) For 5.0 cm root length

Effective soil cohesion of bared soil, c' = 18 kPa

Effective soil cohesion of rooted soil = 26 kPa

Enhanced effective soil cohesion due to soil reinforcement by roots, c'_R = 8.0

Effective angle of internal friction of bared soil, ϕ' = 31°

$$FS = \frac{(c'+c'_R)+[\{(\gamma z-\gamma_w h_v)+W\}\cos^2 \quad + T\sin\beta]\tan\phi' + T\cos\beta}{\{(\gamma z+W)\sin \quad + D\}\cos}$$

$$FS = \frac{(18+8)+[\{(18.0\times1.0 - 9.80\times0)+0.1\}\cos^2 45^o + 0.4\sin 0^o]\tan 31^o + 0.4\cos 0^o}{\{(18.0\times1.0+0.1)\sin 45^o + 0.1\}\cos 45^o}$$

$$=3.2$$