PERFORMANCE OF ECOLOGICAL REVETMENT IN HAOR AREAS OF BANGLADESH

by

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Dhaka, Bangladesh

March, 2020

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A Thesis Submitted by

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A Thesis Submitted to the Department of Civil Engineering in
Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil and Geotechnical Engineering

DEPARTMENT OF CIVIL ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
Dhaka, Bangladesh

March, 2020

DEDICATED

TO

MY PARENTS

The thesis/project titled "Performance of Ecological Revetment in Haor Areas of Bangladesh" submitted by Tanzila Islam, Roll No.: 0417042219F, Session: April 2017, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil and Geotechnical Engineering on 21st March 2020.

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It is hereby declared that this thesis has been composed solely by the author, and that it has not been submitted in whole or in part for the award of any degree (except for publication). Apart from where states otherwise by reference or acknowledgment, the work presented is entirely by the author.

T.islam

Tanzila Islam

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LIST OF ABBREVIATIONS OF TECHNICAL SYMBOLS AND TERMS

Symbol	Description
c	Cohesion
^{o}	Degree
γ_{dry}	Dry density
γ_{w}	Unit weight of water
σ_{n}	Normal stress
τ_{max}	Shear stress
Φ	Angle of internal friction
ω_{u}	Natural Moisture Content
M_{d}	Mass of dry soil
M_{o}	Mass of organic matter
G_{s}	Specific gravity
G_{T}	Specific gravity of water at T degree temperature
W_{s}	Mass of dry soil
W_{w}	Mass of water
ΔV	Volumetric change
A	Exposed area
C	The degree of soil cover
FM	Fineness Modulus
K	Soil erodibility
LS	Land slope and length factor
OM	Organic Matter
P	conservation practices
R	Rainfall erosivity
V:H	Vertical : Horizontal
BM	Model fabricated with *haor* soil
VM	Model fabricated with *haor* soil and vetiver
VFM	Model fabricated with *haor* soil+8.5% fly ash (w/w) and vetiver
VFGM	Model fabricated with *haor* soil+8.5% fly ash (w/w), JGT and vetiver

ACKNOWLEDGEMENT

At first, I will express my sincere gratefulness to Almighty ALLAH for his blessings by giving me opportunity, determination and strength to complete my thesis work efficaciously.

I would like to express whole hearted gratitude and obligation to my respected supervisor, Dr. Mohammad Shariful Islam, Professor, Department of Civil Engineering, BUET for his extreme guidance, constructive criticisms, encouragement and enthusiastic support throughout the progress of the thesis work, without which this thesis work would not come into reality.

Sincere appreciation to Dr. Md. Habibur Rahman, Professor and Head of the Department of Civil Engineering, BUET for his guidance and support from the Department. The author states her gratitude to Dr. Mohammed Kabirul Islam, Professor, Department of Civil Engineering, BUET for his valuable information, supervision and recommendations that made this work resourceful. I am also very grateful to Dr. M. Matiur Rahman, Ex-Director, Bangladesh National Herbarium for giving his valuable comments, thoughtful questions and suggestions.

I will express my thankfulness to IFAD-UN, Gopal Chandra Sarkar (Project Director, *Haor* Infrastructure and Livelihood Improvement Project (HILIP), LGED), LGED officials and engineers awarding a research work to BUET entitled “Monitoring the Performance of Village Protection, Model Village, Upazila/Union Road, Slope Protection” under which this thesis work was completing, for sharing their research data, creating opportunity for completing field study and providing fund for the research work. I must express my very profound gratitude to the Team Leader of the research, Dr. Mohammad Shariful Islam, for his relentless expert guidance, keen interest in this research, valuable advice, encouragement, interest, contribution, efforts, dedication and supervision in field works and workshops. Without his passionate participation and input, the research could not have been successfully conducted. I would like to thank Dr. Mohammed Kabirul Islam, Construction Specialist of the research for his insightful comments, suggestions and encouragement. I would also like to acknowledge Dr. M. Matiur Rahman for helping to identify plants of *haor* region, who contributed as a Botanist of the team.

I am thankful to Engr. Sadman Hossain; Research Associate, Department of Civil Engineering for his participation in field, laboratory work and workshop arrangements. I am appreciative to Khan Md. Osama Elias and Akif Hasan Miraj; under graduate students, Department of Civil Engineering for their cordial help in laboratory work. Thanks to Engr. Md. Zahidul Islam and Engr. Esrat Jahan Eva, for their cordial help in workshop engagements.

I want to express my thanks for the co-operation for nutrient tests from Soil Resource Development Institute (SRDI). Thanks are due to all staffs and lab instructor of Geotechnical Engineering Laboratory in the Department of Civil Engineering for their help for successful completion of all lab experiments.

I would like to acknowledge the research grant received for this study from the Committee for Advanced Studies and Research (CASR) of BUET, Dhaka.

Finally, I am indebted to my parents, sister, husband and family members for their love, concern, care and faith without which this thesis work would not come into reality.

ABSTRACT

The main objective of this study was to investigate the performance of ecological revetment for protecting *haor* infrastructures such as road embankment, village island, *killa* (raised land) against submergence and wave action. To accomplish the study aims, laboratory investigations, model study and performance monitoring of four schemes (Type I to Type IV) in field trial sections were conducted. Four models were fabricated naming BM (slope constructed with *haor* soil), VM (vetiver protected slope constructed with *haor* soil), VFM (vetiver protected slope constructed with *haor* soil stabilized with 8.5% fly ash by w/w), and VFGM (vetiver and JGT protected slope constructed with *haor* soil stabilized with 8.5% fly ash, by w/w) to study the effectiveness of the selected ecological revetments. Besides, efficacy of the ecological revetment was studied at 23 field trial sections in 5 *haor* districts.

Soil samples were collected from 23 locations of the *haor* areas. Based on the laboratory test results, *haor* soil is found to be acidic to alkaline and classified as silty sand/sandy silt. Fineness modulus (FM) of the soils varies between 0.55 and 1.57. From consolidated direct (CD) shear tests, it is found that angle of internal friction vary between 27^o and 36^o. The coefficient of permeability of the *haor* soils is found to be low (8.05×10^{-5} - 1.16×10^{-3} cm/sec). It is found that Phosphorus, Potassium and Sulphur contents in *haor* soils are adequate for vegetation growth, but the soils lack of Nitrogen, Organic Matter, Boron, and Zinc. From the microscopic analyses, it is observed that the spherical particles of fly ash increase the soil density by filling the voids of the irregular angular soil particles.

It is found that vetiver grows satisfactorily in *haor* soil without fertilizer addition. From the growth study of vetiver for a period of 172 days in model soils (BM, VM, VFM and VFGM), it is found that shoot and root length of vetiver vary in the range 130–170 cm and 61–74 cm, respectively. It is also found that the number of tillers per point grew between 13 and 31 from 3 tillers within the same time. In the model soils, fly ash and JGT preserved moisture and provided nutrients to soil, which accelerated the tiller growth in respective models. From the field trials, it is found that shoot length and number of vetiver tillers vary from 58 to 178 cm and from 42 to 500 within a period of 2-3 years, respectively. Monitoring of field trials indicated that other vegetation like *Ikhar, Dholkolmi, Koroch, Bonnya, Hijal, Pitali*, can be planted with vetiver for a combined sustainable effect of ecological revetment.

From the model investigations, it is observed that VM sustained against wave action (velocity of 0.2-0.3 m/s) 15 times higher duration with 19% less soil loss than that of BM. VFM sustained 28 times longer duration with 29% less soil loss and VFGM sustained 43 times greater duration with 67% less soil loss than that of BM. Based on the turbidity and damage pattern of the model slopes, VFGM is found as the most stabilized model.

From the performance of 23 field trial sections in five *haor* districts, design Type II (vetiver and JGT protected slope) and Type III (vetiver, CC hollow Blocks and JGT protected slope) out of selected four design types are found as the most suitable and cost-effective as ecological revetments. From the cost comparison it is found that that Type II and III are 99% and 73% cheaper than that of traditional measures by CC solid blocks. To get better performance in case of stability and protection against wave actions in *haor* areas, proper soil compaction, adequate slope ratio, mix ratio and thickness of CC blocks and post maintenance of the sites (trimming of vetiver, fencing of the sites) are needed.

Based on the laboratory investigations, small scale model study, field performances and cost analyses it can be concluded that, vetiver based ecological revetment is a cost-efficient, sustainable and compatible solution for *haor* infrastructures.

Chapter One
INTRODUCTION

1.1 General

Bangladesh is a part of Bengal basin which is situated in the largest 'Ganges' Delta of the world. 75% of the country is less than 10 m above Mean Sea Level (MSL), and 80% area covers as flood plain (Brammer, 1990), therefore rendering Bangladesh at a high risk of widespread damage by repeated cycle of floods, cyclones, and storm surges. These recurring natural hazards are causing loss of lands, agriculture and houses. It also destroys embankments, other hydraulic structures and livelihood along coastlines and estuaries. There are some swampy lands in the north-eastern zone of this country called the '*haor* basin'. *Haor* areas comprise 17% of Bangladesh (Alam and Hasan, 2010). This region is subjected to special agro-ecological and irregular climatic conditions. These areas suffer from extensive annual flooding often more than once in a year during April-May and during June-October. Due to overflow of rivers and heavy rainfall of 3000-4000 mm from July to November, these naturally depressed areas become submerged in 4 to 5 meters of water and highly damaged by erosive waves which are locally called '*afal*' (Alam and Hasan, 2010). '*Afal*' means tremendous wave action which has duration of 3 to 5 days. It can potentially wash away the artificially raised homestead lands and pose a major threat to villagers in the *haor* areas causing erosion, ultimately leading to slope failure in different modes.

Maximum roads of this country are built on raised embankments. In *haor* region, submersible roads are constructed generally to maintain the biodiversity. These roads of this region become fully or partially submerged during monsoon and suitable as walkways in dry season. Now-a-days, due to lack of clay material, embankments are being constructed with dredged fill sand with clay capping. Most of these embankments are kept unprotected and with poor maintenance. As a result these earths get erased easily by wind and water flow. Hossain et al. (2008) acknowledged the major causes of embankment failure of Bangladesh are breaching of the embankment, cutting by public, overflow, erosion, seepage, sliding and also for poor planning, design and faulty construction. These occur great economic loss every year (Islam and Arifuzzaman, 2010; Nasrin, 2013). Mainly, soil erosion triggers the embankment failure in Bangladesh, which is caused by heavy rainfall (Islam, 2013; Shahriar, 2015). Soil particles get loose by rain impact, wash away by surface runoff and blow away by winds (Young and Wiersma, 1973). Detachment of soil particle by rain impact is related to the grain size of the sediments, and the highest detachability was found for fine sand with a median grain size of 96 μm (Poesen, 1981). Besides soil loss, significant quantities of plant nutrients are also depleted from top layer causing tremendous soil degradation.

Designed to control or prevent flooding, flood control embankment is one of the several types of embankments on the floodplains. A system of routine maintenance is not possible always 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 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 (Nasrin, 2013). Conventional practices to protect *haor* villages and roads against erosion are: long stem grass in bamboo, concrete blocks with geotextile, cable connected blocks, gabion fill material, brick wall, RC wall, cement concrete (CC) blocks, sandbags, stone or wood revetments, geotextile, geo-bags, guide bunds, boulders, brick matressing, geo textile laying, etc. There are also some biological protection such as vegetation (tree plantation), willow post, wooden piling, crisscross and bandallings (Hensler, 2013; Shahriar, 2015). These are found unfeasible in many locations due to construction and maintenance problem or cost and sometimes do not fulfil the purposes satisfactorily (Bosunia et al., 2001; Islam, 2011). So, cheaper maintenance and construction cost of embankment would be a great relief for these problems (Jotisankasa and Sirirattanachat, 2017). Consequently, protection of *haor* infrastructures by technically suitable, cost-effective, human oriented, sustainable and environmental friendly solutions is consequential for maintaining communication in *haor* areas.

Revetments are sloping structures placed on banks or cliffs in such a way as to absorb the energy of incoming water. There are many kinds of ecological revetment, including main constituents of natural vegetation, masonry, eco-concrete etc. (Wand and Wang, 2011). This technique has received much attention worldwide due to its relatively low cost, aesthetic and environmental value, as well as sustainability (Jotisankasa and Sirirattanachat, 2017). Ecological revetment can be a compatible, sustainable and cost-effective solution from the all perspectives.

1.2 Background of the Research

Low shear strength of soil and erosion of top soil are the main causes of waterside infrastructure failures in Bangladesh. Usually the velocity of flow remains from 1 to 2 m/s in the *haor* region of Bangladesh. Early floods in the *haor* areas are flash floods, damaging standing *Boro* rice, the main crop of the region while late floods in June-October damage *Aus* and *Aman* rice, as a result of inundation of crop land during wet season for 6 to 7 months. Such occurrence of flood makes livelihoods vulnerable and it limits the potential of agricultural production and growth of rural enterprise. Rural poor households in the area depend upon fisheries and various off-farm activities for livelihood. The transport infrastructure is poorly developed with submersible rural roads providing connectivity during the dry season with boats being the main mode of transport during the wet season. The poor transportation network limits access to markets, agricultural production and off-farm employment opportunities, all of which adversely affect economic growth. Further, the poor transport network limits access to social services like health and education and centers of administration and judiciary (Islam, 2020).

Studies in many countries around the world have revealed that embankment stability can be escalated by using bio-engineering techniques and capable of providing for long-term sustainable low-cost and low maintenance solution for slope protection (Islam et al., 2017). Even it is very common practice in this country to plant trees on both side slopes of highway road embankments, but these plantations are done randomly and are not well planned. Vegetation and mechanical structures can be used alone or in conjunction to stabilize slopes (NCHRP SYNTHESIS 430, 2012; Islam et al., 2013). For soil erosion control, use of vegetative cover is an ancient method and being practiced till now all over the world (Pinners, 2000; Truong and Loch, 2004; Bhattacharyya, 2006; Eboli et al., 2011; Suleiman et al., 2013). This vegetative cover includes both large trees and grasses (Coder, 2010; Jain, 2013). Besides, these vegetative cover acts as a shield against rain drop and decreases the rain impact significantly. Grass roots are very effective in reducing soil detachment (De Baets et al., 2006; Gyssels et al., 2006; Shit and Maiti, 2012). Different plants have different root structures with different root strength (Nyambane and Mwea, 2011). The variations of root matrix and strength also have an effect in the increase of soil shear strength. It means different species of vegetation provides different factor of safety. Root content also has significant effect on soil shear strength (Nasrin, 2013). Same species with different percentage give different factor of safety.

Protection of slopes by long rooted vegetation by vetiver grass (*Vetiveria zizanioides*) is being used in many countries efficiently. Hengchaovanich (1998) analyzed slope stability based on vetiver root strength. Ke et al. (2003) tested vetiver as a bank protection measure on several test sites (in Australia, China, Philippines and Vietnam). Their tests showed favorable results for the use of vetiver grass as a bank protection measure. 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. Huq (2006) studied on types of vetiver grass in Bangladesh and their propagation in different soil and climatic condition. Plants such as vetiver (*Vetiveria zizanioides*), wild cane (*Saccharum spontaneum*) and tiger grass (*Thysanolaena maxima*) have potential to increase soil shear strength (Mickovski et al., 2005; Islam et al., 2013; Jain, 2013). The presence of root matrix increases stability of slopes by increasing the soil shear strength (Islam, 2000; Jain, 2013; Islam et al., 2013; Islam and Hossain, 2013). Strong roots with dense matrix hold soil particles and acts as fiber reinforcement. The current indigenous practices can be greatly improved through the introduction of engineering principles, better soil compaction and slope stabilization using deep-rooted grass varieties. One of the major benefits of using vetiver on slope stability is through root reinforcement of soil, which is considered as additional soil strength via root cohesion (Mallick, 2017).

In Bangladesh, a good number of research works have been conducted to evaluate 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 (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. (2013) conducted the in-situ test and also conducted direct shear test on laboratory reconstitute soil samples at different root content to know the shear strength of vetiver. Parshi (2015) determined that vetiver rooted soil provides better strength-deformation characteristics than other plants, and a mathematical model has been developed for shear strength prediction of vetiver rooted soil (Islam and Badhon, 2020). In case of river bank and char land protection, a successful eco-slope protection and intervention system is developed using vetiver grass at the north-west flood prone region of this country (Islam and Hoque, 2018). Recently, bio-engineering techniques are being increasingly favored in Bangladesh to control soil erosion in general and for slope protection in case of coastal areas (Mallick, 2017; Islam et al., 2017; Islam and Hoque, 2020) and hilly regions (Elahi et al., 2019; Islam et al., 2020a). Vetiver has also been found effective in case of decreasing landslide vulnerability and water-logging in hilly areas by erosion reduction (Islam and Islam, 2018).

Bio-engineering technology using vetiver can be applied for constructing eco-revetment for *haor* infrastructures protection in this context. Ecological revetment is one of the effective, cost-efficient, sustainable technologies that can be used to restore urban ecological systems. The practice of this revetment is being implemented all over the world like China, Vietnam (Yong and Yu, 2014, Liu et al., 2014, Shi et al., 2009, Tian et al., 2016). Tang et al. (2018) performed a study with an aim to investigate the performance of ecological revetments implemented on the bank of the Cuatien River in Vinh city, Vietnam. The results indicated that the gabion and riprap revetments purified the river water and increased the ecological diversity in the region. Wang and Wang (2011) studied on Huang Jia River, China by combing landscape ecology theory and water conservation requirements, putting forward the ecological revetment restore technique.

In this country, ecological revetment technique is not adopted in large scale especially for *haor* areas. This research aims to evaluate the performance of ecological revetment system for *haor* soils by conducting model studies and recommend this technology by bio-engineering method for *haor* region in this country. The application of this technology is now being implemented by LGED in the *haor* areas; Brahmanbaria, Habiganj, Kishoreganj, Sunamganj and Netrokona (Islam, 2020). Village island, *killa* (raised land) and road slope stability of *haor* areas can be augmented by using ecological revetment as an alternative to traditional approaches.

1.3 Research Objectives

The overall research is conducted based on the following objectives:

(1) To determine the properties of *haor* soil i.e., index properties, shear strength parameters, permeability, nutrient contents collected from selected locations.
(2) To study the growth performance of locally available vegetation such as vetiver, kash, nolkhagra, ikhar for the purpose of using in ecological revetment for *haor* environment.
(3) To study the performance of ecological revetment against wave action and submergence by conducting small scale model tests, as well as to evaluate the performance of vegetated revetment used in field for road slope protection, embankment and village protection in *haor* areas.

1.4 Outlines of Methodology

At first, soil samples were collected from the *haor* districts for laboratory and model study. Laboratory tests including specific gravity, grain size, direct shear, permeability were conducted according to ASTM standards, and nutrient tests were conducted including available Nitrogen, Phosphorus, Potassium, Sulphur, Zinc, Boron, pH of the soil and organic matter in SRDI. Four glass models were constructed for four conditions (*haor* soil only, *haor* soil+vegetation, *haor* soil+8.5%fly ash+vegetation, and *haor* soil+8.5% fly ash+JGT). Growth performance of vegetation was recorded regularly, and after the growth of vegetation, wave action was produced to observe and compare the sustainability of revetments of *haor* areas during monsoon considering the actual parameters i.e., wave height, wave length and wave velocity. The model and field trial performances were implemented under the project HILIP by LGED. Based on all the results, an ecological revetment system is proposed in this study for slope protection that will be suitable for infrastructures used in *haor* districts in Bangladesh.

1.5 Thesis Layout

To describe the sequential progress of this study, the complete research work is distributed in five chapters so that it becomes easier for achieving the stated objectives. The contents of each chapter are:

Chapter One includes the problem statement and difficulties of *haor* region, background and objectives and outcome of this study along with the thesis organization.

Chapter Two presents the literature review which includes the overview of *haor* areas and types of its infrastructures, causes and different measures of erosion and disasters in this region. This chapter also discusses on the available low-cost solution for erosion control like vegetation by vetiver grass (*Vetiveria zizanioides*), role of vegetation in the stability of slopes, the mechanism of vegetation in the stability of slopes and its performance in Bangladesh and all over the world. Finally, the significance of soil bio-engineering and ecological revetment is deliberated.

Selection of Study areas in *haor* regions for the research, model fabrication details against wave action and laboratory test schemes have been discussed in Chapter Three.

Chapter Four presents the results from experimental data, model study and field trial performance. The topographic and sub-soil characteristics of *haor* are determined, and growth, submergence and wave tolerance of vegetated slope is described through model and field study outcomes. Finally, the validations of the studies are presented by cost estimation and applicability of ecological revetment by bio-engineering method in this chapter.

To conclude, in Chapter Five, the main conclusions of the study are pointed out, and some recommendations for future work are also provided.

Chapter Two
LITERATURE REVIEW

2.1 General

This chapter presents an overview on overall condition of the *haor* region of Bangladesh and the significance to protect *haor* infrastructures. Study related slope protection technique by ecological revetment and implication of this bio-engineered technique in *haor* area has also been delineated in this chapter. Slope protection by vegetation has become a prominent method for its sustainability and climate change adaptation (Clark and Hellin, 1996; Truong and Loch, 2004; Rasel et al., 2011; Suleiman et al., 2013). This method has unique requirements and is not suitable for all sites and situations (Parshi, 2015). But if this technique is conserved properly, it works effectively and is also is known as a low cost solution (Allen and Leech, 1997). This literature review focuses the effects on *haor* infrastructures due to flood and the significance of ecological revetment by vegetation to stabilize these infrastructures.

2.2 Overview of *Haor* Region

Bangladesh is usually viewed as a vulnerable country with respect to climate change like temperature and rainfall especially in *hao*r areas because of its geographic location, dominance of flood plains, high population density and elevated level of poverty, overwhelming dependency on nature, resources and services (Hasan, 2019). '*Haor*' is the local name of the wetland ecosystem in the north eastern part of this country which is physically a bowl or saucer shaped shallow depression, also known as back swamp (Alam, 2004, Alam and Hasan, 2010). Originally, the word '*haor*' is derived from a Sanskrit word 'Shagor' which means sea. *Haor*s with their unique hydro-ecological characteristics covers about 1.99 million hectares of area and accommodating about 19.37 million people (CEGIS, 2012).

2.2.1 Topography of *Haor*

A *haor* is a combination of cluster of beels, so it is difficult to differentiate from other water bodies. Some *haor*s are changed to other form of wetland, some gets interconnected with each other, and some meets with the river. During monsoon period it is hard to categorize *haor*s specifically as the whole area is covered by water and the *haor*s and other water bodies having similar patterns appear to be same in remotely sensed images. There are about 373 *haor*s located in the districts of Sunamganj, Habiganj, Netrokona, Kishoreganj, Sylhet, Moulovibazar and Brahmanbaria (Figure 2.1) covering an area of about 858,000 ha which is around 43% of the total area of the *haor* region (CEGIS, 2012). It is an assortment of wetland including rivers, streams, canals, large areas of seasonally flooded cultivated plains and beels. Figure 2.2 shows the percentage of *haor* area of the total area of the districts, which denotes that maximum *haor*s are situated in Sunamganj and Sylhet. The *haor* basin is bounded by the hill ranges of India – Meghalaya on the north, Tripura and Mizoram on the south, and Assam and Manipur on the east. The basin extends north to the foot of the Garo and Khasia Hills, and east along the upper Surma Valley to the Indian border (Alam and Hossain, 2012). This area is situated between latitude 23º59´04.75´´N to 25º12´49´´N and longitude 90º27´22.13´´E to 92º30´10.19´´ E (Hossain, 2013).

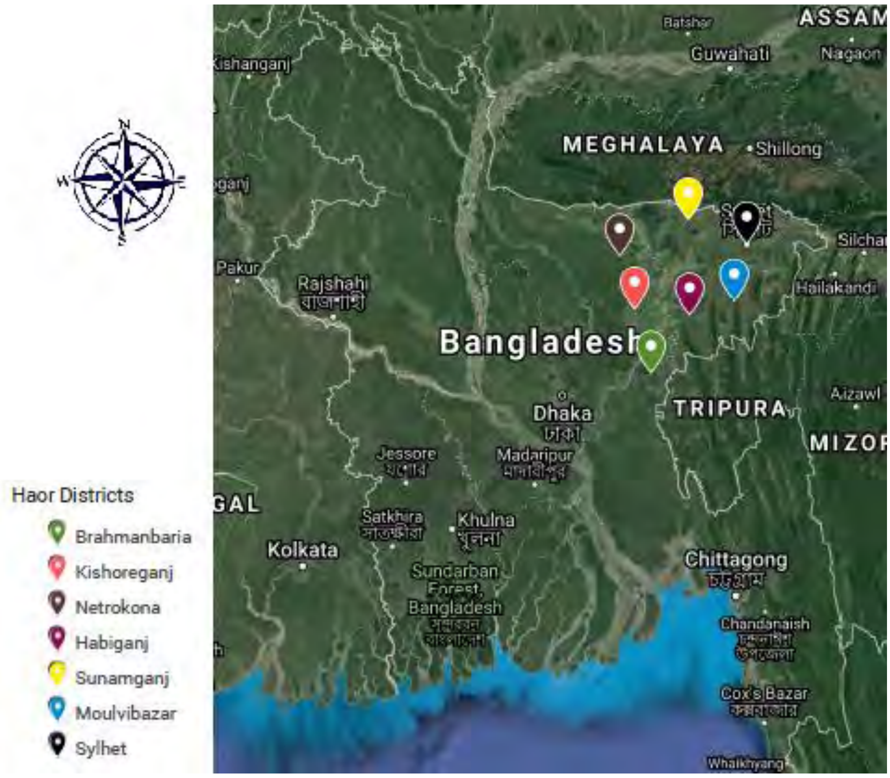


Figure 2.1: Map Showing the *Haor* Districts of Bangladesh

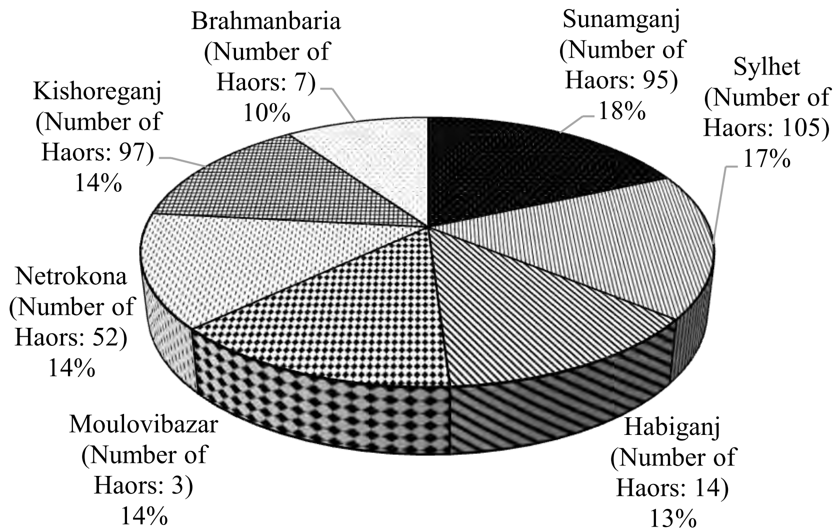


Figure 2.2: Number of *Haors* and Their Proportion (%) over Total *Haor* Area of Bangladesh (CEGIS, 2012)

The Tippera surface lies directly to the south of the *haor* basin, and is partly low and deltaic and partly higher ground with a piedmont fringe to the east (Akonda, 1989). Three major river systems that cover the whole *haor* area are: (1) Kangsa-Dhanu, (2) Surma-Baulai and (3) Kalni-Kushiyara. Patnai, Baulai, Jadukata and Chalti are the major rivers in the north side of the basin that regulate the flow into Bangladesh from India (CEGIS, 2012). It includes about 47 major *haor*s and some 6,300 beels of varying size, of which about 3,500 are permanent and 2,800 are seasonal (Alam and Hossain, 2012). Figure 2.3 summarizes the topography according to the elevation of the *haor* area. It shows that most of the area comprises an elevation of 5-8 m from MSL.

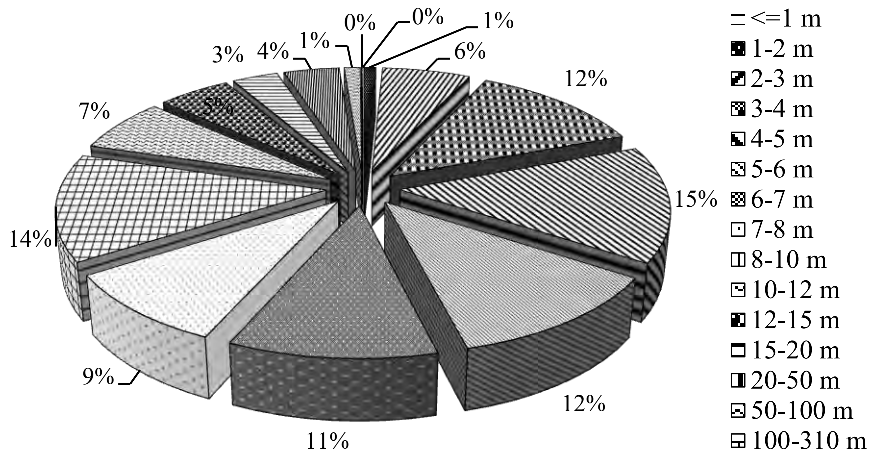


Figure 2.3: Percentage of Area (km^2) according to the Elevation (m) from MSL of the *Haor* Region (CEGIS, 2012)

2.2.2 Geological Formation

The *haor* area encompasses nine Agro-Ecological Regions (AEZs) namely: (1) the Sylhet Basin, (2) the Eastern Surma Kushiyara Floodplain, (3) the Old Meghna Estuarine Floodplain, (4) the Old Brahmaputra Floodplain, (5) the Middle Meghna River Floodplain, (6) the Young Brahmaputra and Jamuna Floodplain, (7) the Northern and Western Piedmont Plains, (8) the Northern and Eastern Hill and (9) the Akhaura Terrace.

Table 2.1: Zoning of *Haor* Area (Hossain and Nishat, 2011)

Zone	Description
The piedmont area	This area is an accretion zone where rapid siltation of coarser materials takes place along the levees by flash floods.
The floodplain area	The floodplains, with milder slopes, are located at the middle of the basin.
The deeply flooded area	During monsoon, the floodplains become deeply flooded and turn into a single water reservoir, especially in the Surma-Kushiyara-Meghna basin.

Among these, only three AEZs comprise the main *haor* basin, the Sylhet Basin, the Eastern Surma Kushiyara Floodplain and the Old Meghna Estuarine Floodplain

(Alam et al., 2012). This area is further divided into three zones by standards of morphology and hydrology (Hossain and Nishat, 2011), shown in Table 2.1. *Haor* basin is low because of the subsidence of tectonic Dauki fault. The Sylhet Basin has subsided 10-12 m in the last several hundred years. A subsidence rate of 21 mm/year in the Surma Basin was reported by the Master Plan Organization (1985), which means 10 m subsidence in 500 years. Therefore, if it is considered that the Sylhet Basin is subsiding at a rate of 2-4 mm every year and the soil compaction rate is 1-2 mm/year, then the actual subsidence rate of the Sylhet Basin might be 3-6mm/yr. In the geological depression of the *haor* basin, subsidence is continuing at an estimated rate of 20 mm per year.

2.2.3 Soil Characteristics

The soils within the same *haor* system can vary in texture, drainage class, fertility and other parameters. The soil fertility level of the area is medium to high. About 44% of the area is covered with high to medium high organic matter where organic content is more than 3.4%. The rest of the area has low to very low organic matter (CEGIS, 2012). The soil types according to the *haor* districts are summarized below (Saha et al., 2016).

(i) Brahmanbaria: Grey cohesive and brown and grey non-cohesive soil layers are observed. Soft to very stiff cohesive soil layers are found up to a maximum depth of about 0-11 m, whose sizes vary about 0.0013-0.074 mm. The non-cohesive soils vary up to a maximum depth of 22 m, whose sizes vary about 0.074-0.84 mm and the stiffness varies from loose to dense.

(ii) Habiganj: Brown and grey cohesive and non-cohesive soil layers are found. Cohesive soil layers are found up to a maximum depth of about 0-22 m, with sizes of 0.0014-0.074 mm and the relative density varies from very soft to very stiff. However, very loose to dense non-cohesive soils with a size of 0.074-4.76 mm are also found up to a depth of about 22m.

(iii) Kishoregonj: Cohesive soil of brown and grey in color and grey non-cohesive soil layers are found. Very soft to stiff cohesive soil layers are found upto a maximum depth of about 0-8.5 m, whose sizes vary within 0.0013-0.074 mm. Loose to very dense non-cohesive soil layers up to a maximum depth of about 22 m and sizes within 0.074-0.42 mm are found. But exception has been found in Astagram Upazila, where cohesive soil layer is up to 0-15 m.

(iv) Netrokona: Grey cohesive and non-cohesive soil layers are observed. Cohesive soil layers are found up to a depth of 0-8.5 m, whose sizes vary within 0.0014-.074 mm and the relative density varies from very soft to stiff. Non-cohesive soils differ up to a depth of about 22 m, whose sizes vary within 0.074-0.84 mm and the stiffness varies from very loose to dense.

(v) Sunamganj: Brown and grey cohesive and grey non-cohesive soil layers are observed. Very soft to stiff cohesive soil layers are found up to a maximum depth of about 0-20 m, whose sizes vary between 0.0014mm and 0.074 mm.

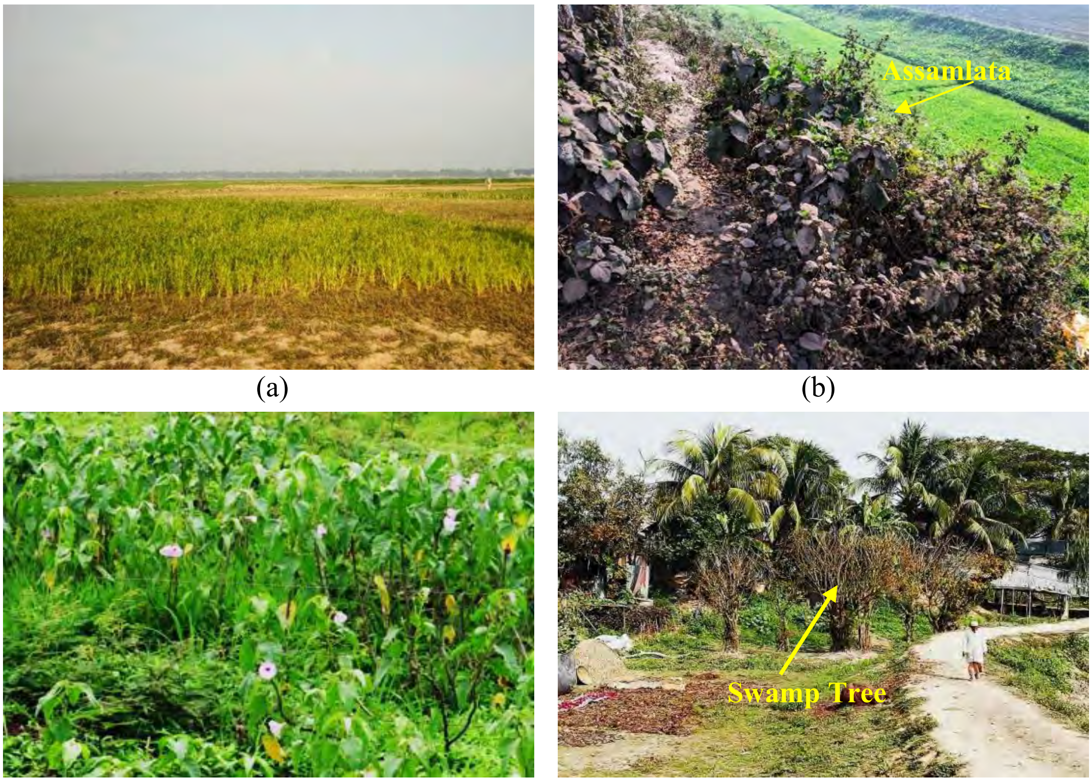
There are also non-cohesive soils with loose and medium dense stiffness up to a depth of 22m whose sizes vary from 0.074-4.76 mm. In Dharmapasha Upazila, soil particle sizes are found varying up to 4.76 mm.

(vi) Sylhet: Brown and grey cohesive soil layers are found up to a maximum depth of about 0-31 m, whose sizes vary about 0.0014-0.074 mm and stiffness varies from very soft to very stiff. Brown and grey non-cohesive soil layers are observed with relative density of very loose to dense, whose sizes vary about 0.074-0.84 mm. Some soils are found as reddish brown in color.

(vii) Moulovibazar: Brown and grey cohesive and non-cohesive soil layers are found in color. Cohesive soil layers are found up to a depth of about 0-22 m, whose sizes vary within 0.0013-0.074 mm and stiffness varies from very soft to very stiff. Sizes of non-cohesive soil layers vary about 0.074-2.0 mm and the relative density varies between loose and medium dense.

2.2.4 Biodiversity

The biodiversity of *haor* wetlands is very rich. These wetlands have also a rich wildlife community including birds, reptiles, mammals and amphibians. A survey by Bangladesh National Herbarium (BNH) recorded 78 plant species in the area (Khan, 2001). Figure 2.4 shows photographs of some plants of this region.



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

Figure 2.4: Photographs of Some Floras of *Haor* Region; (a) Dhani Ghash, (b) Assamlata, (c) Dholkolmi, and (d) Koroch

The following plants are found to grow at different sites in *haor* basin of Brahmanbaria, Habiganj, Kishoreganj, Netrokona and Sunamganj (Islam, 2020).

Herbs

(i) Binna (*Vetiveria zizanioides*): A plant sometimes grown as a hedge and is useful in dryland restoration to reduce soil erosion.
(ii) Durba (*Cynodon dactylon*): A creeping grass working as a turf on the road shoulder.
(iii) Malankuri (*Eleusine indica*): A small tufted grass scattered here and there on road shoulder, and holding the ground.
(iv) Moida/Moujja/Ikhar (*Sclerostachya fusca*): A robust, largely tufted, rhizomatous grass protecting the toes of the slopes.
(v) Kuksim (*Vernonia patula*): A delicate erect, short herb scantily growing in the intervening spaces among the slabs as well as on the road shoulders.
(vi) Kash (*Saccharum spontaneum*): A perennial grass of more than 1 m tall with fibrous roots was found to grow in some holes and intervening spaces of slabs, anchoring very firmly to the ground and resisting water logging.
(vii) Bherenda/Bhenna *(Ricinus communis*): Tall robust shrubs of this species were found to grow at one side side of the slope, and more or less stabilizing the soil.
(viii) Notey (*Amaranthus viridis*): A delicate, short herb growing in the intervening spaces of slabs, hardly imparting any protecting effect on slopes.
(ix) Fern: A few ferns were found to grow in the intervening spaces of slabs holding the soil.
(x) Malankuri (*Eleusine indica*): A small tufted grass, scattered here and there on road shoulder, and holding the ground.
(xi) Kuksim (*Vernonia patula*): A delicate erect, short herb scantily growing in the intervening spaces among the slabs as well as on the road shoulders.
(xii) Makur-Jali (*Digitaria ciliaris*). A delicate annual grass growing on the Killa.
(xiii) Fola Ghash (*Echinochloa crusgalli*): This grass was cultivated near the slopes. It is a partially aquatic grass.
(xiv) Dhani Ghash (*Panicum repens*): A creeping perennial grass with long horizontal rhizomes growing on the margins of slopes. It stabilizes the soil very strongly and can withstand inundation.

Shrubs

(i) Chhitki/Khoi/Khoibabla (*Pithecellobium dulce*): A stout, branching shrub found to grow scattered in the intervening spaces among the slabs, and firmly holding the slope.
(ii) Kudura/Dumur/Kakdumur (*Ficus hispida*): An erect, stout shrub of about 1 m tall growing in the intervening spaces of the slabs, and firmly holding the slope.
(iii) Bherenda/Bhenna (*Ricinus communis*): Tall robust shrubs found to grow scantily on the upper sides of the slope, and more or less stabilizing the soil.
(iv) Rongon (*Ixora coccinea*): A dwarf, stout shrub scantily growing in a few intervening spaces of slabs, and strongly protecting the slope.
(v) Dhutura *(Datura stramonium*): A bushy, soft solitary shrub, found to grow at one end of the slope, and moderately holding the earth.
(vi) Berela/Bola (*Sida cordifolia*): A dwarf, coarse, solitary shrub found to grow in

the intervening space of slabs, fixing the soil.

(vii) Ghagra (*Xanthium indicum*): A short, coarse shrub found here and there in the intervening spaces of slabs, and holding the soil.

(viii) Bhat (*Clerodendrum inerme*): An erect small shrub growing profusely along the road shoulders on top of slopes, and firmly stabilizing the ground.

(ix) Borohalkasunda (*Cassia occidentalis*): A shrub of about 1 m tall found to grow scantily in the holes *of slabs upon the slope.*

(x) Agrajit *(Clitoria* ternetea): A small bushy shrub about 2 ft tall growing in the intervening spaces of the slabs, and holding the soil.

(xi) Dholkolmi (*Ipomoea fistulosa*): A large gregariously growing shrub stabilizing the margins and slopes of Killa. It can withstand considerable period of inundation.

(xii) Bishkatali (*Polygonum orientale*): A bushy small shrub growing scattered on the Killa slopes.

(xiii) Muktapati (*Clinogyne dichotoma*): A stout, erect, clump forming shurb very strongly holding the habitat with long inundation surviving efficiency.

Climbers

(i) Telakucha/Gutum (*Coccinea cordifolia*): A delicate climber straggling over the Vetiver clumps, but hardly retarding their growth.

(ii) Assamlata (*Eupatorium odoratum*): A gregarious climber straggling over Vetiver tufts and other vegetation, and seriously retarding their growth.

Trees

(i) Assheora/Sheora (*Streblus asper*): A few small trees of about 1 m tall with strong roots were found to grow in the intervening spaces among the slabs, and strongly holding the slope.

(ii) Norcha/Naricha/Jiban (*Trema orientalis*): A small tree of more than 2 m tall standing erect in some holes of slabs as well as in their intervening spaces. It is capable of surviving inundation of flood water as well as in firmly holding the slopes.

(iii) Kul (*Zizyphus mauritiana*): Small trees were found to grow very scantily along the road shoulders above the slopes, and stabilizing the earth.

(iv) Rendikoroi/Raintree Koroi (*Samanea saman*): Large trees growing along the road shoulders and playing an important role in the stability of slope protection.

(v) Banana (*Musa paradisiaca*). Clumps of banana trees were found to grow at one end of the slope, and substantially holding the earth.

(vi) Rendikoroi/Raintree Koroi (*Samanea saman*): A few medium sized trees growing along top margins of the slopes, and fixing the ground.

(vii) Bhatam/Lattu (*Trewia polycarpa*): A few small trees found in the toes of slopes, capable of protecting the slope.

(viii) Jarul (*Lagerstroemia speciosa*): A medium sized tree growing along the road shoulders as well as on slopes, capable of resisting flood water inundation.

(ix) Koroi (*Albizia procera*): A couple of large trees growing along the margins of roads up the slopes, and playing an important role in the stability of slope protection.

(x) Mehogini (*Swietenia mahagoni*): A few of this large tree were found to grow along the margins of the road up the slopes, and providing support to earth stabilization.

(xi) Barun (*Crataeva nurvala*): Saplings of a medium sized tall tree of this species were found to grow in numbers along the toes of the slopes. This plant can resist long duration of inundation, and is effective in the protection of slopes.

(xii) Koroch (*Pongamia pinnata*): It is a medium to large sized tree growing in the toes of slopes. It is a highly water resistant plant that can survive long duration of inundation during the rainy season.

(xiii) Mera/Meragoda (*Trewa polycarpa*): The only tree found at one end of the slope. It is a water resistant plant.

(xiv) Hijal (*Barringtonia acutangula*): A low tree that can stand water logging and work as slope stabiliser.

(xv) Kodom (*Anthocephalus chinensis*): A large tree found to grow on the road margins.

(xvi) Jiga (*Lannea coromandelica*): A small sized tree usually grows along margins of slopes near water. It is a water resistant plant which can overcome long duration of inundation.

2.2.5 Rainfall and Wind Speed

Rainfall is the most distinctive component of climate in *haor* region. The region is located entirely to the north of the tropic of cancer; hence its monsoon climate is known as sub-tropical. The sub-tropical monsoon climate tends to have more sharply defined seasons than the tropical climate. Annual rainfall of *haor* area ranges from 2200 mm along the western boundary to 5800 mm in north-east corner and is as high as 12000 mm in the headwaters of some catchments extending to India.

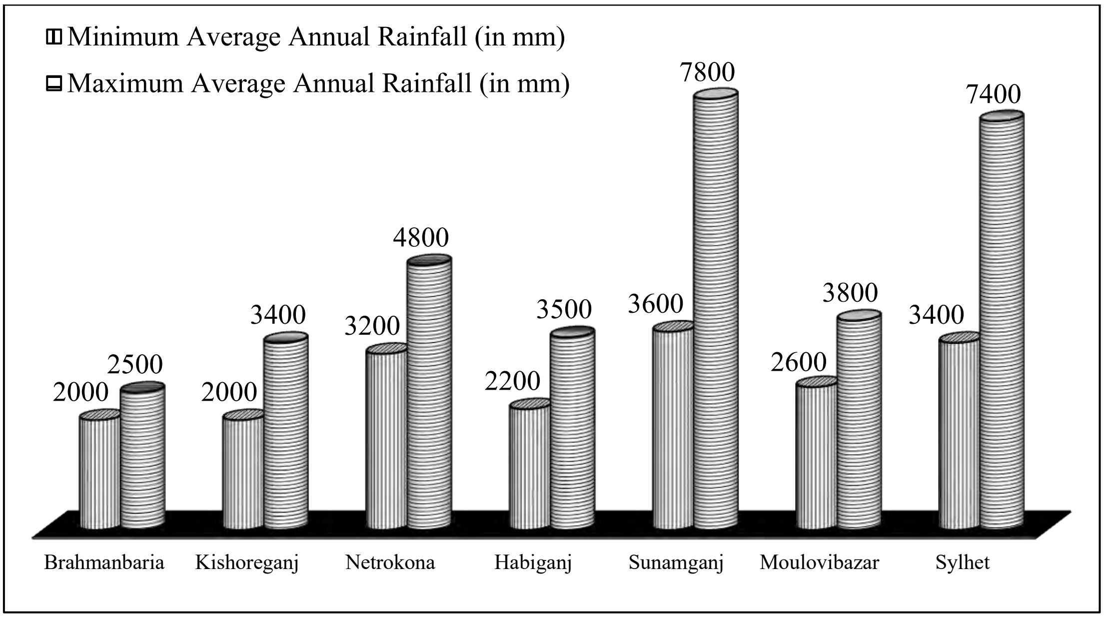


Figure 2.5: Mean Annual Rainfall (mm) in *Haor* Region (CEGIS, 2012)

The region receives water from the catchment slopes of the Shillong Plateau across the borders in India to the north and the Tripura Hills in India to the southeast

(Hossain, 2013). Since rainfall on the adjacent Indian side largely affects flooding in the *haor* area, the rainfall pattern of the upstream catchment has great influence here. There is a huge variation in rainfall in the different catchments of the river systems of the upstream area in India. Among the locations of the *haor* districts, the highest rainfall was recorded in Sunamganj closest to Cherrapunji (annual precipitation is 12 m), which is the highest precipitation area in the worlds. Even the mean annual rainfall varies between 3600 mm and 7800 mm in Sunamganj. Figures 2.5 and 2.6 show average annual rainfall map and data of all *haor* districts. The average monthly evapotranspiration of *haor* districts varies from 2.0-3.4 mm/day during dry period and from 3.9-4.8 mm/day during wet period. Daily maximum and daily average wind speed is observed to be highest in the months of April and May which has varied from 26-37 km/hr. The minimum monthly average wind speed is found as 5-11 km/yr over the region (CEGIS, 2012).

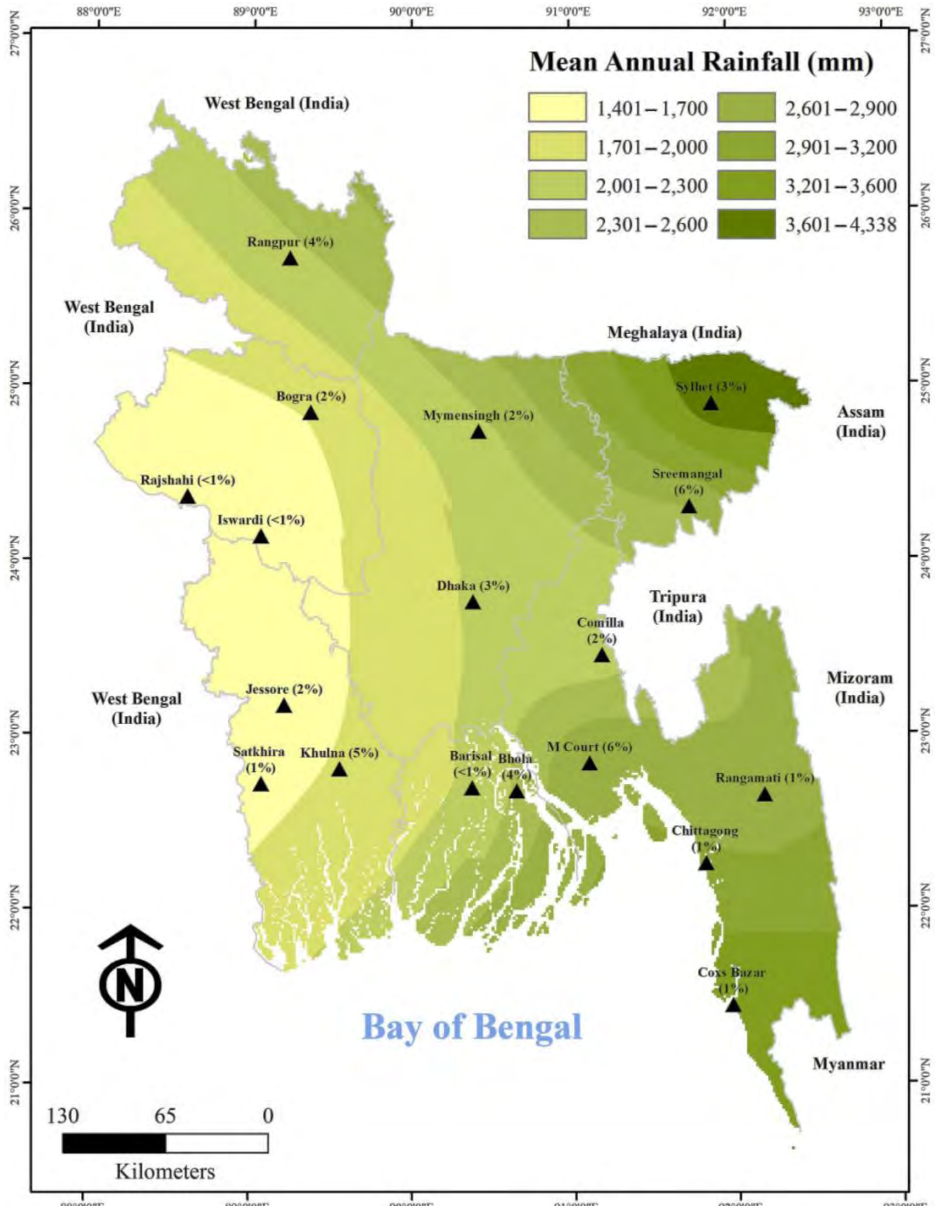


Figure 2.6: Mean Annual Rainfall Map (Chowdhury et al., 2019)

The *haor* basin has been classified according to agro-ecological zone land classes into four types of land levels in order to delineate four hazard categories (Hossain, 2013), such as:

(i) Medium highland: Land which is normally flooded up to 90 cm deep during the flood season.
(ii) Medium lowland: land which is normally flooded between 90 cm and 180 cm deep during the flood season.
(iii) Lowland: land which is normally flooded between 180 cm and 300 cm deep during the flood season.
(iv) Very lowland: land which is normally flooded deeper than 300 cm during the flood season.

An additional class, bottomland, is recognized for depression sites in any land level class which remains wet throughout the year. The main characteristics of *haor*s are flooding by normal flood during the rainy season every year. For more than six months *haor*s remain submerged and with the passing of the rainy season some deep beel areas at deepest point of the *haor* region remain submerged. The people in *haor* areas live in isolated settlements that are located on earthen mounds or on raised platforms. The *haor* basin is estimated to be sinking at between 4 mm and 2.1 cm annually because of the down-thrusting under the Shillong massif.

2.2.6 Recent Floods of *Haor*

During the flood of April-May 2017, it is estimated that 4,667,000 people in 450 Unions (out of 530) in 60 Upazilas (out of 62) have been affected (to varying degrees) in the six districts of Sunamganj, Sylhet, Netrokona, Kishoreganj, Habiganj, and Moulvibazar. With 65% of its population affected, Sunamganj district is worst hit followed by Netrkona (33%) and Sylhet (25%). Approximately 21% of the population is affected in the other districts (HCTT, 2017). The flood in 2017 also devastated crops, poultry and fisheries of *haor* districts (The Daily Star, 2017).

Extremely severe cyclonic storm ‘Fani’ originated from a tropical depression that formed west of Sumatra in the Indian Ocean on 26 April 2019. People in the *haor* region in started facing flash flood on 28 April 2019 because of heavy rainfall more than 50 mm caused by cyclone Fani inside Bangladesh and upstream in neighboring India. Thousands of hectares of cropland in south-western Bangladesh went under water as the weakened cyclone crossed Bangladesh on Saturday affecting 8,500 km protection embankment with high wind and tidal surges (New Age Bangladesh, 2019). On 28 April 2019, vast *haor* areas went under water after embankments were breached by rapidly rising rivers in five upazilas of Sylhet, Sunamganj and Netrakona districts. Flash flood situation at two upazilas in Netrakona was reported to be deteriorating by the flood forecasting center in the afternoon. Overflowing Sarigowain River caused flash flood at Gowainghat upazila. The flood forecasting center said that rivers in the *haor* region, including Kangsha, Jadukata, Sarigowain and Someshwari, rose up to over three meters in 24 hours. Figure 2.7 shows an affected village in Sunamganj during the flash flood of April 2019. It also shows the tremendous wave action during *afal*.

Figure 2.7: Floodwater from the Hills Overflows into Villages of Halir *Haor* under Jamalganj, Sunamganj in 5th May 2019 (New Age Bangladesh, 2019)

2.3 Soil Erosion and Slope Failure

Soil erosion, sedimentation and mass movement are endemic phenomena during the flash floods of *haor*. Erosion is the action of surface processes (such as water flow or wind) that removes soil, rock, or dissolved material from one location on the earth's crust, and then transports it to other location (Encyclopedia Britannica, 2015). Erosion removes the smaller and less dense constituents of topsoil. These constituents and organic material hold nutrients that plants require. The remaining subsoil is often hard, rocky, infertile and droughty. Thus, reestablishment of vegetation is difficult and the eroded soil produces less growth. When carried into water bodies, the nutrients trigger algal blooms that reduce water clarity, deplete oxygen, lead to fish kills, and create odors. Turbidity from sediment reduces in-stream photosynthesis, which leads to reduced food supply and habitats. There are several methods for reducing soil erosion and protecting slopes such as stabilization using fly ash (Sharma et al., 2012; Islam et al., 2020b), reinforcing the soil by polymer and natural fiber (Islam and Iwashita, 2010), earth retaining structures, nailing and anchoring (Shahriar et al., 2020), ecological revetment etc.

2.3.1 Types of Erosion

Erosion is fundamentally a twofold process that involves:

(i) Particle detachment: Loosening the soil particles caused largely by raindrop impact, or freezing and thawing and wetting and drying cycles.
(ii) Particle transportation: Transportation of soil particles are largely occurred by flowing water. The process of soil transportation by running water is completed under the following forms:
  (a) Solution: The water soluble contents present in the water are transported by

the water in solution form.

(b) Suspension: It involves the transportation of finer soil particles, which are present in suspension form in the flowing water.

(c) Saltation and Surface Creep: It involves transportation of medium size soil particles that are not able to stand in suspension form, but are mixed in water and flow over the stream bed in the form of mud. The surface creep action is responsible for transporting the coarser soil particles.

The major types of erosion are described below.

Splash Erosion

When vegetative cover is stripped away, the soil surface is directly exposed to raindrop impact. On some soils, a very heavy rain may splash as much as 100 tons/acre of soil. Some of the splashed particles may rise as high as 0.6 m above the ground and move up to 1.5 m horizontally. If the soil is on a slope, gravity will cause the splashed particles to move downhill. When raindrops strike bare soil, the soil aggregates are broken up. This crust inhibits water infiltration and plant establishment, and runoff and future erosion are thereby increased. Figure 2.8 shows the splash erosion process.

Sheet Erosion

Sheet erosion is caused by shallow 'sheets' of water flowing over the soil surface, as shown in Figure 2.9. These very shallow moving sheets of water are seldom the detaching agent, but the floe transports soil particles that have been detached by raindrop impact. The shallow surface flow rarely moves as a uniform sheet for more than a few feet before concentrating in the surface irregularities.

Rill Erosion

Rill erosion begins when shallow surface flow starts to concentrate in low spots in the soil surface (Figure 2.10). As the flow changes from sheet flow to deeper flow in these low areas, the velocity and turbulence of flow increases. The energy of this concentrated flow is able to both detach and transport soil particles. This action begins to cut tiny channels called rills.

Gully Erosion

Gully formation is a complex process. Some gullies are formed when runoff cuts rills deeper and wider or when the flows from several rills come together and form a large channel, displayed in Figure 2.11. Gullies can enlarge in both uphill and downhill directions. Water flowing over the headwall of a gully causes undercutting. In addition, large chunks of soil can fall from a gully headwall in a process called mass-wasting. This soil is later carried away by storm water runoff. Once a gully is created, it is very difficult to stop it from growing, and it is costly to repair.

Channel Erosion

Channel erosion occurs when bank vegetation is disturbed or hen the volume or velocity of flow in a stream is increased. Natural streams have adjusted over time to the quantity and velocity of runoff that normally occur in the watershed.

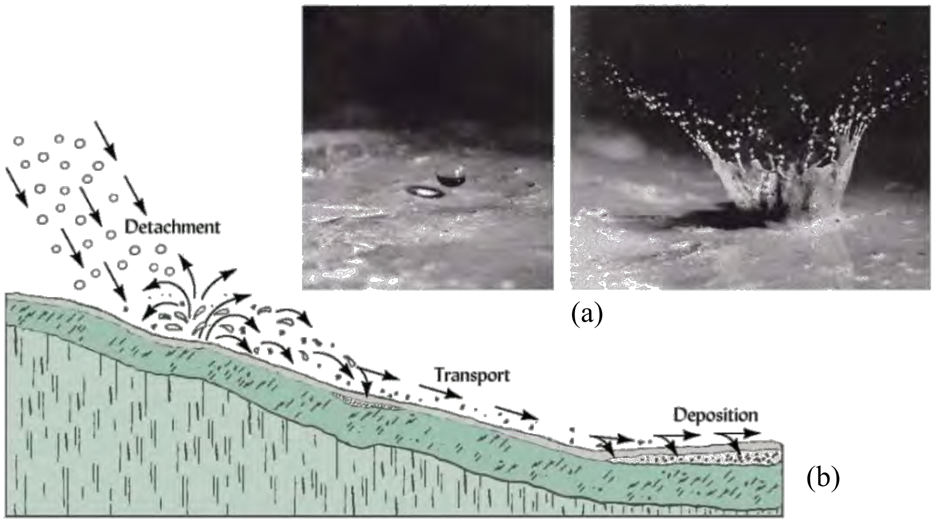
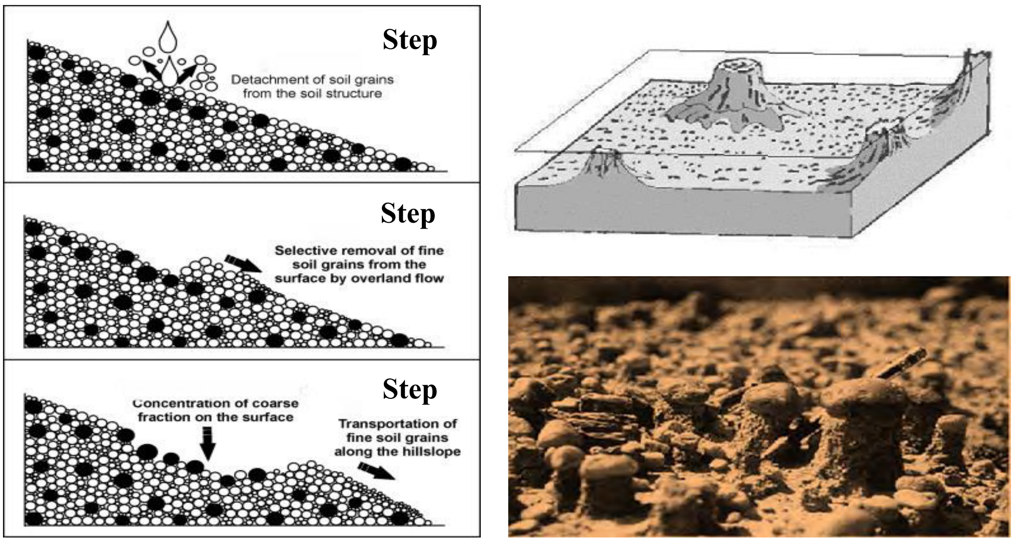


Figure 2.8: Splash Erosion Process on Slopes: (a) Close View; and (b) Schematic Overview (Bashir et al., 2018)



(a) (b)

Figure 2.9: Photographs of: (a) Sheet Erosion Process Step by Step; and (b) Close View of Land Condition after Sheer Erosion (Bashir et al., 2018)

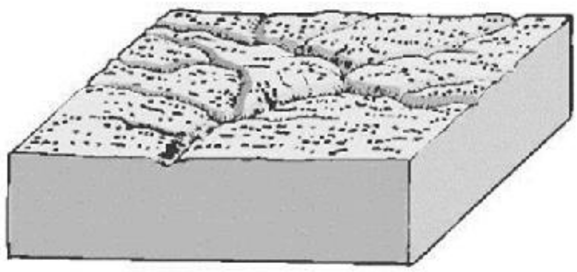


Figure 2.10: Land Condition after Rill Erosion (Bashir et al., 2018)

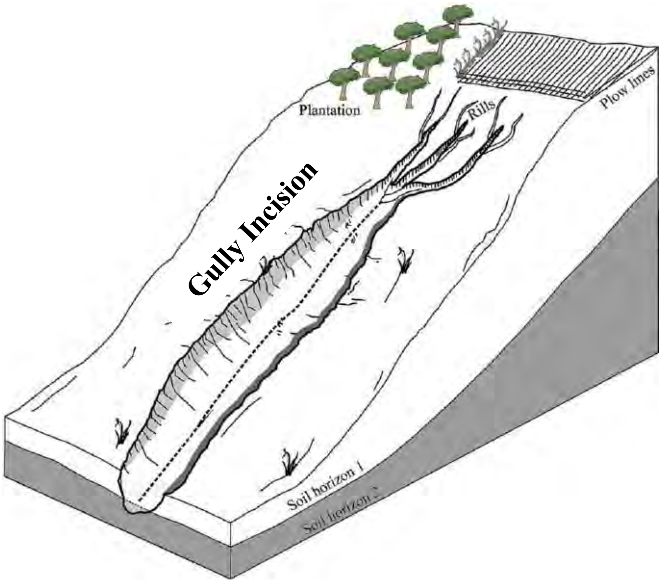


Figure 2.11: Gully Erosion on Slope (Shruthi et al., 2011)

The vegetation and rocks lining the banks are sufficient to prevent erosion under these steady-state conditions. However, when a watershed is altered by removing vegetation, by increasing the amount of impervious surfaces, or by paving tributaries, stream flows also are changed. Typical changes are an increase in the peak flow during storms and an increase in stream velocity. Either of these changes can destroy the equilibrium of the stream and cause channel erosion to begin.

2.3.2 Mechanism of Erosion

Erosion mechanisms depend on the soil characteristics, soil's erodibility, erosivity (potential of raindrop impact), land use, slope and land cover. Prevention and control of erosion depends on understanding of the mechanics of the erosion process. Different categories of slope erosion are shown in Figure 2.12. Erosion protection essentially consists of:

(i) 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,
(ii) Increasing resistance to erosion by protecting/reinforcing the surface with a suitable cover or by increasing inter-particle bond strength.

Some soils (e.g., silts) are inherently more erodible than others (e.g., coarse, well graded gravels). In general, increasing the organic and clay size fraction of a soil decreases erodibility. There is no simple and universally accepted erodibility index for soils. Instead, various tests have been proposed for this purpose, including the SCS dispersion test (Volk, 1937), crumb test (Emerson, 1967), and pinhole test (Sherard et al., 1978). A suggested hierarchy of erodibility based on the Unified Soil Classification System is shown below (after Gray and Sotir, 1996).

Most Erodible ⟶ Least Erodible

ML > SM > SC > MH > OL > CL > CH > GM > SW > GP > GW

Where,
GW = Well graded gravel, GP = poorly graded gravel, SW = Well graded sand, GM = Silty gravel, CH = High plasticity clay, CL = Low plasticity clay, OL = Low plasticity organic soil, MH = High plasticity silt, SC = Clayey sand, SM = Silty sand, ML = Low plasticity silt.

Topographic variables influencing rainfall erosion are: (1) slope angle, (2) slope length, and (3) size and shape of watershed. The influence or importance of length tends to increase as slopes become steeper. Soils susceptible to down slope migration will satisfy the following conditions, PIANC (1987):

(i) A proportion of particles must be smaller than 0.06 mm.
(ii) Additionally, the soil will satisfy at least one of the following:
  (a) The uniformity coefficient, $C_u = \frac{D_{60}}{D_{10}} < 15$
  (b) 50% or more of the particles will lie in the range 0.02 mm < d < 0.1 mm.
  (c) The plasticity index (PI) will be less than 15. If PI is unknown at the preliminary design stage then the following criterion may be substituted:

$$\frac{\text{Proportion of Clay } (d < 0.002 \text{ mm})}{\text{Proportion of Silt } (0.002 < d < 0.06 \text{ mm})} < 0.5$$

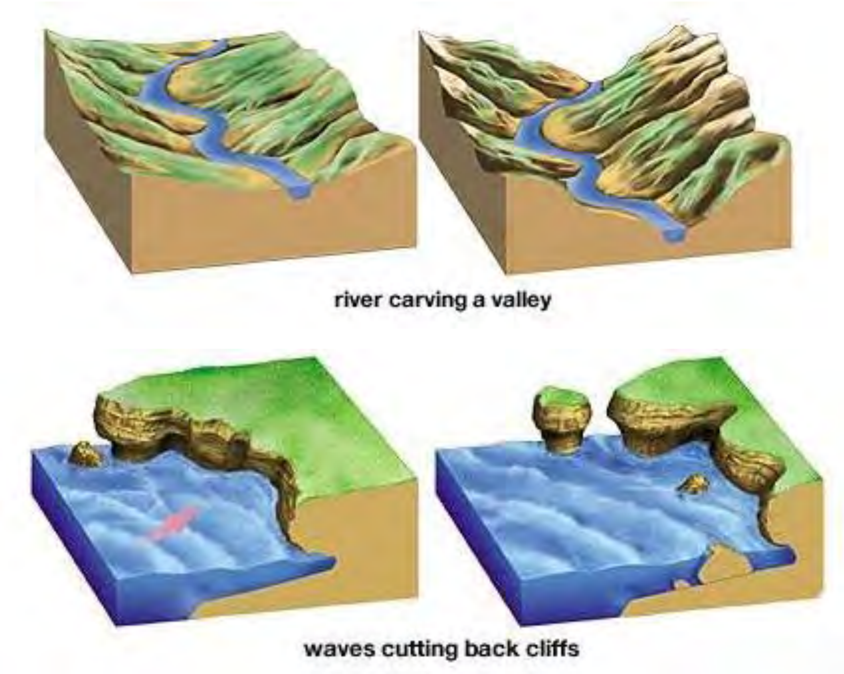


Figure 2.12: Failure by Erosion (Encyclopedia Britannica, 2015)

The severity of erosion is dependent on the combination of a number of factors. This is summarized in a model known as the universal soil loss equation (USLE).The USLE (Wischmeier and Smith, 1978) relates the rate of erosion from an exposed area (A) to the erosive power of the rain (R), the soil erodibility (K), the land slope and length (LS), the degree of soil cover (C), and conservation practices (P), shown in Equation 2.1:

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

Soil detachment plays an instrumental role in the erosion process. Soil detachment, defined as the soil particles being separated from the soil matrix at a particular location on the soil surface by erosive agents (Wang et al., 2014; Zhang et al., 2003), is a key process affecting soil erosion since it determines the amount of sediment that is potentially transferred to surface water bodies. Erodibility represents the soil's response to rainfall and runoff erosivity. Soil erodibility is not a measurable single parameter because it includes all the soil characteristics (both static and dynamic ones) that control a range of sub-processes affecting soil erosion. Hence, the soil characteristics that control the soil's behavior with respect to soil–water interaction (i.e. infiltration rate, permeability, water retention forces, porosity, exchangeable ions, primary particle sizes and mineralogy, aggregate size and stability, soil organic matter) are all important, as they interact, directly and indirectly, with rainfall to produce ponding water in soil surface depressions and surface runoff.

2.3.3 Causes of Embankment Failure by Erosion

From the field survey and past studies it is observed that, the most common causes of embankment and river bank failure can be broadly classified into two major groups:
(i) Natural forces
(ii) Human interference

Natural Reasons

The natural forces which are responsible for embankment erosion or damage are mainly caused for rainfall impact, wave action, turbulent wave current and wind action. The slope erosion caused by rain runoff is enormous and its speed or 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.

Wave actions cause damage to the embankments located too near to the sea or in *haor* areas. A severe hydraulic load is steadily exerted on the toes and slopes and causes erosion. The waves 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 (Chowdhury et al., 2017). Figure 2.13 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.

Figure 2.13: Road Slope Damage by Flood on 6th December 2017 in Jagannathpur Upazila, Sunamganj (The Daily Star, 2018)

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. 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 and thus inundated induce a parallel water current to flow along very near the embankment toes and slopes, thereby eroding the surfaces. 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. So, the factor of safety of embankment becomes lower and the vulnerability of embankment increases.

Human Disturbance

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 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.

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. 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. Forestation without appropriate planning and management techniques destroys the undergrowth grass cover and becomes ineffective for erosion protection.

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 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 Soil Bio-engineering Technology

Soil bio-engineering pursues technological, ecological, economic as well as design goals and seeks to achieve these primarily by making use of living materials, i.e. seeds, plants, part of plants and plant communities, and employing them in near–natural constructions while exploiting the manifold abilities inherent in plants. Its application suggests itself in all fields of soil and hydraulic engineering, especially for slope and embankment stabilization and erosion control (Schiechtl, 1980). Soil bio-engineering is the use of living plant materials to provide some engineering function. It is now widely practiced throughout the world for the treatment of erosion and unstable slopes (Gray and Leiser, 1982; Clark and Hellin, 1996).

Bio-engineering is generally appropriate for immediate protection against surface erosion, cut and fill slope stabilization, earth embankment protection and where plants can be submerged for extended period. Vegetation is the most cost-effective form of erosion control in bio-engineered way. It is also self-healing and attractive. Figure 2.14 shows the multipurpose effectiveness of vegetation in slope stability. Since vegetation prevents erosion, it is a much more desirable control measure than straw bale dikes, silt fences, and sediment traps and basins. Those devices can only trap sediment after soil has already eroded. Only a fraction of the eroded soil can be recaptured on the site, and the land is often left gullied and scarred. Vegetation reduces erosion by:

(i) Absorbing the impact of raindrops
(ii) Reducing the velocity of runoff
(iii) Reducing runoff volumes by increasing water percolation into the soil
(iv) Binding soil with roots
(v) Protecting soil from wind

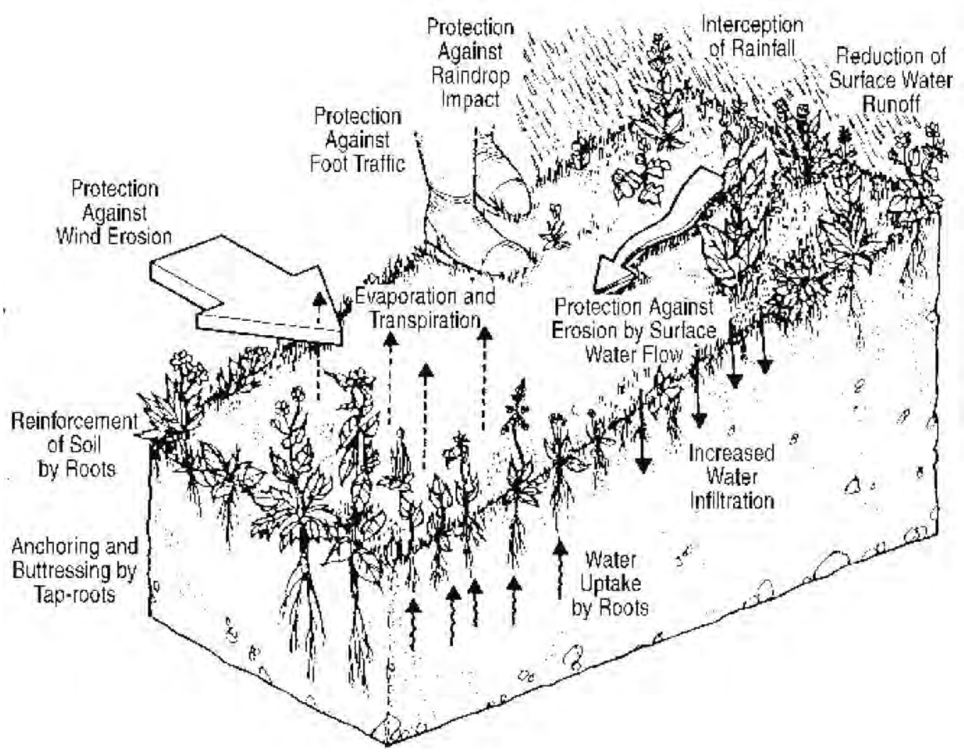


Figure 2.14: Effectiveness of Vegetation (Coppin and Richards, 2007)

Soil bio-engineering is now widely practiced throughout the world for erosion control and unstable slopes (Clark and Hellin, 1996; Allen and Leech, 1997; Battacharyya, 2006; Petrone and Preti, 2010). Soil bio-engineering techniques have been used in many centuries. These techniques are used alone or in conjunction with conventional engineering techniques (Barley, 1994). This technique can be used to revegetate steep slopes, to treat seepage zones and to control surface erosion (Gray and Leiser, 1982), in construction to provide soil reinforcement and as living retaining walls (wattle fences) and live reinforced earth walls (Polster, 2003). Soil bio-engineering method is effective to prevent and control surficial erosion and shallow mass wasting (Islam, 2013). Different methods or combination of methods can be used on: (i) natural hill slopes, (ii) cut and fill slopes along roadways, (iii) landfill covers, (iv) spoil banks, (v) stream banks and (vi) site reclamation work. Some methods are better and suited than others depending on the particular site conditions and objectives. In Bangladesh, this technique is also being practiced by the rural people for soil protection purpose.

2.4.1 Plants used for Soil Bio-engineering

In general, grasses and forbs are superior for preventing and controlling surface erosion, whereas woody vegetation (shrubs and trees) are superior for preventing shallow slope failures or mass erosion (Gray and Sotir, 1996). Both herbaceous and woody vegetation can be used as a soil bio-engineering material (Coder, 2010). Vegetative soil stabilization will be effective only if the site is geologically stable and is engineered properly. Thus, slopes should not be overly steep and diversion devices such as dikes and ditches should be installed to prevent runoff from crossing newly planted slopes.

Plants for erosion control must be well suited to the local environment. They must be vigorous and trouble-free and adapted to the soils and climate of a site. While it is important to select plants that are suited to the local area, it is also desirable to select plants that will survive best under construction site conditions. Plant species that require irrigation, fertilization, high maintenance, and just right conditions are not ideal; however, easy to grow, trouble-free plants are the best. Plants with special features such as dense, strong and deep root matrix, ability to intake pollutants and can grow in hostile environment such as drought, flooding, salinity, deposition, heavy grazing, waste soil etc. are used for these techniques. Important attributes of plants under consideration for soil bio-engineering use include availability, habitat value, size/form, root type, and ease of propagation as well as site characteristics (topography, elevation, aspect, soil moisture and nutrient levels), existing vegetation, intended role of vegetation in the project such as rooting characteristics, growth characteristics and ecological relationships of the plants, logistical and economic constraints (WSDOT, 2003).

Figure 2.15: Failure of Embankment due to Overturning or Uprooting of Trees during Cyclone (Mohammad Shariful Islam, BUET)

Figure 2.15 indicates that only vegetation cannot protect the embankment, rather than topple in high winds and cause problem after disaster. So, it is essential to select long rooted trees with suitable vegetation for environment friendly solution and the best performance of embankments. Plant selection should be based on the effectiveness of the plants for erosion control and on a number of other criteria (Jackson et al., 1986) shown below:

(i) Complete soil protection: Plants should have dense growth and fibrous roots that provide a continuous soil cover with no soil exposed between individual plants.
(ii) Fast growing: Plants should be able to germinate and grow rapidly to a size and areal extent that can provide good erosion protection.
(iii) Easy to plant: Plants should be suitable for seeding by hand broadcasting (using a hand-held, mechanical broadcaster), by drilling, or by hydraulic jet.
(iv) Adapted to poor soils: Plants should grow adequately in lo-fertility, rocky, acid, or alkaline soils or in soils with poor drainage.
(v) Adapted to local environment: Plants should grow well in the local climate and be competitive with undesirable local plants.
(vi) Regrowth in subsequent years: Annual plants should reseed well, and perennials should provide adequate regrowth after dormancy.
(vii) Available commercially: Seeds should be readily available from seed supply companies.
(viii) Low maintenance: Plants should require little or no irrigation, fertilization (after the first year), or mowing.
(ix) Low cost: The cost for seed, application, maintenance, and slope repair should be minimal.
(x) Low fire hazard: Plants should not produce excessive fuel volumes, particularly in dry climates.
(xi) Drought tolerance: Plants should be able to survive dry periods without irrigation, particularly in climates with a dry season.

The plants to be selected should meet as many of the above criteria as possible. The first two criteria are particularly important for erosion control in the first few years after grading. A mix of plant species should be used when replanting. Having a variety of species will increase the chances for success. A single plant type is always more susceptible to failure because of disease, unusual weather, lack of key nutrient, or some factor peculiar to it.

2.4.2 Root Characteristics of Appropriate Vegetation

Plant roots may have a strong erosion-reducing effect. Studies show the existence of a strong correlation between the plant roots spread inside the subsoil area and shear strength of that soil. The higher tensile strength of roots contributes to thriving the soil shear strength and binding capacity, which prevents surface and subsurface soil erosion, a common occurrence especially in the wetland and coastal areas.

Root Architecture

The roots and rhizomes of the vegetation interact with the soil to produce a composite material in which the roots material are fibers 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. Roots with special bushy structure such as having numerous branches and root hairs are effective and mainly used for soil bio-engineering technology. Another main requirement is to have enough tensile strength (Jain, 2013). Both requirements are necessary to work out correctly; otherwise this technology will not work effectively. If the roots are strong enough but do not have branches, it will topple in tension and pull straight out of the ground with minimal resistance. The root reaches its maximum pullout resistance, then rapidly fails at a weak point and easily slips out of the soil due to the gradual tapering (progressive decrease in root diameter along its length). As the root is pulled out it, is moving through a space that is larger than its diameter which consequently has no further bonds or interaction with the surrounding soil (Norris, 2005). If the roots do not have enough tensile strength but have multiple branches or forked branches also can undergo tensile failure but predominantly fail in stages as each branch breaks within the soil. Figure 2.16 shows the root architecture of different fibrous plants.

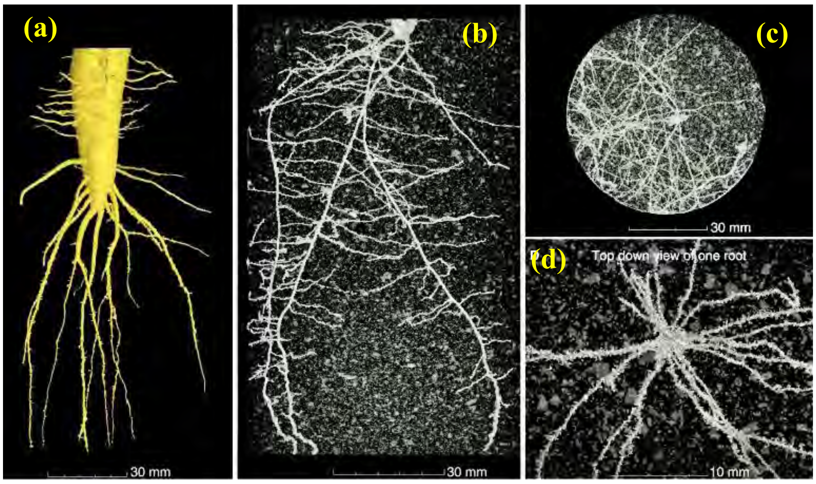


Figure 2.16: Fibrous Root System of Different Plants: (a) Tap Root (*Raphanus sativus*); (b) Fibrous Root (*Triticum aestivum*); (c) Top Down View of Whole Root System of *Triticum aestivum*; and (d) Top Down View of One Root of *Triticum aestivum* (Morris et al., 2017)

Root Tensile Strength

Vegetation root has already been recognized as a factor useful for increasing the shear resistance of soil on an unstable slope and thus contribute to preventing soil erosion (Operstein, 2000). The significant factors that influence the shear resistance of root-permeated soil are the quantity and directional distribution of roots as well as their tensile strength, soil shear strength, and soil-root interaction (Comino et al., 2010). The tensile capacity of plant roots provides mechanical reinforcement to fine-grained soils at shallow depth and has the potential to increase shear strength ability (Shewbridge and Sitar, 1989). Thus, vegetation roots play a significant role in improving soil slope stability by supporting the prevention of mass soil sliding and erosion (Wu et al., 2014). Subsurface parts of vegetation consist of rhizome and primary roots. Rhizomes of are short internodes, forming a dense underground horizontal mat where roots are branched out from the rhizome at almost normal direction. Therefore, in most occasions, the probability of roots crossing a specified slip surface and acting as shear reinforcement was found to be higher in comparison to the rhizomes (Figure 2.17). Root tensile strength varies with individual roots as well as their morphological characteristics (Nyambane and Mwea, 2011). Root tensile strength of some plants are presented in Table 2.2. From the Table 2.2, it is seen that *Vetiveria zizaniodes* provides the maximum root tensile strength among other vegetation, so using this plant is effective as a measure of erosion control by bio-engineering method.

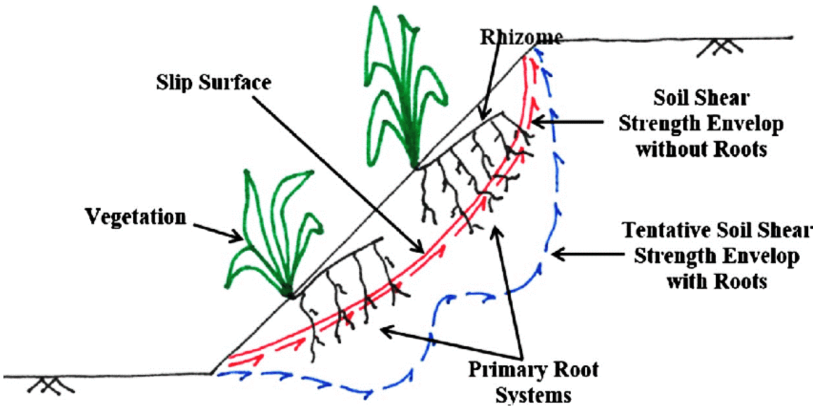


Figure 2.17: Schematic View of Primary Root System Crossing the Slip Surface (Alam et al., 2018)

Table 2.2: Tensile Strength of Roots of Particular Vegetation

Scientific name	Common name	Tensile strength (MPa)	Source
Paspalum dilatatum	Dallis grass	17-23	after Schiechtl, 1980
Trifolium repens	White Clove	21-28	
Eremochloa ophiuroides	Centipede grass	26-29	
Paspalum notatum	Bahia grass	16-23	
Zoysia matrella	Manila grass	16-20	
Cynodon dactylon	Bermuda grass	11-16	
Salix	Willow	9-36	Wu, 1995
Populus	Poplars	5-38	
Alnus	Alders	4-74	
Pseudotsuga menziesii	Douglas fir	19-61	
Acer sacharinum	Silver maple	15-30	
Tsuga heterophylia	Western hemlock	27	
Vaccinum	Huckle berry	16	
Hordeum vulgare	Barley	15-31	
Chionophila tweedyi	Grass, forbs	2-20	
Dicranum scoparium	Moss	0.002-0.007	
Vetiveria zizanioides	Vetiver grass	40-120 (Average 75)	Hengchaovanich and Nilaweera, 1996

2.5 Vetiver System as Bio-engineering

In 1986, World Bank introduced a distinct grass named vetiver (*Vetiveria zizanioides*). Initially the World Bank promoted the use of vetiver through its vetiver department and now through the "The Vetiver Network International (TVNI)". The Vetiver System (VS) is dependent on the use of this unique tropical plant, vetiver grass (*Vetiveria zizanioides*), recently this grass is reclassified as *Chrysopogon zizanioides*. Most developed and developing countries like Australia, China, India, Malaysia, Spain, Thailand and Zimbabwe are using 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 (local name of vetiver) or vetiver grass is used in more than 100 countries of the world (Truong, 2000).

2.5.1 Characteristics of Vetiver

The specific name vetiver was given first by the great Swedish taxonomist Carolus Linnaeus in 1771. It means "by the riverside," and reflects the fact that the plant is commonly found along waterways. The plant can be grown over a very wide range of climatic and soil conditions, and if planted correctly can be used virtually anywhere under tropical, semi-tropical, and Mediterranean climates (Truong et al., 2002; Rahman et al., 1996; Dudai et al., 2006). When used for civil works, its cost is about 1/20 of the traditional engineered systems and designs. Engineers like the vetiver root to a "Living Soil Nail" with an average tensile strength of 1/6 of mild steel (Hengchaovanich, 1998).

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. Vetiver is a kind of plant that can suitably and rapidly adapt to the environment.

Plant Morphology

The upper surface of the plant 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. 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. Morphological characteristics of vetiver are discussed below:

(i) Vetiver is typically 1 m tall and densely tufted, grows in large clumps from a much-branched 'spongy' rootstock. It is very difficult to break the clustered mass of stems and the thicket of vegetation down near the soil surface. Vetiver grass has no stolon, very short rhizomes and a massive finely structured root system that can grow extremely fast, in some applications rooting depth can reach 3-4 m in the first year. The leaf of vetiver is 45-90 (100) cm long and 0.6-0.9 (1.2) cm wide. This deep root system makes vetiver plant extremely drought tolerant and difficult to dislodge by strong current.

(ii) The stiff and erect stems, which form dense hedges, can stand up to relatively deep water flow which reduces flow velocity and traps sediment. It has a strong fibrous root system that penetrates and binds the soil to a considerable depth, and is propagated by plantation of tillers. It is both a xerophyte and a hydrophyte, and once established it can withstand drought, flood, and long periods of water logging.

(iii) It can grow on various types of soil textures including sands, shales, and gravels.

(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.

Table 2.3: Morphological Characteristics of Vetiver Grass

Properties / Earlier Researches	Soil Type	Shoot length (m)	Root length (m)	Root diameter (mm)	Average range of tensile strength (MPa)
Hengchaovanich, 1999	Sandy loam	-	0.34-0.98	-	53.9-116.3
Michkovski et al., 2005	Silt	-	0.11-0.275	0.30-1.45	-
Michkovski and Van Beek, 2009	Silt	Up to 3.0	-	-	4.91
Islam, 2013	Silt	0.25-0.13	0.2-0.5	0.34-0.98	-
Nasrin, 2013	Silty sand	1.09	0.28	-	-
	Silty clay	1.14	0.13		
Parshi, 2015	Clay with low plasticity	0.1-0.13	0.05-0.4	0.2-2.2	-
Arif, 2017	Silty sand	0.1-0.13	0.5-1.2	1.1-1.3	-
Islam, 2018	Silty clay	0.6-0.96	0.22-0.46	1.1-1.3	-
Badhan, 2018	Clay with low plasticity	0.31-1.42	0.175-1.14	1.15-1.3	27
Mumtahina, 2019	Sand	0.28-0.64	Up to 0.66	0.2	-

Different researchers have studied the morphological characteristics of vetiver with time which is presented in Table 2.3. The characterization of vetiver is shown briefly as photographs in Figure 2.18.

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

Figure 2.18: (a) Leaf blades, (b) Stems, (c) Inflorescence and (d) Root matrix of Vetiver grass (Islam and Hoque, 2020)

Plant Physiology

Vetiver is a climax plant that can survive all kinds of natural adversity, and can remain to protect the ground from the onslaught of the next rains. Fertility enhancement is sometimes done by cultivating vetiver and mixing it with alluvial deposits in newly raised char lands. The physiological aspects are described below:

(i) Tolerance to extreme climate such as prolonged drought, flood, submergence and extreme temperature from from -10˚C to 48˚C (Truong and Loch, 2004).
(ii) 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).
(iii) Ability to regrow very quickly after being affected by drought, frosts, salinity and adverse conditions after the weather improves or soil ameliorants added.
(iv) It grows on acidic to alkaline soil types, i.e., tolerance to wide range of soil pH (3.0 to 10.5).
(v) High level of tolerance to herbicides and pesticides.
(vi) Highly efficient in absorbing dissolved nutrients and heavy metals in polluted water. Highly tolerant to Al, Mn and heavy metals such as As, Cd, Cr, Ni, Pb, Hg, Se and Zn in the soils (Truong and Baker, 1998).
(vii) Vetiver has certain resistance to salinity. Even in the soil with ECse 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).
(viii) Its roots are very strong with high tensile strength of 75 MPa (Hengchaovanich, 1998).
(ix) Vetiver hedges can survive even for more than 100 years (Verhagen et al., 2008).

Environmental Characteristics

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 presence of sunlight and weed control may be needed during establishment phase. Vetiver grass can be eliminated easily either by spraying with glyphosate or uprooting and drying out.

Mechanical Characteristics

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.

Infiltration and Soil Resistance Capacity

Infiltration capacity of soil under vegetative barriers is a major parameter of vetiver to be observed. Soil variables such as bulk density, particle density, porosity, field capacity and hydraulic conductivity affect the infiltration capacity of soil (Dutta and Matin, 1993). 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.

2.5.2 Previous Studies

Sanguankaew et al. (2003) describe the experience of the Thai Department of Highways in implementing the vetiver slope protection works on mountainous highways in the North, Northeast and South Thailand. Standard drawings detailing the quality of slips, planting procedures and maintenance techniques, planting patterns for various types of situation: on slopes, end of drainage lines, at bridge approaches, etc. have been prepared to aid field practice.

Chaowen et al. (2007) experimented on three plots each of 7 m × 20 m with three strips of Vetiver grass (*Vetiveria zizanioides*) from 1998 to 2005. Owino et al. (2006) used nine runoff plots each of 16 m length and 2 m width, runoff and nutrient loss were measured from June 2000 to August 2001 (more than a year). Due to area and time limitations, sometimes performing laboratory experiments on a large area covering a long duration of time become difficult. Sudhishri et al. (2008) used a 150 m^2 (30 m × 5 m) plot with 11% slope on a degraded hill slope for three consecutive years (2000-2002). Hirunpraditkoon and Garcia (2009) presented the results of an experimental study of the pyrolysis kinetics of polypropylene (PP), vetiver grass, and PP composites containing vetiver grass powder and developed mathematical models of the kinetics.

Dass et al. (2010) found that vegetative barriers with longer and thicker roots and significantly higher dry weight and volume can make the soil profile more porous and permeable than bare soil condition, resulting in greater channeling and infiltration of runoff. Donjadee and Tingsanchali (2012) prepared three experimental plots which are 10.44 m, 8.08 m and 6.71 m in length respectively, vetiver grass (*Vetiveria nemoralis*) used here took one year to grow up. Oshunsanya (2013) used Vetiver grass *(Vetiveria nigritana)* alleys to observe the infiltration capacity of soil which increases with the installation of Vetiver Grass Hedgerows (VGH) with respect to the control plot. The reason is, soil particles deposit in higher rate in front of Vetiver hedgerows resulting in higher rate of infiltration in that area (Machado et al., 2018).

D'Souza et al. (2019) investigated on increase in shear strength of soil by vetiver roots. Using a custom made large-scale in situ direct shear test apparatus, in situ direct shear tests were conducted at different depths on a soil plot with one-year-old vetiver grass planted at 0.15 m spacing in an equilateral triangular pattern. The tests proved that the vetiver grass roots increased the shear strength of soil by up to 139% at 0.15 m depth and up to 47% at 0.75 m depth.

(a) (b)

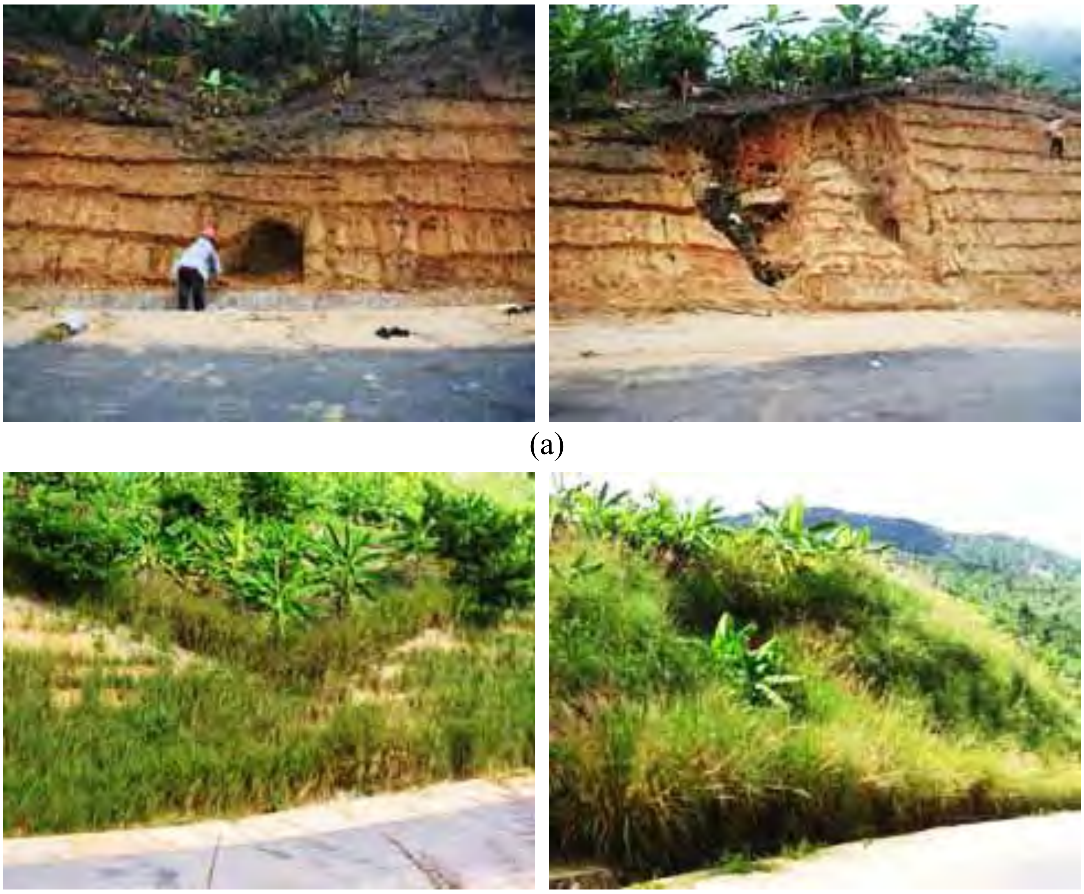
Figure 2.19: (a) Community Members Planting Vetiver; and (b) Bank Remains Intact Following the Flood Season in Quang Ngai Province, Vietnam (November 2005, funded by AusAid)

(a) (b)

Figure 2.20: Photographs of Da Deo Pass, Quang Binh; (a) Vegetation cover was Destroyed, Revealing Ugly and Continuous Failures of Cut Slopes; and (b) Vetiver Rowed on Top of the Slope Very Slowly Squeezed Down, Considerably Reducing the Failed Mass

Panja et al. (2020) investigated the potential of vetiver to remove two widely prescribed antibiotics, ciprofloxacin (CIP) and tetracycline (TTC) from secondary wastewater effluent. Significant ($p<0.05$) removal of antibiotics and nutrients (N & P) by vetiver grass from secondary wastewater effluent was observed within 30 days. Vetiver grass removed more than 90% antibiotics from secondary wastewater matrix. In addition to antibiotics, vetiver grass also removed nitrate (>40%), phosphate (>60%), total organic carbon (>50%), and chemical oxygen demand (>40%) from secondary wastewater effluent.

Figure 2.19 to Figure 2.21 (Truong et al., 2008) show the efficacy of vetiver plantation in case of slope protection in different places all over the world.



(a)

(b)

Figure 2.21: Photographs of Pham Hong Duc Phuoc; (a) Severe Erosion on Newly Built Batter Occured after only a Few Rains; and (b) Eight Months after Vetiver Planting, Vetiver Stabilized This Slope, Totally Stopping And Preventing Further Erosion During The Next Wet Season

2.5.3 Research on Vetiver System in Bangladesh

Soil bio-engineering research using vetiver has been started recently in Bangladesh and already few researches had been conducted. In Bangladesh vetiver grass is locally known as '*binna'*, *bennashoba, gondhabena* or *ecorban* (Rahman et al., 1996; Huq, 2006). This grass is being used for land demarcation and sometimes soil protection purposes. Though local people do not have any technical knowledge, they sometimes plant this grass for reservation of their personal pond. But recently this system is being applied for different research purposes.

This system has been applied in shrimp pond slope protection in Baliapur, Nil dumur and Kaliganj in Satkhira district (Shahriar, 2015), in Keraniganj highway road side slope, in tarash beside the pond (Islam, 2013). Vetiver was applied to protect dykes of shrimp ponds in saline prone area with the help and cooperation of GIZ, Germany. This technology has been adopted by WAB in other shrimp farming for green covering using vetiver grass (Sarder, 2014). Also this system is used for hill slope protection with a layer of jute-geotextile (JGT). Nasrin (2013) determined 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 with different percentages and different root lengths; and bared soil was determined for block samples.

Parshi (2015) selected four plants namely hardy sugarcane, wild cane, tiger grass and vetiver grass for the evaluation of effectiveness of plants as bio-engineering solution. Growth of these plants in different soils (dredge fill sand, red clay, nursery soil, contaminated soil and saline soil) had been studied in plain land and slope ground. It was found that hardy sugarcane and wild cane grew well in nursery soil and sand whereas vetiver grew better in sandy, clayey, saline and contaminated soil. In addition to these, effectiveness of vetiver grass in remediation of heavy metal from soil had also been studied. It was found that the concentrations of heavy metals (Pb, Cu, Cr, Ni and Zn) in this soil are above tolerance level. Plant root mechanically increased soil shear strength by transferring soil shear stress from soil into tensile forces of the root themselves, via interface friction along the root surface. Orientation and geometry of the root also influenced the effectiveness in reinforcing.

Islam et al. (2016) conducted three case studies of vetiver plantation in slope protection against rain-cut and wave-induced erosion. Islam et al. (2018) proposed a bio-engineering based solution in order to protect the side slope of the raised village mounds. In the proposed method, locally available materials i.e., vetiver grass, dholkolmi, geo-jute (JGT) and gunny bags (filled with cement and sand at ratio 1:8) were used for village side slope protection. The proposed technique was applied in Noonkhawa, Nageswari and Astamir Char, Chilmari of Kurigram district. The system was found to be successful in both of the sites that kept the side slope of the raised village mounds safe from rain cut erosion and immense wave action generated during the North-West flood in 2017.

Islam (2018) developed a study on the effectiveness of vetiver grass plantation to protect the hill slopes against top soil erosion and surface runoff. Efficacy of vetiver in soil erosion has been studied with small scale laboratory model study. Performance of slope against erosion has been studied under rainfall for both bare slope and vetiver rooted slope. It is found that sediment yield for bare soil is very much higher compared to the sediment yield for rooted slope. Amount of infiltrated water increased with time resulting in reduced surface runoff and soil loss for the vegetated slope. Sediment yield tends to be zero after a certain rainfall which proves the effectiveness of vetiver grass against erosion.

This grass has been planted in twelve districts under the implementation of Local Government and Engineering Department (LGED), mainly in saline regions of Bangladesh under a project named ‘Coastal Climate Resilient Infrastructure Project (CCRIP)’. The project areas are Satkhira, Khulna, Bagerhat, Pirojpur, Jhalkathi, Borguna, Patuakhali, Bhola, Barisal, Madaripur, Shariyatpur and Gopalganj (Islam and Hoque, 2020). Effectiveness of vetiver grass against rain-cut erosion and tidal wave in coastal zones of Bangladesh were examined using model study and field trials. It has been found that the vetiver based bio-engineering technique can provide an effective and environment-friendly solution for embankment slope protection.

Figure 2.22: Road Slope Protection by Vetiver at Barisal, Bangladesh under CCRIP (Islam and Hoque, 2020)

(a) (b)

Figure 2.23: Charland Protection under UNDP with Vetiver at (a) Nageswari, (b) Chilmari, Kurigram, Bangladesh (2017) (Islam and Hoque, 2017)

Figure 2.22 to Figure 2.24 show some implantation of vetiver in field in Bangladesh in different sectors. Chattogram City Corporation has been established a “Vetiver Grass Display Center” at Tiger Pass, Chattogram (Figure 2.25) with the joint collaboration of Bangladesh and Thailand government. At 30th May 2019 Thai Princess, Her Royal Highness Maha Chakri Sirindhorn inaugurated the display center. Professor Dr. Mohammad Shariful Islam worked as the advisor of this work.

Figure 2.24: Hill Protection at Ukhia, Cox’s Bazar (Mohammad Shariful Islam, BUET)

Figure 2.25: Vetiver Display Center in Chattagram (Mohammad Shariful Islam, BUET)

2.6 Revetment

Revetments are used to protect banks and shorelines from erosion caused by waves and currents. These structures are always made as sloping structures and are very often constructed as permeable structures using natural stones or concrete blocks, thereby enhancing wave energy absorption and minimizing reflection and wave run-up. However, revetments can also consist of different kinds of concrete slabs, some of them permeable and interlocking. Revetments can be an exposed structure as well as a buried structure. In this way their functionality is increased in terms of absorption and strength. Many revetments are used to line the banks of freshwater rivers, lakes, and man-made reservoirs, especially to prevent damage during periods of floods or heavy seasonal rains. A buried revetment can be constructed as part of a soft protection, e.g. as a hard emergency protection built into a strengthened dune which acts as shore protection and/or sea defense (Coastal Wiki, 2007).

Practical Features

All types of revetments have the inherent function of beach degradation as they are used at locations where the coast is exposed to erosion. A revetment will fix the location of the coastline, but it will not arrest the ongoing erosion in the coastal profile, and the beach in front of the revetment will gradually disappear. However, as a revetment is often made as a permeable, sloping structure, it will normally not accelerate the erosion, as did seawalls; on the contrary, rubble revetments are often used as reinforcement for seawalls which have been exposed due to the disappearance of the beach. Such reinforcement protects the foot of the seawall and minimizes the reflection. A revetment, like a seawall, will decrease the release of sediments from the section it protects, for which reason it will have a negative impact on the sediment budget along adjacent shorelines.

Applicability

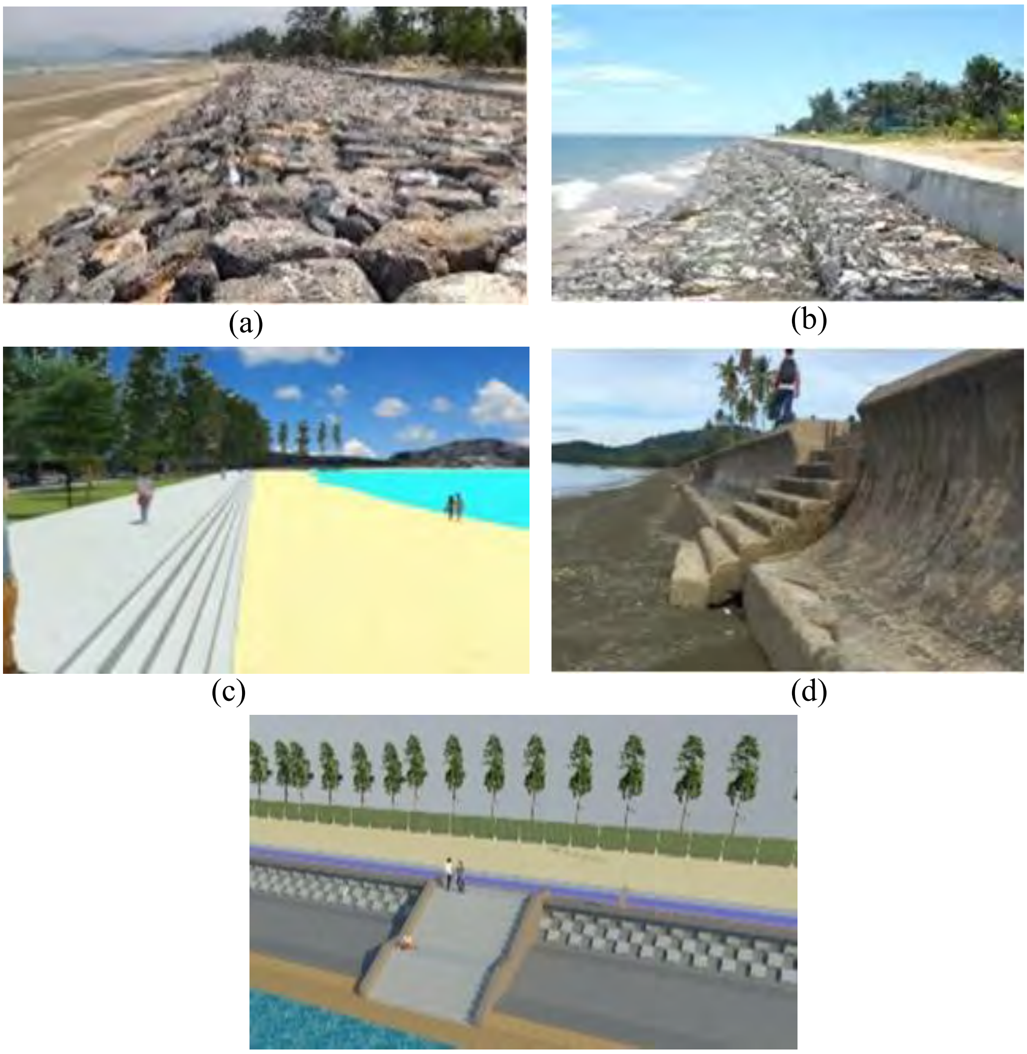
A revetment is a passive structure, which protects against erosion caused by wave action, storm surge and currents. The main difference in the function of a seawall and a revetment is that a seawall protects against erosion and flooding, whereas a revetment only protects against erosion. A revetment is thus a passive coastal protection measure and is used at locations exposed to erosion or as a supplement to seawalls or dikes at locations exposed to both erosion and flooding. Revetments are used on all types of coasts. Rubble revetments and similar structures have a permeable and fairly steep slope; normally a 1:2 slope is used. This slope is suitable neither for recreational use nor for the landing or hauling of small fishing boats. Consequently, this kind of structure should not be used at locations, where the beach is used for recreation or fishing activities. For such locations, other types of protection measures must be considered, but if a revetment is required, a more gently sloping structure with a smooth surface is recommended.

Types of Revetment

Sloped bank protection and earth retention structures come in a great variety of types and forms. On open water such as facing oceans or bays, they are usually called as revetment. Along river banks they are usually known as levees. When used for retention or impounding purposes, they are generally referred as dike structures. Figure 2.26 shows different types of revetments and dikes. Based on the construction material, they can be divided into the following groups.

(i) Stone rip-raps of loose construction
(ii) Grouted or cemented slopes of stones, gravels or other aggregates
(iii) Manufactured blocks, usually made of concrete
(iv) Impervious layers such as asphalt and bituminous paved banks
(v) Gabion structures constructed with metal wires (Gabions are rectangular baskets or mattresses made of galvanized, and sometimes also PVC-coated, steel wire in a hexagonal mesh. The individual baskets are wired together and filled with 4- to 8-in.-diam stone)

(vi) Vegetation on top soil such as hard clay and/or retention structures
(vii) Flexible structures such as sand bags, longard tubes (Longard tubes are patented, woven, polyethylene tubes that are hydraulically filled with sand and available in 40- and 69-in. diameters and lengths up to 328 feet)



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

Figure 2.26: Photographs of (a) Rock Revetment; (b) Gabion Revetment; (c) Stepped Concrete Revetment; (d) Curve Faced Concrete Revetment; (e) Concrete Revetment with Blocks (Saengsupavanich, 2017)

Design Considerations

There are varietys of sloped bank protection structures. To select a specific type for local application a number of criteria should be considered (Abbot and Price, 1995).

(i) Strength and vulnerability: Structure strength is the primary concern in design. The vulnerability is measured in terms of the steepness of the damage curve; the steeper the damage curve the more vulnerable the structure. Therefore, for structures with comparable costs, the selection should favor those with milder damage curves.

(ii) Flexibility: This is associated with vulnerability. For earth retention structures, a certain degree of settlement is anticipated. A compliant structure that adjusts to the change is usually less vulnerable to catastrophic failures.
(iii) Material availability: The availability of material becomes a major factor for large size projects. This may dictate the type of structure selected.
(iv) Construction: Easy and fast construction usually translates into lower costs. Also, when construction time is a major factor, construction may dictate the selection of structural types.
(v) Maintenance: The cost of maintenance should be factored in the at the design stage.
(vi) Durability: The durability of material concerning physical, biological, sea water effects, sun light effects, etc. should be considered.
(vii) Others: Environment impact, recreation value, aesthetic, other utilities, etc.

2.6.1 Ecological Revetment

Environmental friendly design has become the catch word in recent years. Substantial research effort has been spent mainly in the direction of utilizing vegetation as bank protection, or mixing vegetation with compliant structures. At present, erosion prevention by plants and grasses is only suitable for mild environments. In a hostile environment such as along an open coast, vegetation can only serve as a secondary defense and as a sand trapping device. The whole systematic diagram is shown in Figure 2.27. Ecological revetment is one of the effective, cost-efficient, sustainable eco-technologies that can be used to restore urban ecological systems. This technique is effective where urban development planning and more efficient construction technologies are required for flood control and environmental protection.

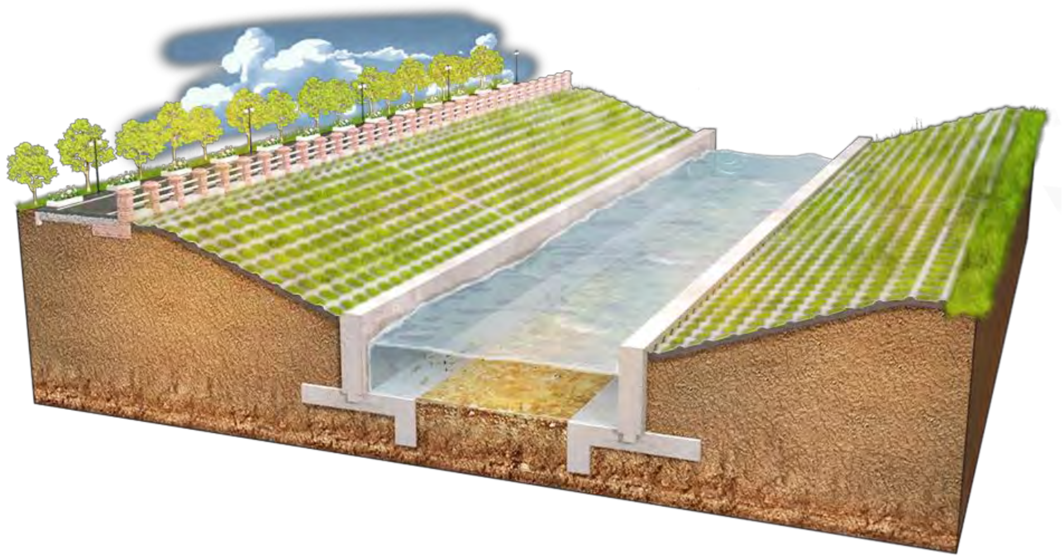


Figure 2.27: Ecological Revetment System (ACE Geosynthetics, 2015)

Conventionally, concrete and rock materials have been widely used in river bank revetment to control flooding and erosion. Revetment with stable construction is essential to ensure the safety of people and their property. However, an appropriately designed, hard revetment can negatively affect the ecosystem, including aquatic and amphibian habitats, river water quality, and aesthetic value (Bohm et al, 2011). In addition, after heavy rainfall events, storm water runoff scours the road surface, which results in riverbed erosion and water pollution related problems (Chen et al., 2010). In order to construct a secure bank revetment with fewer negative effects on the river ecosystem, the ecological impact of revetment must be considered.

With the consideration of topographical, hydrological, and ecological conditions of the river, ecological revetment must be combined with civil engineering technologies and ecological science to ensure good stability of the bank slope and ecological restoration effects (Yao et al., 2012). Ecological revetment (which integrates plants and a more porous structure) can have a positive effect on the ecosystem as it can facilitate ground and river water circulation, and river bank ecological restoration. Ecological revetment can also be constructed using locally-available limestone materials (Wu and Feng, 2006; Chen et al., 2016; Gabriel and Bodensteiner, 2012). Ecological revetment with a porous structure can provide a habitat for microbial and plant reproduction, which plays an important role in removing water pollutants. Plant and microbial growth and their diversity can also improve the river water quality.

Types of Ecological Revetment

There are many kinds of ecological revetment, including types of natural vegetation, masonry, eco-concrete, and so on. What is more, the engineering characteristics, economic cost, suitable condition of application are all different. Therefore we should choose appropriate types of ecological-type revetment in the construction of river channel for small cities and towns (Wang and Wang, 2011).

(i) Revetment of grass and trees: Mainly to protect the banks of rivers, streams and some local erosion of the corner location ensures, vegetation, such as planting fir, willow and other water features with highly developed roots which can help to stabilize soil particles and to increase the stability of the embankment. The method is simple and low cost. But the anti-erosion property of the embankment is poor by the beginning erosion. In this case, geotextile slope works as a good assist. With the growth of trees and plants, the erosion capacity will grow gradually. With root system to protect native vegetation and ecological stability of embankments, plants in soil and water conservation of soil has a good effect. The use of plant roots for bank protection developed solid earth to protect both the sand and prevent soil erosion, which also meet the needs of the ecological environment and landscape formation. Ecological stream bank protection in rural areas can be given priority. Solid soil plants are plants like seabuckthorn forest, *Dalbergia*, *Taxodium ascendens*, *Eulaliopsis binata*, honeysuckle, etc. According to the region's soil, climate, and local people's preferences, the choice of plant species varies. This form of bank protection works well for the small towns with small surrounding flow and small rivers with low flow speed. Figure 2.28 and Figure 2.29 subsequently show the schematic diagram and construction procedure of vegetated riprap.

    Artificial bamboo stakes (wickers), which have good anti-erosion ability, good integrity, and abilities to adapt to ground deformation, are more suitable for the flow rate of a large embankment of the river. They can guarantee that the water exchange between the river water and groundwater benefit to the reproduction of aquatic plants and animals, growth, and meet the needs of river flood erosion. They also have the ability to adapt to ground deformation, simple construction and low cost advantages. For natural narrow rivers or artificial narrow river course due to houses and other barriers, bamboo stakes should be replaced with pine, willow or other wood stakes made of a certain length, vertical or inclined into the ground, forming almost vertical shore to protect the embankment from erosion (Gray and Sotir, 1992). Some small streams are suitable to the use of Wickers wood piles, willow piles which may be alive after surviving the formation of the vertical revetment. Slope planting vegetation helps to stabilize revetment. This type of bank protection works well for urban parks and wetlands which has a low landscape river flow.

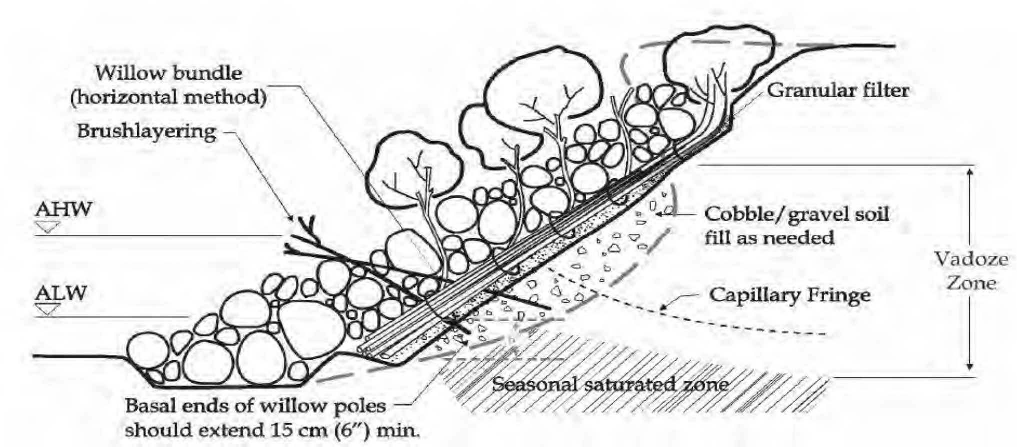


Figure 2.28: Vegetated Riprap (Salix Applied Earth Care, 2004; Holanda and Rocha, 2011)

(a) (b)

Figure 2.29: (a) Interlocking Concrete Grids Serve as Base for Plants (b) Salt Water Resistance Grass Planted on Top (USACE, 1984)

(ii) Stone revetment: By fully utilization of local stone, a vertical or a certain slope of the revetment could be formed in the form of dry assembling. It works best for the larger river flow and high flow rates. For a better effect, during the dry assembling, the gap could be filled with planting soil, and planted grass and other plants. Constant water level is generally right above the upright wall for the retaining and water erosion. Gentle slope is usually added above the constant water level, making space for local plants and trees. This form of bank protection works fine for small and medium rivers near big cities and towns with heavy traffic as there is some erosion control requirements. Stone revetment is perpendicular retaining wall formed by mortar cement and brick stone. This form of revetment has good stability, high strength, easy construction, nice appearance, and relatively high cost. This type of revetment makes fully use of river cross section, further increases the anti-erosion capacity, and could be used for large rivers flow dike revetment (Li, 2008). To reduce the amount of cement, rock blocks can be used for back wall to form a semi-vertical stone masonry revetment. Walls are able to meet the strength, stability conditions, and saving cement is also beneficial to the exchange of river water and groundwater.

For big rivers, erosion damage is likely to be caused to the toe at the sharp bends on the flow section of the top red groove parts. In this case, riprap protection (foot) could be introduced. Riprap revetment is generally placed underwater, with advantages like easy dumping, can be highly deformed, high hydraulic roughness characteristics. Because the deformation and failure of the riprap happen slowly, riprap body has certain self-healing capability. This form applies to the larger flow revetment, rivers with high erosion control requirements. It demands the combined applications of masonry, masonry and concrete revetment. Using wire or bamboo strips to fix gravel and stone into a larger overall size can prevent the erosion of the larger floods. Gabions are usually spray wire cages or bamboo cages loaded with (crushed) pebbles, fertilizer Branch and planting soil composition. Barbed wire (bamboo) cage can hold the rock or gravel with fixed wire (bamboo). Cage density is determined according to the diameter of gravel. Cage size should meet the construction requirements (Fu et al., 2008).

(iii) Revetment of artificial materials: In order to overcome the shortcomings of conventional cast concrete slope protection, concrete slope protection have been developed in an ecological way. Eco-concrete slope protection is the use of precast concrete plate polygons which are regularly piled on the river slope. There are holes among the pre-cast concrete blocks, in which grass and planting plants could be grew and thus form green ecological revetment (Xu and Yue, 2005). Box-shaped or plum-shaped arrangement of holes could be used as underwater lairs for the fish and amphibians. The revetment has certain level of anti-erosion ability of water. Moreover, the holes for plant growth, reproduction habitat for amphibians, help the formation of harmony in the water, slope symbiotic systems and the achievement of the ecological revetment.

Ecological wetland management should also be comprehensive system engineering. Therefore, it is necessary to meet flood control, drainage, water supply, etc. production and living requirements, while also taking ecosystem health and sustainable development needs into account (Ji and Liu, 2001). Bank protection must comply with the principles of hydraulics and engineering to ensure that the security, stability and durability of engineering facilities. Engineering design standards must be satisfied to withstand floods, erosion, wave, ice, drought and other natural forces load.

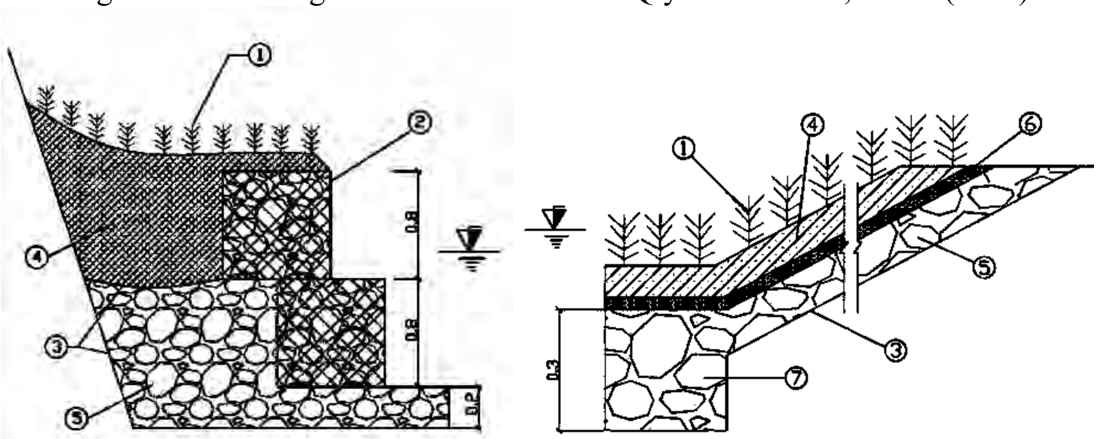
2.6.2 Past Researches

Many existing ecological engineering works have proved the feasibility, ecological restoration, and bank slope stable effectiveness of the ecological revetment and vetiver grass. In 2001, the Soil and Water Conservation Department of Taiwan worked on the development and integration of ecological engineering, and presented some examples of existing ecological engineering methods using stone revetment, boxed gabion revetment, and arc-shape stone streambed sill for bank protection, respectively (Wu and Feng, 2006). In another study, Chen et al. (2016) evaluated the ecological restoration capability of the revetment, and proposed hexagonal precast blocks, bamboo, and complex natural material to construct ecological revetment works for the Liudaxian channel bank in China. Gabriel et al. demonstrated that a well-designed riprap can have positive effects in increasing the ecological diversity and the amount of fauna, flora, and microbial communities present in the region, and enhancing pollutant removal. Plant roots and the stones present in the ecological revetment provide a good habitat for microbial reproduction, which can improve the water quality, as well as the stability of river slopes. Ramli et al. (2013) studied the ability of gabion to collectively deform under aggravated loads, under the influence of soil-hydrostatic pressures, and evaluated the stability of the gabion wall for earth retaining structure in flood-prone areas.

Tian et al. (2016) developed a design of ecological restoration and eco-revetment construction for the riparian zone of Xianghe Segment of China's Grand Canal. They applied the concept of landsenses ecology, ecological restoration principles and a range of eco-revetment models in riparian zone restoration for Xianghe Segment of China's Grand Canal (XSCGC). The riparian zone was divided into five typical sections: the wetland ecological conservation section in the upper reaches, the wetland ecological conservation section in the lower reaches, the riverside leisure and entertainment section in the middle reaches, the restoration and reconstruction section in the middle reaches, and the ecological agricultural section in the lower reaches. Based on the spatial form, human senses and the flood control function of the riparian zone, three typical revetment models were applied, namely original natural revetment, natural revetment, and hybrid revetment. A vegetation plan was proposed for every functional section. Concrete revetments are the most common type of infrastructure used to control the Mississippi River. More than 1,000 miles (1,600 km) of concrete matting had been placed in river bends between Cairo, Illinois and the Gulf of Mexico to slow the natural erosion that would otherwise frequently change small parts of the river's course (Washington Post, 2018).

Wu et al. (2017) developed ecological bank slope revetments for surface water bodies to improve aquatic environmental quality and maintain channel stability against soil erosion, using a combination of prefabricated porous concrete spheres and vegetation methods, and a model set-up consisting of two equal-sized ditches with different types of bank slope revetments was constructed to evaluate the purification effects of ecological and hard revetments on water quality. Pollutant removal from the ecological bank revetment ditch was significantly better in terms of the overall removal efficiencies of the chemical oxygen demand of manganese (COD_{Mn}), ammonia, total nitrogen (TN), and total phosphorus (TP), with two- to four-fold greater removal compared with that from hard slope revetments under the same operational conditions. Nutrient pollutants, including ammonia, TN, and TP had higher removal efficiencies than that for COD_{Mn} in both experimental ditches.

Figure 2.30: Ecological Revetment Built in Qiyun Mountain, China (2013)



(a) (b)

Figure 2.31: Schematic Design of: (a) Gabion Revetment Structure; and (b) Riprap Revetment Structure (1. Vetiver Plants; 2. Gabion; 3. Geotextile; 4. Fill Soil; 5. Limestone; 6. Gravel; and 7. Base Structure) (Tang et al., 2018)

Tang et al. (2018) performed a study with an aim to investigate the performance of ecological revetments implemented on the bank of the Cuatien River in Vinh city, Vietnam, shown in Figure 2.31. Based on the ecological, topographical, and hydrological conditions of the Cuatien River, the gabion and riprap models were introduced to investigate the effect of ecological revetment on the slope stability and ecological restoration characteristics. The effect of prevailing climatic indicators, such as temperature, precipitation, sunlight hours, and humidity were investigated to ascertain the characteristics of weather conditions on the subtropical area. On the surface soil layer of the gabion and riprap, the nutrient indicators of soil organic matter (SOM) and available nitrogen (AN) increased in the spring, summer, and winter, but decreased in autumn, and available phosphorus (AP) did not show an obvious change in the four seasons.

In Bangladesh, Islam (2003) conducted a study by monitoring the performance of vetiver grass on eighteen coastal polders over eighty seven kilometers of earthen embankments of Bangladesh. As a finding of his study he stated that water borne erosion (either surface run-off or rain cut or wave action or all) is the main problem in maintaining those earthen embankments. Alam and Hasan, (2010) performed two case studies in Bangladesh, including (1) a wave protection embankment at Mithamain *haor*, Kishoreganj; and (2) a wave protection work at Joydorkandi Village of the Akashi-Shapla *haor*. The traditional soft protection (bamboo mat with chailya grass) was found as not effective against wave attacks in the *haor* areas of Bangladesh. Even with under-designed conditions and the practical limitations of the CC block revetment structures with geotextile; this infrastructure served the purpose of saving lives and property of residents because of the resistant property of geotextile. The construction of the protection infrastructure should be completed at a time before the next wave attack. Dependence on the natural process of soil compaction of embankment during the following monsoon and rehabilitation in the dry season is a serious lapse in the construction procedure, which increases maintenance cost.

2.6.3 Eco-Revetment in Bangladesh

The Government of the People's Republic of Bangladesh (GoB) has received funds from the International Fund for Agricultural Development (IFAD) for implementation of the Climate Adaptation and Livelihood Protection (CALIP), a supplementary project of *Haor* Infrastructure and Livelihood Improvement Project (HILIP) of the Local Government Engineering Department (LGED). The project intends to apply part of the proceeds of the IFAD grant to cover expenditures for monitoring the performance of village island protection methods as well as model village, upazila road slope protection. The research is being conducted by Bangladesh University of Engineering and Technology (BUET). This research work is being conducted in 28 upazilas of five districts namely Brahmanbaria, Habiganj Kishoreganj, Netrokona, and Sunamganj. LGED is conducting a study entitled "Monitoring the Performance of Village Island Protection, Model Village, Upazila/Union Road Slope Protection". This thesis work is being conducted with the collaboration of the research work.

Project Area

The project area consists of 5 (five) *haor* districts which includes 28 upazilas as mentioned in Table 2.4. In this field study, slope protection, and village mound protection is being done by bio-engineering methods using vetiver grass. The study location of this thesis work is shown in map in Figure 2.32. These representative *haor* areas have been selected on the basis of topographical (shallow and deep *haor*), ecological and socio-economic parameters.

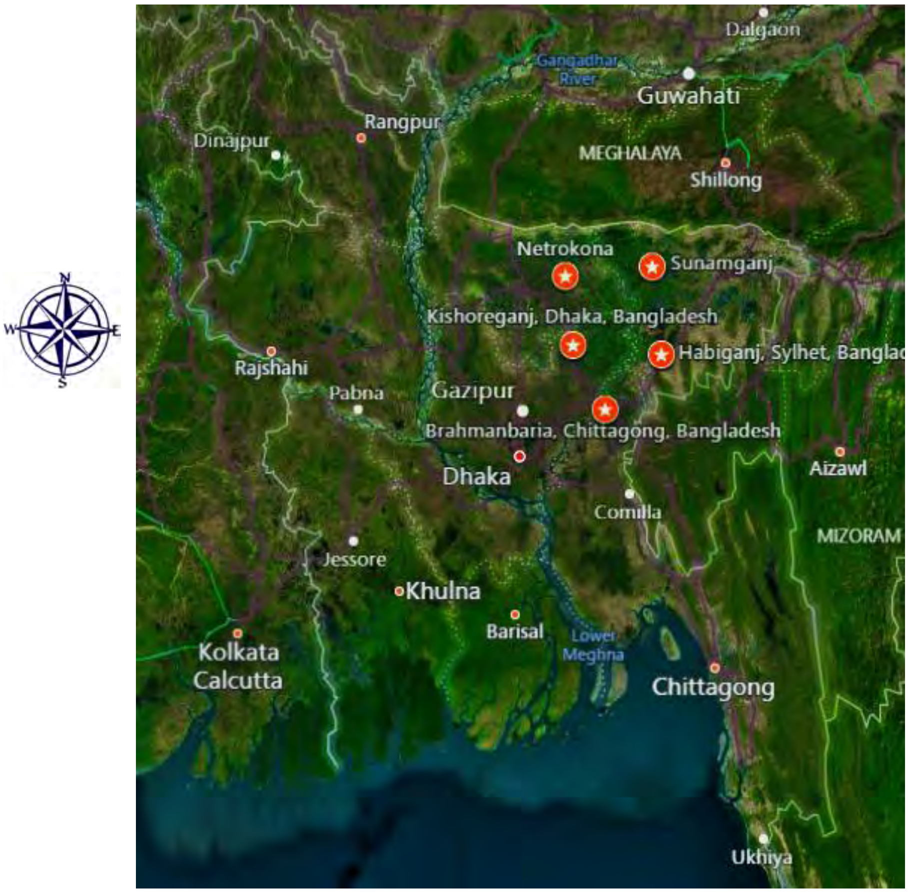


Figure 2.32: *Haor* Districts Selected for Current Study on Bangladesh Map

Table 2.4: Project Area of HILIP

District	Number of Upazilas	Name of Upazilas
Sunamganj	11	Sunamganj Sadar, Tahirpur, South Sunamganj, Bishwambarpur, Jamalganj, Derai, Sulla, Chhatak, Dowarabazar, Dharmapasha, & Jagannathpur
Habiganj	3	Azmiriganj, Lakhai, Baniachong
Netrokona	4	Khaliajuri, Kolmakanda, Modon, Mohanganj
Kishoreganj	4	Itna, Mithamoin, Austogram, Nikli
Brahmanbaria	6	Nasirnagar, Nobinagar, Sarail, Ashuganj, Brahmanbaria Sadar, Bancharampur
Total	**28**	

2.7 Summary

This chapter summarizes the overall scenario and difficulties due to hazards of this area, and as a solution the significance of ecological revetment has been established. Information related to fundamental findings of past researches related to this study, as well as theoretical and methodological description has been discussed in this chapter. These can be summarized as follows:

(i) Most common types of erosion of the *haor* infrastructures are due to wave action, locally called *afal*, rainfall and the soil condition. Mass movement also occurs due to wave action which involves the sliding, toppling, falling, or spreading of fairly large and sometimes relatively intact masses, resulting in a great loss of land in this area. To protect *haor* village islands and roads against erosion, the traditional cover layer materials are found unfeasible in many locations due to construction and maintenance problem or cost. So, cost-effective embankments with cheaper maintenance system are requisite against these problems.

(ii) Soil bio-engineering has become very popular in past few decades worldwide. Vegetative cover not only decreases soil loss but also increases the stability of slopes against landslides. From literature it is established that vegetation can effectively absorb the rainfall impact energy, grips soil to protect from wave action and reduces the chances of rain cut erosion. The stabilizing or protective benefits of vegetation depend both on the type of vegetation and type of slope degradation process. Conventional 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. Vetiver grass system is now becoming the highest practiced bio-engineering plant.

(iii) Findings of the past researches related to this study have been discussed here. In Bangladesh, research on bio-engineering is being practiced, and people are applying this technique by their own (for land barrier mark, raised yard boundary, pond slope protection) in some areas. This technique also earned Governments' attraction recently and few projects (CCRIP, CALIP, HILIP) are being initiated for field applications.

(iv) Although different studies have been conducted all around the world, few investigations have been conducted on protecting the infrastructures of *haor* areas of Bangladesh through field and model study. Hence, it is necessary to establish the compatible solution by ecological revetment against wave action on Bangladesh perspective. To that context, ecological revetment can be a sustainable and cost-effective solution. This technique envisages the use of appropriate vegetation, single plants, and bio-engineering technology with minimum artificial human intervention resulting in economic and environmental benefits.

Chapter Three
METHODOLOGY

3.1 General

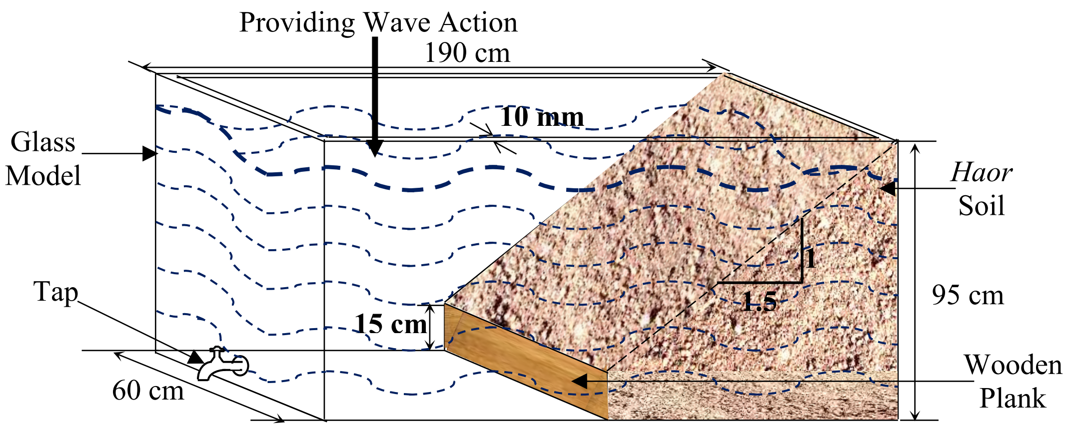
This chapter presents the research methodology adopted by model study on *haor* soils using vegetation, performances of field trial section and laboratory testing of the *haor* soils. Field study includes observing the actual scenario of *haor* infrastructures, and evaluate the performance of existing protection systems against wave action to establish the model study. The locations of the piloted areas has been shown here. During field investigation, disturbed soil samples were collected. As the main element of earthen embankment is soil, it is very important to determine the properties of the soil to understand their behavior. The submergence and wave tolerance of vetiver was observed through model study and field trials, and the growth of vegetation according to the *haor* topography was also perceived.

3.2 Description of the Models

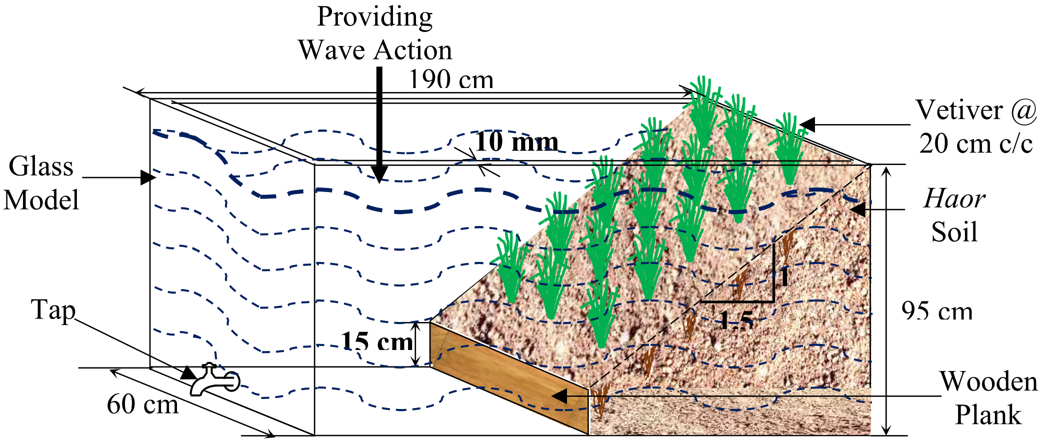
Four models were fabricated to investigate the growth performance, propagation and sustainability of vegetation in submergible condition and against wave action. Table 3.1 describes the models according to the naming, and schematic diagram of the models are presented in Figure 3.1.

Table 3.1: Illustration of the Small Scale Models

Model Name	Containing Materials
BM	*Haor* Soil (Control Model)
VM	*Haor* Soil and vetiver @ 20 cm c/c
VFM	*Haor* Soil+8.5% (w/w) fly ash and vetiver @ 20 cm c/c
VFGM	*Haor* Soil+8.5% (w/w) fly ash, vetiver @ 20 cm c/c and JGT (600 gsm)



(a)



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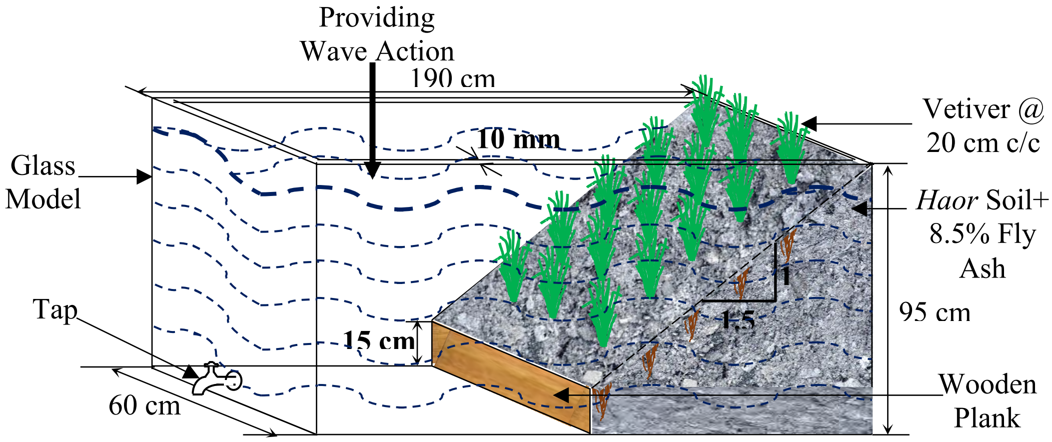
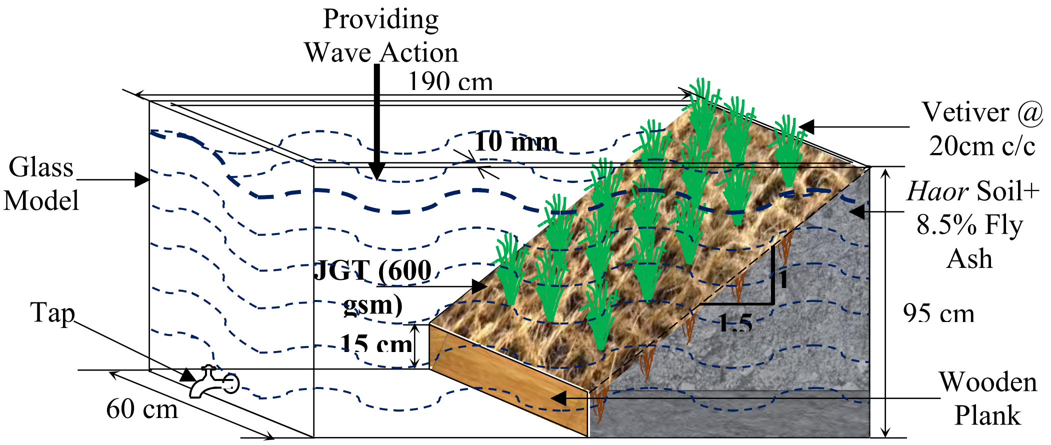


(c)



(d)

Figure 3.1: Schematic Illustrations of Models (a) BM; (b) VM; (c) VFM; and (d) VFGM

3.2.1 Fabrication of the Models

At first to conduct the experimental study for fabricating small scale ecological revetments, four glass models were made shown by Figure 3.2. The length of the rectangular glass models were 190 cm, width of 60 cm and height of 95 cm. 10 mm thickness glass was used to construct the models, and a tap was attached 6 cm above from the bottom of each models to avoid water-logging. The glass models were fabricated and placed just beside BUET-Japan Institute of Disaster Prevention and Urban Safety (BUET-JIDPUS), (GPS: N23.725555, E90.387777) on 20th May 2019.

Figure 3.2: Photographs of Fabricated Glass Models in BUET

3.2.2 Soil Collection and Model Preparation

For the purpose of model setup, soils were carried out from a *haor* area named Ramrail Upazila, Brahmanbaria (GPS: N23.91964, E91.11228) with the cooperation of LGED officials. Soils were filled up within the model on 8th August 2019, shown in Figure 3.3. To fill up each model as per slope construction requirements, total 385 kgs of soils were required to fill each model (Wet unit weight of soil = 22.21 kN/m^3).

(a) (b)

Figure 3.3: Photographs of (a) Model after Completion of Soil Filling (VM); and (b) VFM Filling by Compaction

At first, the soils were pulverized properly. Half of the models were filled up with the powdered *haor* soils with a slope of 1:1.5 (V:H) as shown in Figure 3.3(a). The models BM and VM were filled with soils by compaction of ten layers by a wooden hammer. In case of VFM and VFGM, 8.5% fly ash (w/w) as stabilizer was mixed with the pulverized soil at first, and filled up by ten layer compaction afterwards, shown in Figure 3.3(b). VFGM was covered with JGT of 600 gsm (thickness at warp direction=0.19 cm, weft direction=0.48 cm) after soil compaction and slope preparation. After final slope preparation, a small wooden plank of 15 cm was installed at the toe of the soil slopes for each models as temporary guide walls.

3.2.3 Vetiver Collection and Plantation

Vetiver tillers were collected from Pubail, Gazipur (GPS: N23.93841667, E90.4674444). 3 (three) vetiver tillers per point were sown on 24th August 2019 in soil of 3 (three) models, VM, VFM and VFGM @20 cm c/c spacing. Figure 3.4(a) shows the picked apart fresh tillers. At first a tiny hole was made within soil as shown in Figure 3.4(b), and then the tillers are sown as Figure 3.4(c). Figure 3.5 shows the photograph after the completion of vetiver plantation within all four models. The weather was sunny during plantation (33^{o}C), but moderate rain occurred during afternoon.

(a) (b) (c)

Figure 3.4: Photographs of (a) Fresh Vetiver Tillers; (b) Creating Hole in Soil before Sowing; and (c) Sowing Process of Vetiver

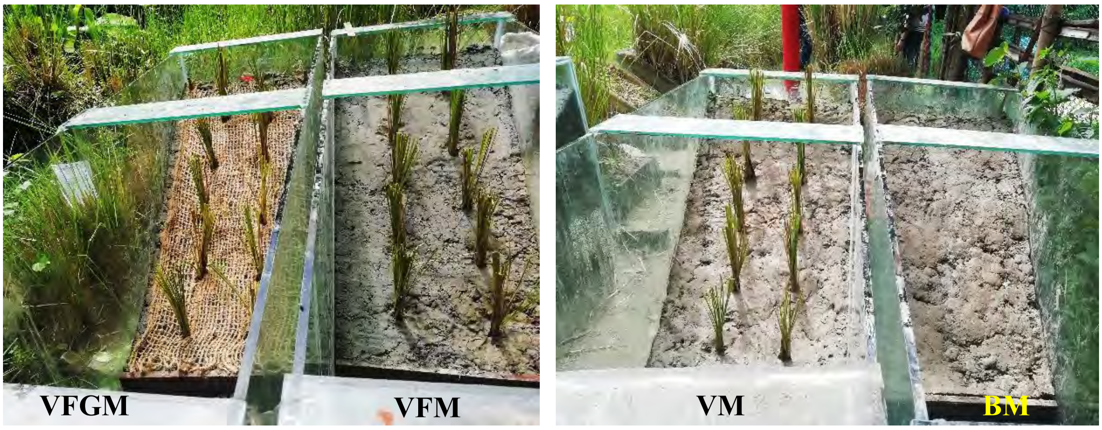
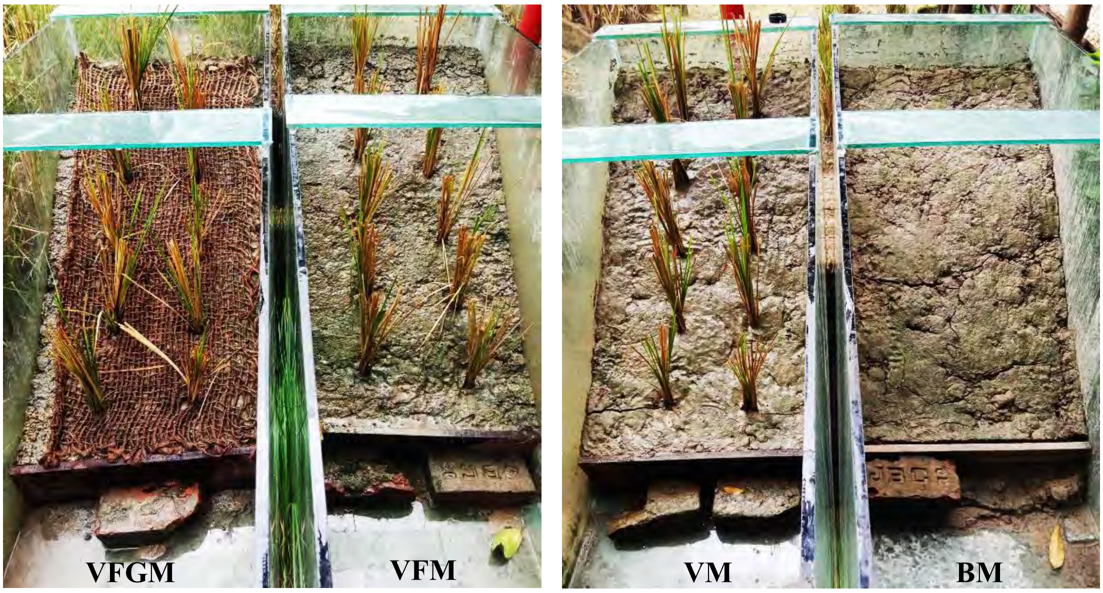


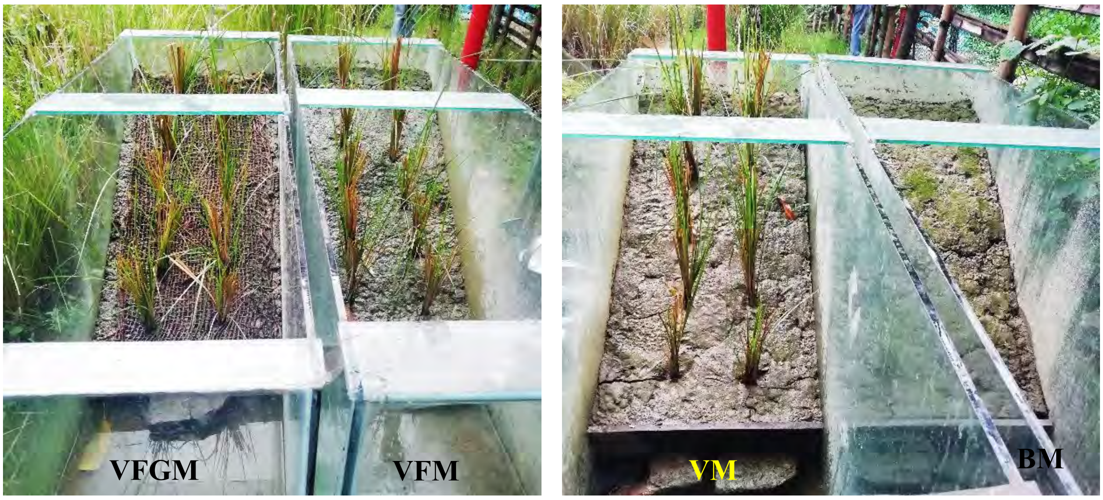
Figure 3.5: Photographs of Models at the Day of Vetiver Plantation (24th August 2019)

3.2.4 Growth Monitoring

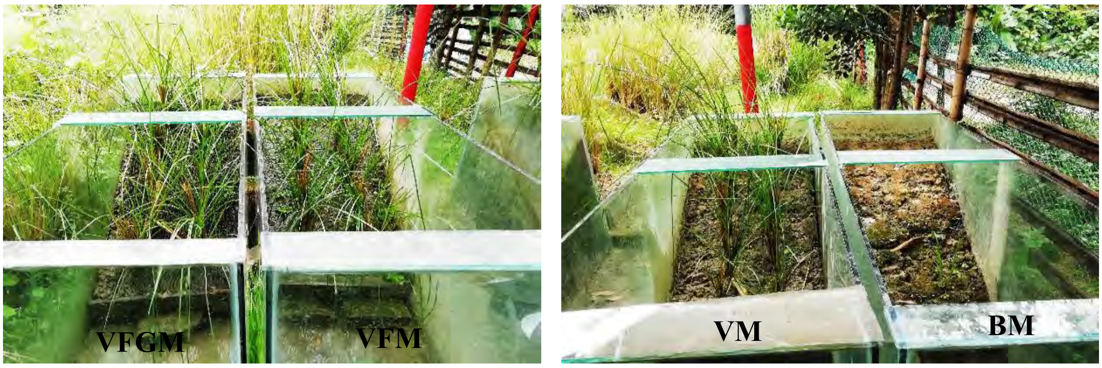
From the day of plantation, proper care was taken of the tillers by watering, nursing, cleaning weeds and monitoring the models. The tillers were allowed to grow up to 172 days (about 6 months) before submergence creation and wave action application. Figures 3.6 and 3.7 show the day by day growth of the vetiver by photographs mentioning the weather conditions.



(a)



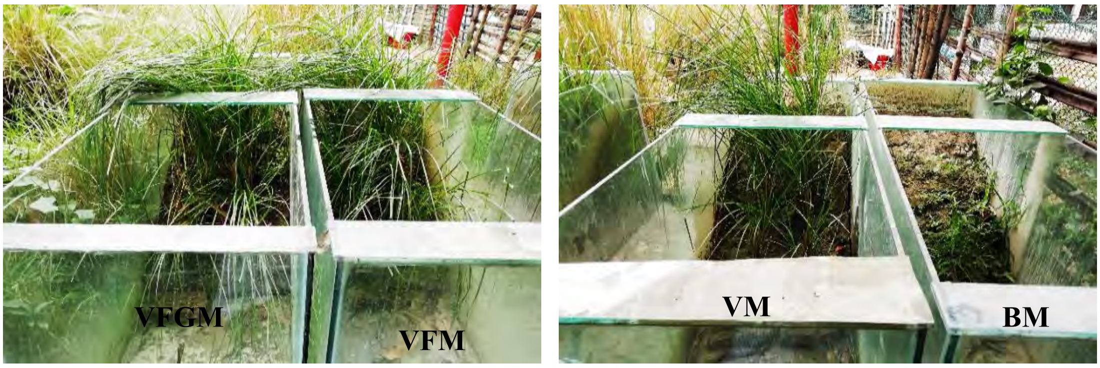
(b)



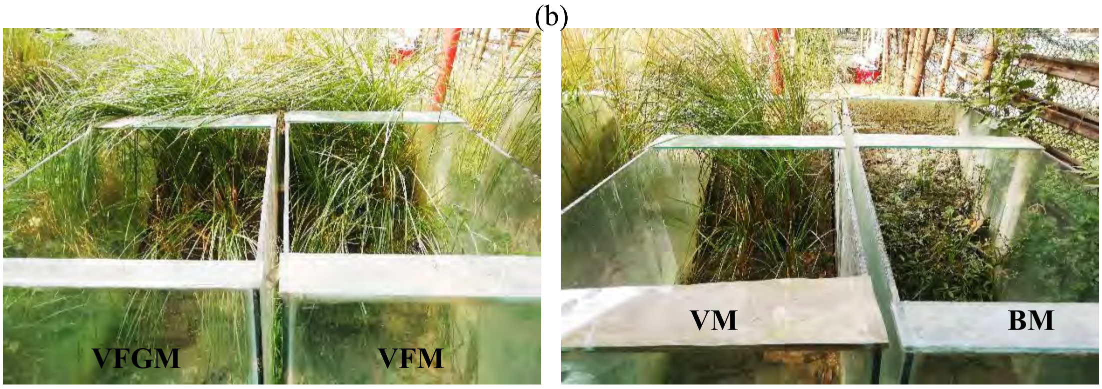
(c)

Figure 3.6: Photographs of Models (a) after 15 Days of Vetiver Plantation (8th September 2019) [Temperature: 30°C, moderate rain at afternoon]; (b) after 30 Days of Vetiver Plantation (23rd September 2019) [Temperature: 30°C, no rainfall]; and (c) after 60 Days of Vetiver Plantation (23rd October 2019) [Temperature: 31°C, no rainfall]

(a)



(b)



(c)

Figure 3.7: Photographs of Models (a) after 100 Days of Vetiver Plantation (1st December 2019) [Temperature: 25°C, no rainfall]; (b) after 120 Days of Vetiver Plantation (21st December 2019) [Temperature: 22°C, no rainfall]; and (c) after 160 Days of Vetiver Plantation (30th January 2020) [Temperature: 24°C, no rainfall]

Watering was done by two times in the morning and in the afternoon for the proper growth of the vegetation. Proper sunlight was ensured also. After 30 days, watering was done for one time per day for the tillers, and no watering was needed when natural rainfall occurred. The average rainfall during the growth of the grasses (August 2019-February 2020) was recorded as 3.2 mm-316.5 mm, and the range of temperature was 19°C-34°C (World Weather Online, 2020).

3.2.5 Submergence Formation

On 11th February 2020, all four models were filled up with tap water (Flow rate= 0.4 liter/second) to create the submerged condition. The model condition prior to the submergence is shown in Figure 3.8. Water was filled up to a height of 70 cm (15 cm below the hill of slope) to simulate with the submergence during flood at *haor* region. Figure 3.9 (a) and (b) show the submerged models. All models were kept under submerged condition for 5 days.

Figure 3.8: Model Condition on 11th February 2020 (Just before Submergence) [Temperature: 27^{o}C, no rainfall]

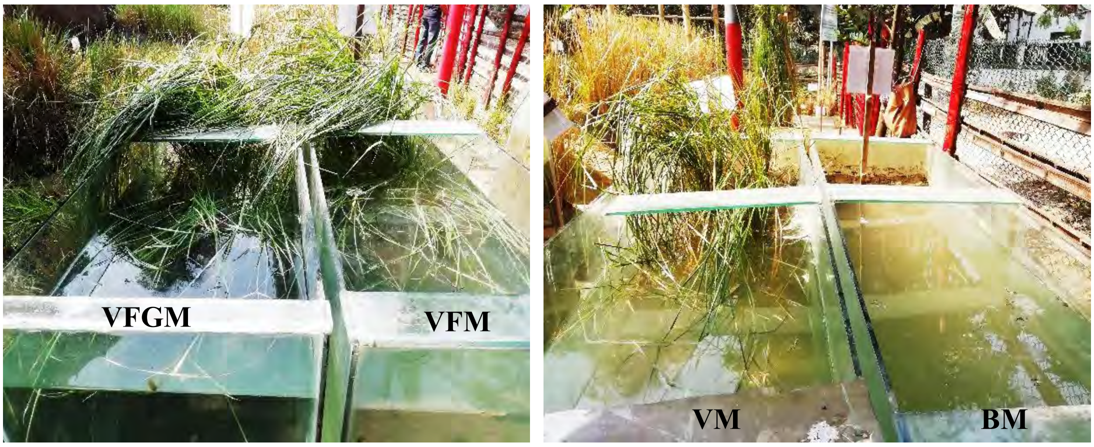


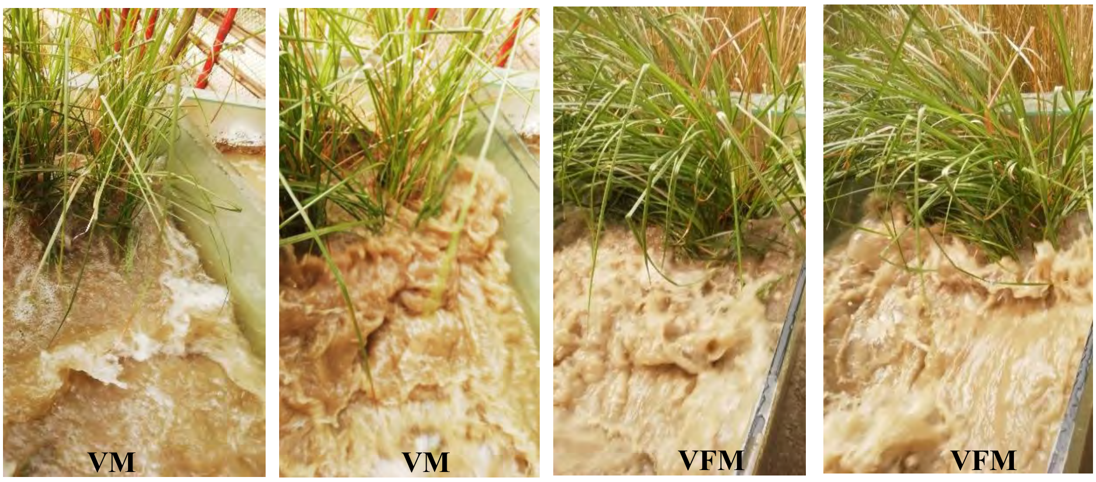
Figure 3.9: Four Submerged Models at 173th Day of Plantation [Temperature: 25^{o}C, no rainfall]

3.2.6 Wave Action Generation

Wave action was produced after 5 days of submergence (on 16th February 2020), to observe and compare the sustainability of revetments of *haor* areas during monsoon considering the actual parameters i.e., wave height, wave length, wave velocity and period. In any water body, waves are usually generated by forces that disturb a body of water. For this study, wave propagation was generated manually by a small wooden plank of a size of 30cm×30cm×2cm, showing in Figure 3.10 (a). The waves acted as strong dynamic forces along the slope without and with vegetation. The water depth, wave height, wavelength, amplitude, time period of wave and time required to break down the slope with losing the slope soil were calculated for each models.

(a) (b)

Figure 3.10: (a) Wave Action Propagation; and (b) Huge Wave Generation at Model BM



(a) (b)

Figure 3.11: Photographs of (a) Wave Action at VM; and (b) Wave Force Hitting upon the Slope of VFM

Figure 3.10 (b) shows wave action propagation on BM. Figure 3.11 and Figure 3.12 shows the wave propagation process of VM, VFM and VFGM, respectively. After wave generation through all four models, slope breakdown time, mass of soil loss and turbidity of each model were estimated. From the each three models, one vetiver tiller was uprooted carefully to measure the shoot and root length, width, diameter, number of tillers grown per point, and occurrence of inflorescence. Figure 3.13 shows the slope condition after wave propagation.

Figure 3.12: Photographs of Wave Action at VFGM

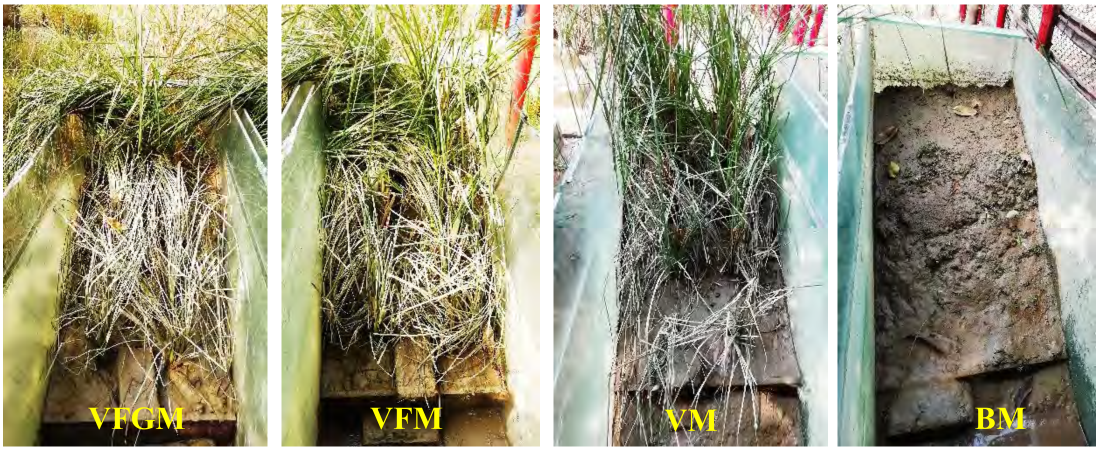


Figure 3.13: Slope Condition of Models after Wave Action

Water samples were collected after full propagation of waves. Turbidity of the diluted mixture of soil and water from the four models were measured via turbidity meter in Environmental Laboratory, BUET. Figure 3.14 shows the change of soil turbidity of the four models for seven days, where 250 ml muddy water were collected at the initiation of each model waters being turbid due to wave action. After seven days, the weight ratio of precipitated soil with water was measured.

(a) (b)

Figure 3.14: Change of Turbidity of Model Soils; (a) First Day (16th February 2020); and (b) after Seven Days (23rd February 2020)

3.3 Performance of Field Trials

Five *haor* districts were selected as study area to simulate the model study according to the depth and effect of wave action of the *haor*s. The sites of have been selected on the basis of topographical, ecological and socio economic parameters. Collected data includes growth measurement and performance of vetiver, growth of other vegetation alongside, soil type, amount of water in soil and soil characteristics, performance of slope (whether erosion has occurred or not, if occurred, how much) and soil loss estimation by erosion according to USLE equation (mentioned in Equation 2.1). The study area is summarized in Table 3.2.

Table 3.2: Field Study Locations

Haor Type	District	Name of Upazilas	Number of Upazilas
Shallow	Brahmanbaria	Sarail, Ashuganj, Brahmanbaria Sadar, Bancharampur	4
Mid-depth	Habiganj	Azmiriganj, Lakhai, Baniachong	3
Deep	Kishoreganj	Itna, Nikli	2
	Netrokona	Kalmakanda, Khaliajuri	2
	Sunamganj	Derai	1
		Total	**11**

Brahmanbaria

Brahmanbaria district has 4 municipalities, 39 wards, 97 mahallas, 9 upazilas, 98 union parishads, 1081 mouzas and 1329 villages. This district is mostly farmland, and according to the depth of surrounding wetlands, it can be categorized as shallow depth *haor* area. Four upazilas of Brahmanbaria district were selected as study area to evaluate the ecological revetment system by monitoring the growth performances of vetiver and application of bio-engineering technology in the field. Figure 3.15 (a) and (b) show the site condition during dry season.

(a)

(b)

Figure 3.15: Photographs of (a) *Haor* of Brahmanbaria (Modhupur Temohoni, Branch of Meghna River) in Dry Season at 15th January 2019; and (b) Water Table Position beside Road Slope (Panchabaty, Brahmanbaria Sadar)

Habiganj

Habiganj is a district of the Sylhet Division in the north-eastern part of Bangladesh. At present, it is a district of Sylhet Division. Habiganj consists of 9 upazilas, 6 municipalities, 54 wards, 78 union parishads, 124 mahallas, 1241 mouzas and 2076 villages (Roy, J.S., 2012). This district can be categorized as mid-depth *haor* area according to the depth of surrounding wetlands. Three upazilas of Habiganj district were selected as study area to evaluate the ecological revetment system by monitoring the growth performances of vetiver and application of bio-engineering technology in the field. Figure 3.16 (a) and (b) show a specific site of Habianj during dry season and after facing a flood of 2019.

Figure 3.16: Photograph of *Haor* of Habiganj (Upazila: Baniachong) after Facing one Flood in Monsoon of 2019

Kishoreganj

Kishoreganj is a district in Dhaka Division of Bangladesh, which consists of 8 municipalities, 13 upazilas, 105 union parishads, 39 wards, 145 mahallas, 946 mouzas and 1775 villages.

(a) (b)

Figure 3.17: Photographs of (a) Village Island of Kishoreganj (Upazila: Nikli) in Dry Season at 8th March 2019; and (b) Road Slope of Kishoreganj (Upazila: Itna) in Dry Season at 8th March 2019

Figure 3.17 (a) and (b) show two sites of Kishoreganj during dry season. This district can be categorized as deep *haor* according to the depth of surrounding wetlands. Two upazilas of Kishoreganj district were selected as study area to evaluate the ecological revetment system by monitoring the growth performances of vetiver and application of bio-engineering technology in the field. Some places were very remote by geographical situation.

Netrokona

Netrokona is situated in the northern part of Bangladesh, near the Meghalayan border. There are five main rivers in Netrakona: Kangsha, Someshawri, Dhala, Magra, and Teorkhali. It is a part of the Surma-Meghna River System (Banglapedia 2018). The total area of Netrakona District is 2,794.28 km^2 of which 9.17 km^2 is under forest. It lies between 24°34' and 25°12' north latitudes and between 90°00' and 91°07' east longitudes. This district is bounded by the Garo Hills in Meghalaya, India on the north, Sunamganj District on the east, Kishoreganj District on the south and Mymensingh District on the west. This district is categorized as deep *haor* according to the depth of surrounding wetlands. One upazila of Netrokona district was selected as study area to evaluate the ecological revetment system by monitoring the growth performances of vetiver and application of bio-engineering technology in the field. All places were very distant by geographical situation. Figure 3.18 shows photograph of a beel connecting the *haor* areas at Kalmakanda, Netrokona during monsson period.

Figure 3.18: *Meda Beel* at Netrokona (Upazila: Kalmakanda) in the Initial Wet Season (23rd May 2019)

Sunamganj

Sunamganj is a district located in north-eastern Bangladesh within the Sylhet Division. This district is categorized as deep *haor* according to the depth of surrounding wetlands, and most of the time of the year the infrastructures of this area remain fully or partially submerged. One upazila of Sunamganj district was selected as study area to evaluate the ecological revetment system by monitoring the growth performances of vetiver and application of bio-engineering technology in the field. Figure 3.19 shows photograph of the village islands at Derai of Sunamganj during monsson.

Figure 3.19: Village Island of Sunamganj beside *Kaliergota haor* (Upazila: Derai) in the Initial Wet Season (30th August 2019)

3.3.1 Design Types

Under the influence of a rainfallor wave action slope collapses abruptly due to weakened self-retainability of the earth. Figure 3.20 shows the failure pattern of slope with no protection.

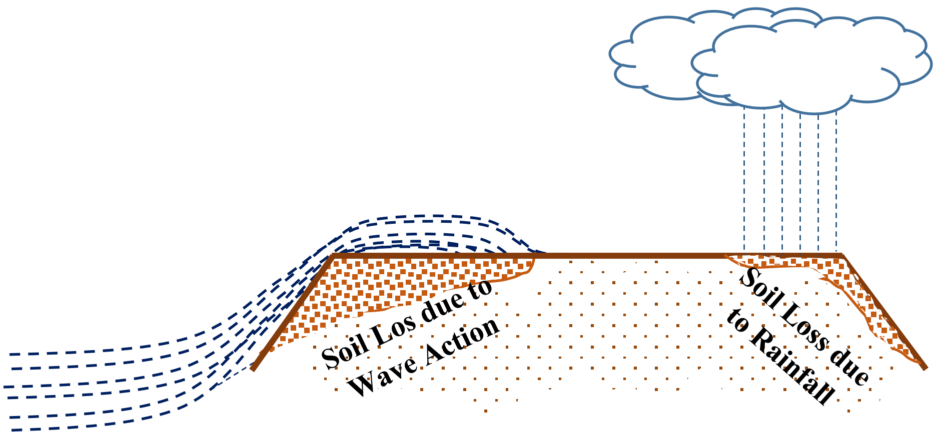


Figure 3.20: Failure of Unprotected Slope by Wave Action and Rainfall

Four different engineering models were designed for haor, whereas two types (Type

II and Type III) are being tested under the implementetation of LGED for the village island, road slope and *killa* protection against wave action. Landscape level reforestation are being undertaken to recreate natural wave barriers (there is significant carbon sequestration potential and quantification were undertaken). Vegetative species are tested as alternative slope stabilizers ad for soil sequestration. The four protection types are:

(i) Type I: Protective Measure with Bamboo and Chailya Grass
(ii) Type II: Protective Measure with Vetiver Grass
(iii) Type III: Protection by CC Hollow Blocks along with Toe Wall and Vetiver
(iv) Type IV: Slope Protection by RCC Poles based Palisading

Type I: Protective Measure with Bamboo and Chailya Grass

The required materials for this design type are treated bamboo, chailya grass (*Hemarthria protensa* Steud.), soil, geo-jute and bamboo pegs.

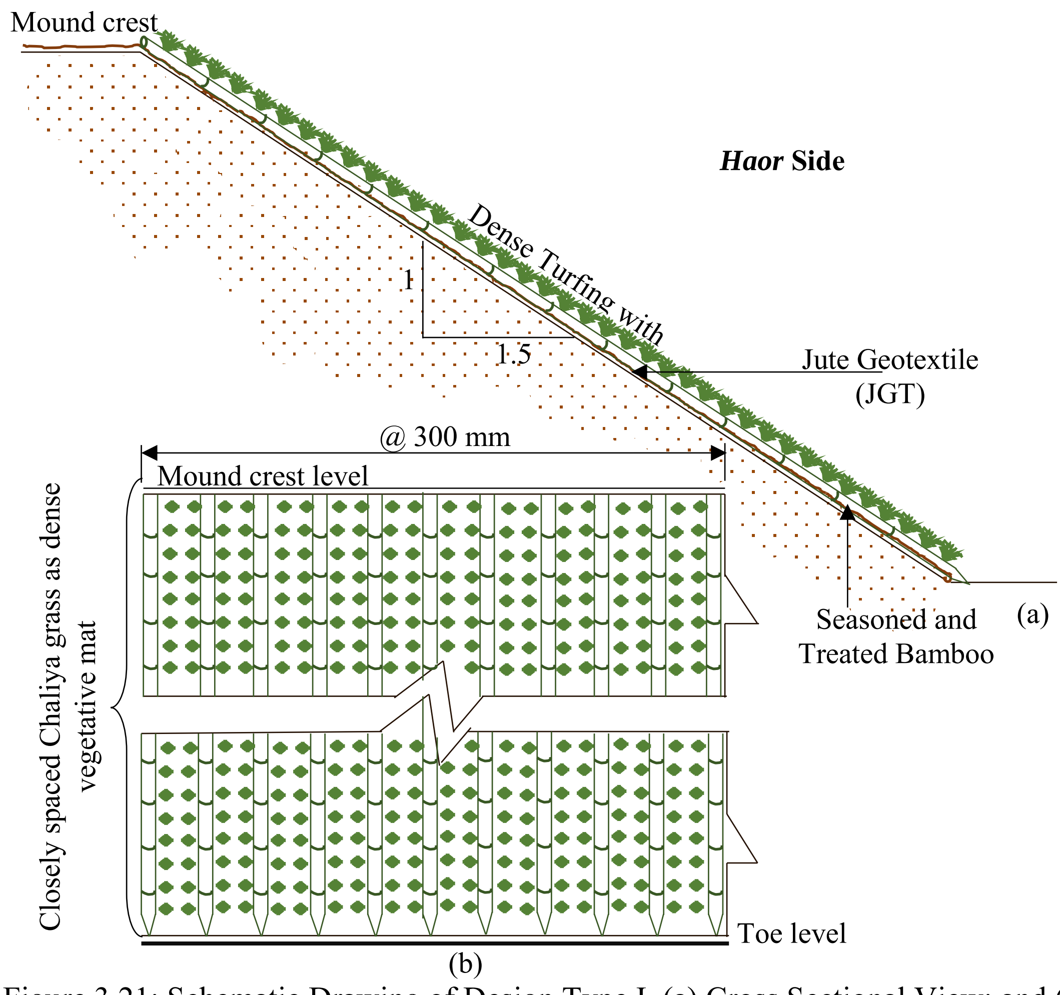


Figure 3.21: Schematic Drawing of Design Type I, (a) Cross Sectional View; and (b) Plan View (Redrawn from Islam, 2019)

The recommended construction sequence in the field is given below:

(i) Preparing 1:1.1.5 slope with 1 m wide berm at mid-level
(ii) Filling 250 mm thick earth

(iii) Compacting slope manually with 10 kg rammer
(iv) Placing jute geotextile (JGT) on the prepared slope
(v) Providing bamboo palisades with seasoned and treated bamboos @ 300 mm interval (as shown in Figure 3.21)
(vi) Bamboo to be removed and preserved for reuse immediately after wet season
 - Care taking by Labour Contracting Society (LCS) for the first two seasons
 -Tree plantation with Hizol and Koroch @ 2.5 m c/c and 5 m from row to row (if land is available)

Type II: Protective Measure with Vetiver Grass

The required materials for this design type are vetiver grass, soil and geo-jute. This type is recommended for light to moderate waves and with less erosion record.

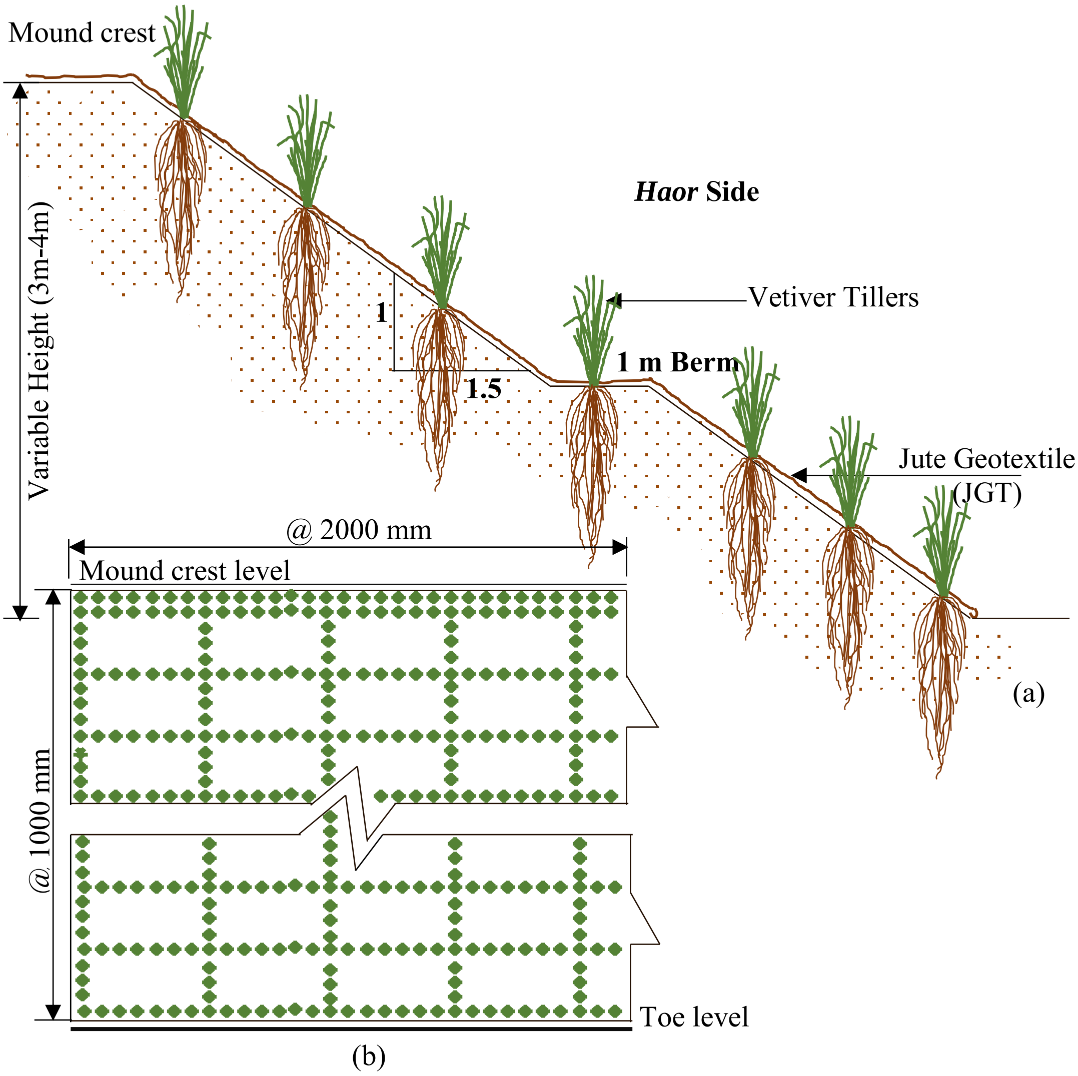


Figure 3.22: Schematic Drawing of Design Type II, (a) Cross Sectional View; and (b) Plan View (Redrawn from Islam, 2019)

The recommended construction sequence in the field is given below:
(i) Preparing 1:1.1.5 slope with 1 m wide berm at mid-level

(ii) Filling 250 mm thick earth
(iii) Compacting slope manually with 10 kg rammer
(iv) Placing geo-jute on the prepared slope
(v) Placing Vetiver in grid pattern @2m×1m interval (as shown in Figure 3.22)
(vi) Fencing (if needed) may be provided to protect Vetiver from animal
 - Care taking by LCS for the first two seasons
 -Tree plantation with Hizol and Koroch @ 2.5 m c/c and 5 m from row to row (if land is available)

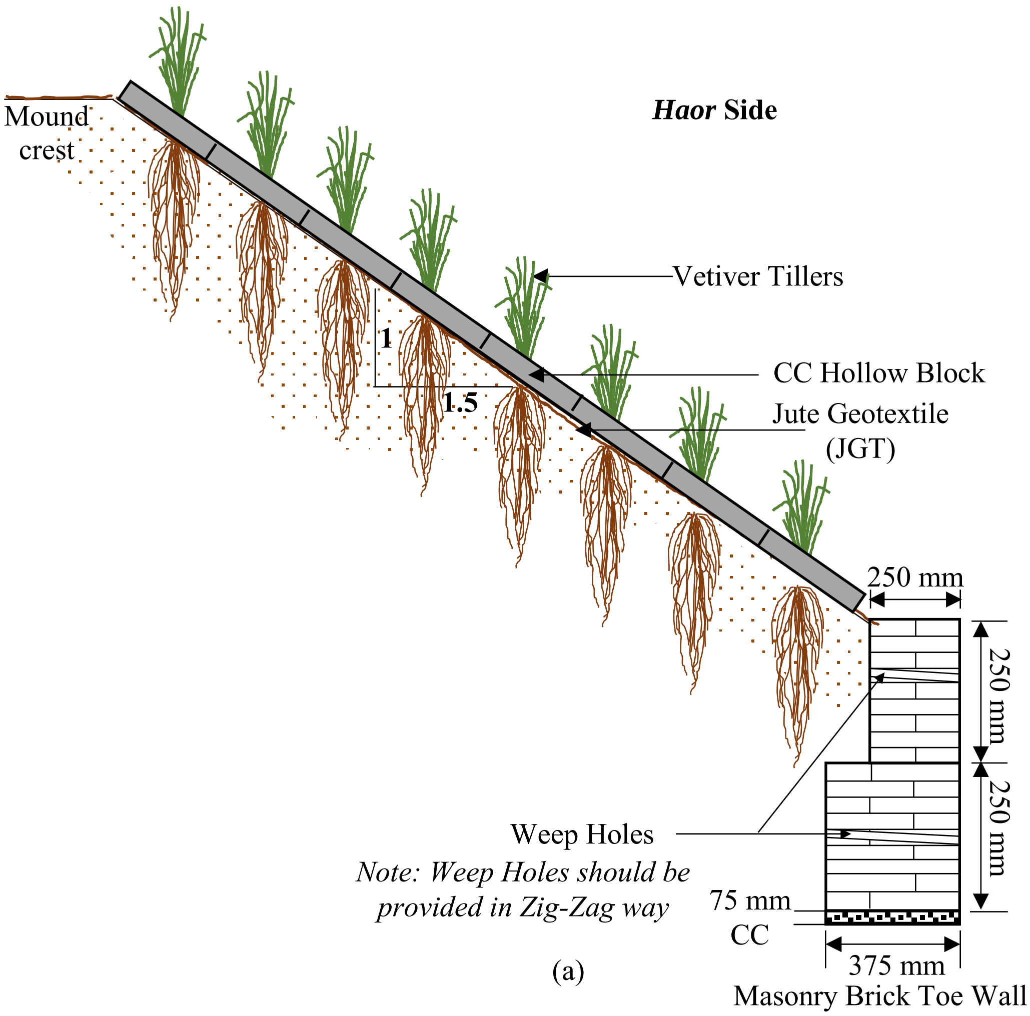
Type III: Protection by CC Hollow Blocks along with Toe Wall and Vetiver

The required materials for this design type are Cement Concrete (CC) block (450×450×75 mm) with 150 mm dia hole at center, Vetiver grass, soil, brick, sand, cement and geo-jute. The LCS labor is the mode of implementation. This type is recommended for moderate to deep *haor* area with severe erosion record. The recommended construction sequence is given below:
(i) Preparing 1:1.1.5 slope with 1 m wide berm at mid-level
(ii) Filling 250 mm thick earth
(iii) Compacting slope manually with 10 kg rammer
(iv) Placing of 1m height continuous toe wall along the slope with 75 mm CC work, 375 mm and 250 mm brick work
(v) Placing geo-jute on the prepared slope
(vi) Placing of 450mm×450mm×75 mm centered 150 mm dia hole CC block
(vii) Placing Vetiver in the block hole @450mm c/c both way (as shown in Figure 3.23)
 -Tree plantation with Hizol and Koroch @ 2.5 m c/c and 5 m from row to row (if land is available)

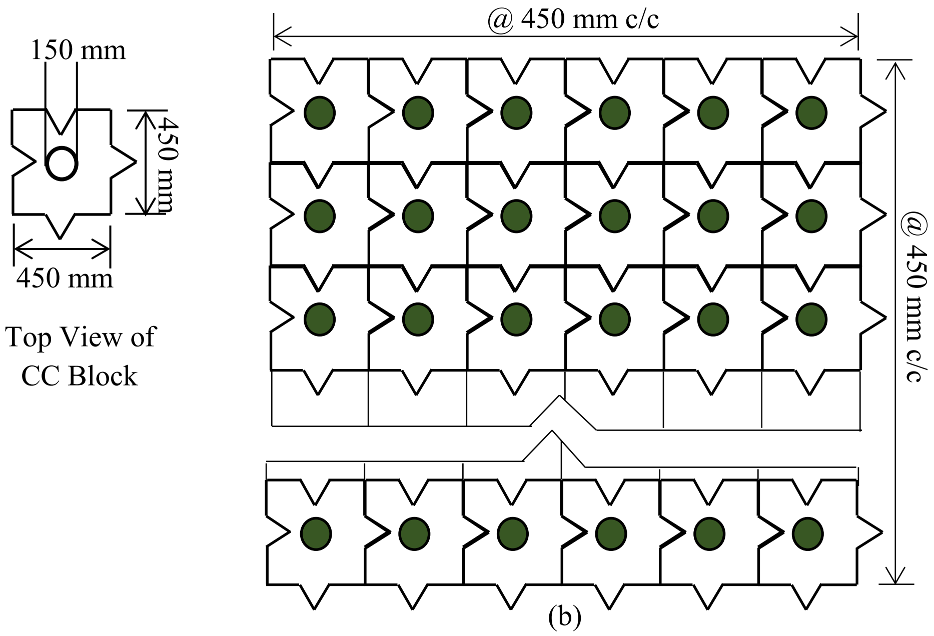
Type IV: Slope Protection by RCC Poles based Palisading

The required materials for this design type are 150mm×125mm RCC poles, Vetiver grass, soil, brick, sand, cement and geo-jute. The mode of implementation is conducted by LCS labor.

This type is recommended for moderate to deep *haor* area with severe erosion record. The recommended construction sequence is given below:
(i) Preparing 1:1.1.5 slope with 1 m wide berm at mid-level
(ii) Filling 250 mm thick earth
(iii) Compacting slope manually with 10 kg rammer
(iv) Placing of 1m height continuous toe wall along the slope with 75 mm CC work, 375 mm and 250 mm brick work
(v) Placing geo-jute on the prepared slope
(vi) Placing 150mm×125mm RCC poles (3 to 4m long) as palisades @ 600 mm c/c on the prepared slope
(vii) Placing Vetiver grass @ 100 mm c/c between poles and 1000 mm c/c between two rows (as shown in Figure 3.24)
 - Care taking by LCS for the first two seasons
 -Tree plantation with Hizol and Koroch @ 2.5 m c/c and 5 m from row to row (if land is available)



(a)



(b)

Figure 3.23: Schematic Drawing of Design Type III, (a) Cross Sectional View; and (b) Plan View (Redrawn from Islam, 2019)

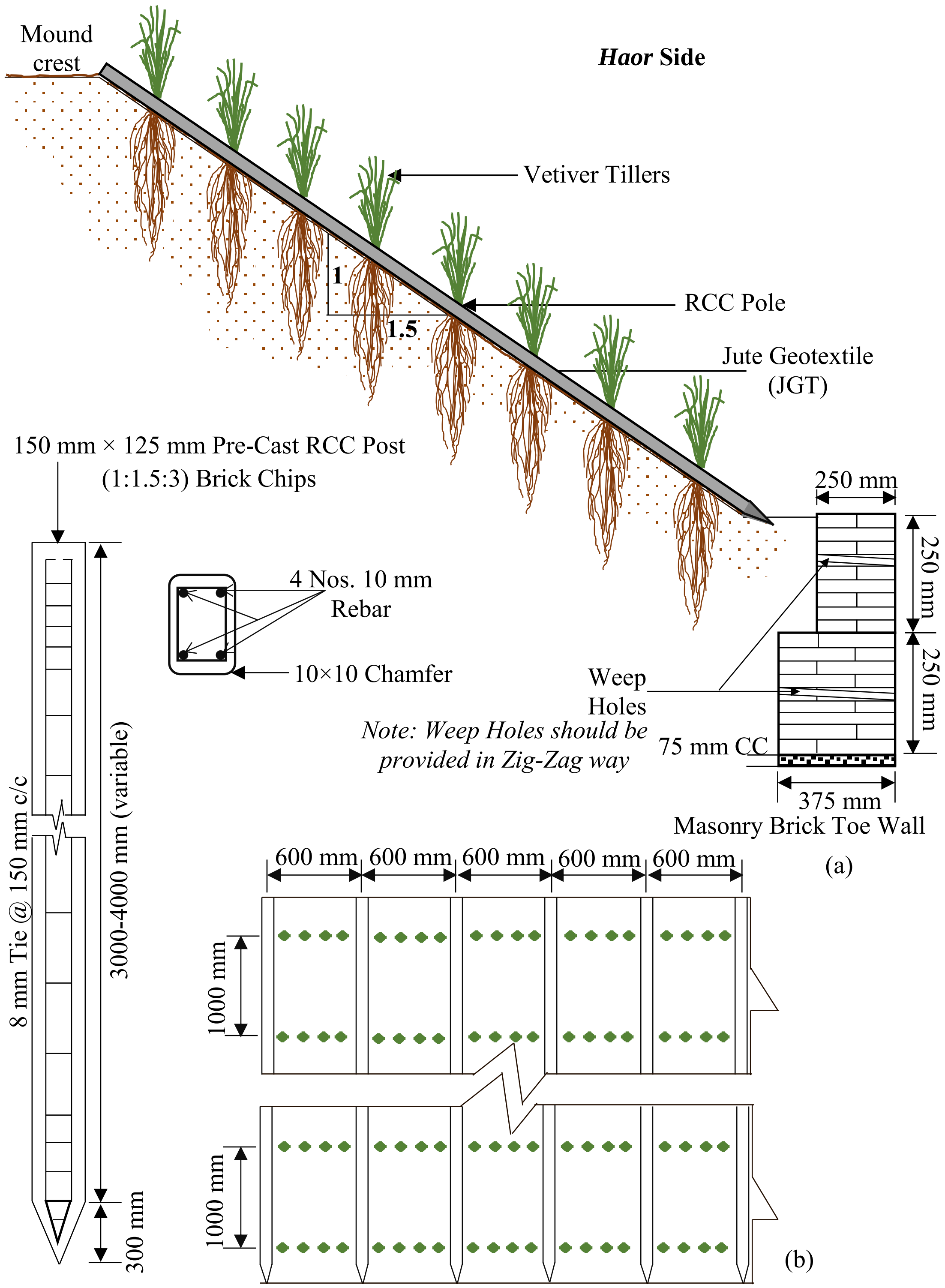


Figure 3.24: Schematic Drawing of Design Type IV, (a) Cross Sectional View; and (b) Plan View (Redrawn from Islam, 2019)

3.3.2 *Haor* Infrastructures

Haor infrastructures are requisite in terms of the basic needs of the locality, i.e., transportation, communication, sewage, water etc., so protection of these structures are very important. From field study, three types of protection work was done by observing the necessity of protecting *haor* area, they are: (i) Road Slope Protection; (ii) Village Island Protection; (iii) *Killa* Protection

Road Slope Protection

10 (Ten) road slope protection works were monitored for the purpose of field study in the *haor* districts. The road slope protection works are important for the economic condition of *haor* people, as it mostly depends on the communication system.

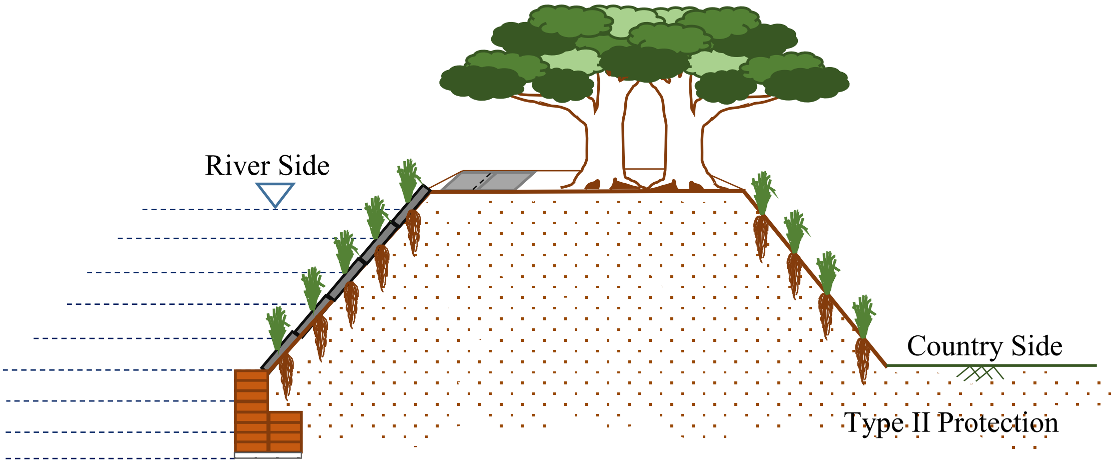


Figure 3.25: Schematic View of Road Slope Protection

Table 3.3: Road Slope Protection Location Details in *Haor* Region

Type of Work	Districts	Upazila	Location	GPS	Design Type
Road Slope (10)	Brahmanbaria	Sarail (1)	Kalikaccha UP – Bariura Bazar Road	N24.055556, E91.147500	Type III
		Ashuganj (2)	Modhupur Temohoni to Lalpur R&H via Lalpur UP Road	N24.008831, E90.990644	Type III
			UP Office (Bhabanipur) – Dogarishwar Bazar Road	N24.001667, E91.010556	Type III
		Brahmanbaria Sadar (2)	Panchabaty R&H to Akhaura Bazar Road (Part 1 & 2)	N23.879444, E91.141281	Type III
			Panchabaty R&H to Akhaura Bazar Road	N23.877222, E91.155556	Type III
		Bancharampur (1)	North West Side Bridge Approach R&H Road	N23.735278, E90.829722	Type II
	Habiganj	Azmiriganj (1)	Paschimbag – Azmiriganj Road	N24.513056, E91.311111	Type III
	Kishoreganj	Itna (2)	Chowganga – Chandrapur Road	N24.521111, E90.955278	Type III
			Itna-Ajmiriganj GC Road	N24.561472, E91.202389	Type III
	Netrokona	Kalmakanda (1)	Guturabazar	N25.039833, E90.902917	Type III

Figure 3.25 shows the schematic diagram of road slope protection by LGED measures. Table 3.3 shows the locations of road slope protection with GPS data and design type applied in that particular location.

Village Island Protection

11 (Eleven) village island protection works were monitored in the *haor* districts for the purpose of field study. Figure 3.26 shows the schematic diagram of village island protection by LGED measures.

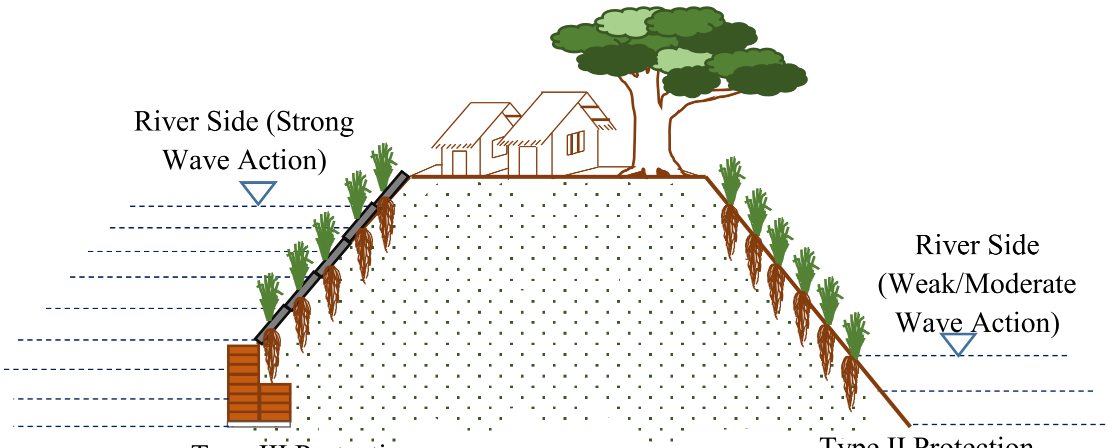


Figure 3.26: Schematic View of Village Island Protection

Table 3.4: Village Island Protection Location Details in *Haor* Region

Type of Work	Districts	Upazila	Location	GPS	Design Type
Village Island (11)	Brahmanbaria	Sarail (1)	East Noagaon	N24.090833, E91.134722	Type III
	Habiganj	Baniachong (1)	Vatipara	N24.456944, E91.372500	Type III
		Lakhai (1)	Chikonpur	N24.282500, E91.219167	Type III
	Kishoreganj	Nikli (2)	Kamalpur	N24.339411, E90.949547	Type III
			Daulotpur-Aglapara	N24.261111, E90.942667	Type III
	Netrokona	Kalmakanda (1)	Janjailpara	N25.024122, E90.925208	Type III
		Khaliajuri (2)	Mujibnagar	N24.684783, E91.165303	Type III
			Hayatpur	N24.652808, E91.189019	Type III
	Sunamganj	Derai (4)	Meghna Barghor	N24.838888, E91.280278	Different Scheme
			Meghna Notunpara	N24.843597, E91.290200	Type III
			Kochua	N24.778594, E91.383638	Type III

In monsoon, the villages of *haor* districts turn into detached islands, and due to rigorous wave action the sufferings of the livelihood becomes immeasurable, so protection of these villages can be very accommodating to a large vicinity. Table 3.4 shows the locations of road slope protection with GPS data and design type applied in that particular location.

***Killa* Protection**

Killa is a comparatively raised fallow land in the *haor* which is usually used in emergency during flash flood or early flood to save paddy & other wealth. As villages are located far away from *haor* basin, people very often use the *killa* land for crop harvesting purposes for the time being before monsoon flood come. Size of *killa* is usually 60 m×30 m. A *killa* was monitored for the purpose of field study. Figure 3.27 shows the schematic diagram of *killa* protection by LGED measures. Table 3.5 shows the location of the *killa* with GPS data and design type applied in that particular location.

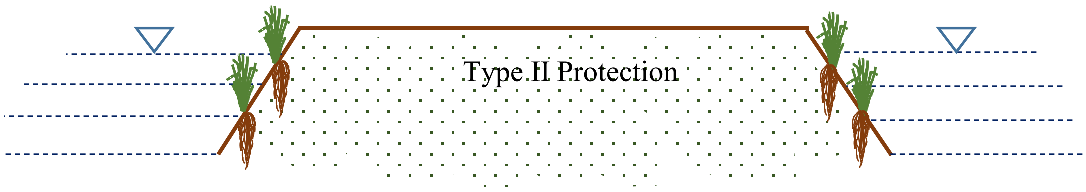


Figure 3.27: Schematic View of *Killa* Protection

Table 3.5: *Killa* Protection Details in *Haor* Region

Type of Work	Districts	Upazila	Location	GPS	Design Type
Killa (1)	Habiganj	Baniachong (1)	Bogir *Haor*, Kagapasha Union	N24.575278, E91.399167	Type II

3.4 Experimental Program

Index, strength and chemical properties of *haor* and model soils were determined to evaluate the sub-soil condition of the *haor* area. Soil samples of *haor* areas has been collected from the eight sites of Brahmanbaria, four sites of Habiganj, four sites of Kishoreganj, four sites of Netrokona and three sites of Sunamganj. The laboratory tests including the index and engineering properties of soils were conducted in the Geotechnical Laboratory in Civil Engineering Department of BUET. The microstructural properties of the mixture of soil and fly ash applied in the models were observed from Glass and Ceramic Department of BUET. The chemical properties of all *haor* and model soils were evaluated from Soil Resources and Development Institute (SRDI). Chemical composition of fly ash was determined from Basundhara Cement Factory (BCF). The experimental program is shown in Figure 3.28 by flowchart. The list of laboratory tests conducted is given in Table 3.6 with appropriate standards.

3.4.1 Laboratory Tests

Laboratory tests include grain size analysis, nature moisture content determination, specific gravity test, permeability test and direct shear (CD) test.

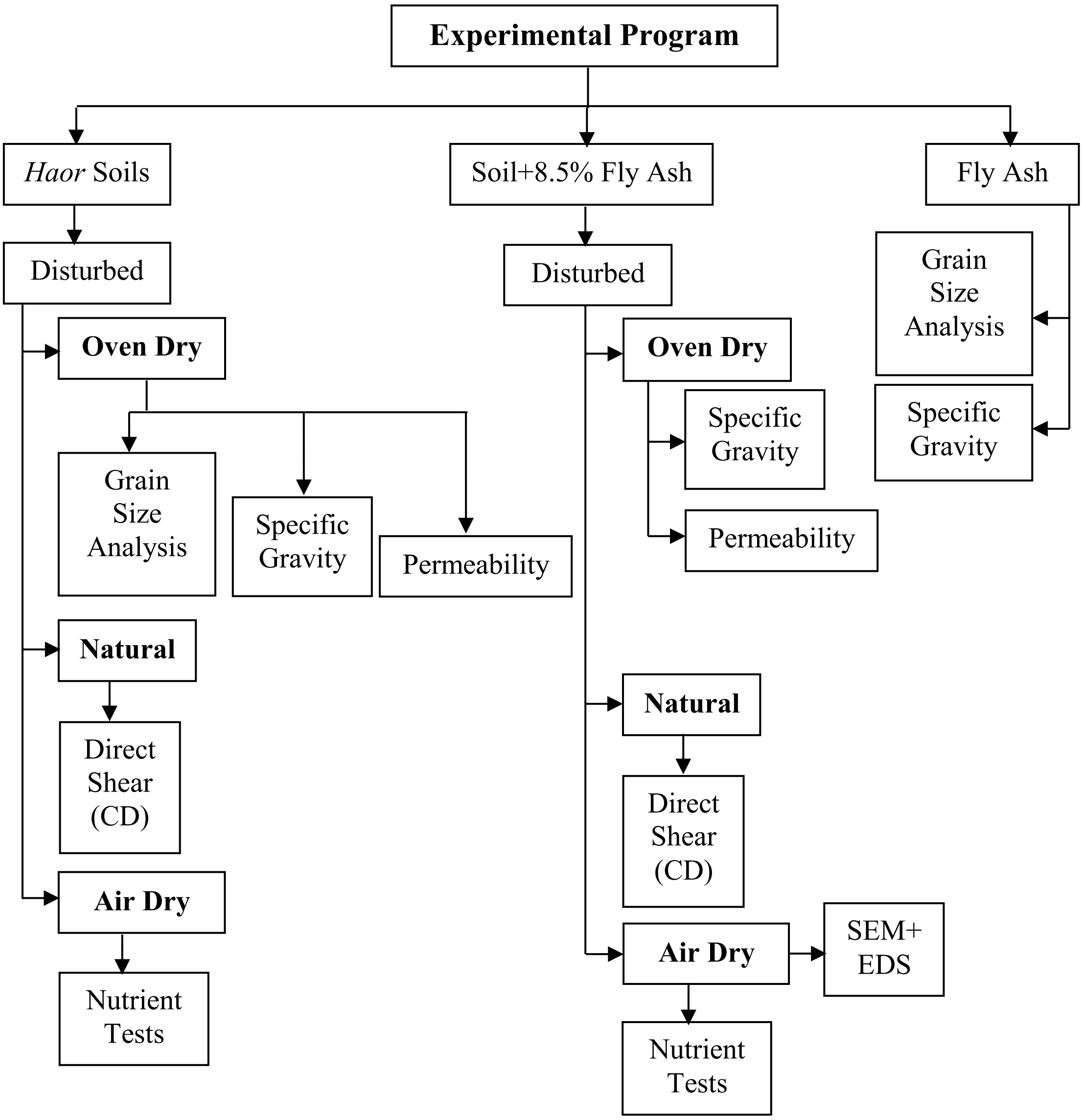


Figure 3.28: Flowchart of Test Program

Grain Size Analysis

To define the characteristics of *haor* soils, grain size analysis was done using #4, #8, #16, #30, #50, #100 and #200 sieves on total twenty three (23) samples to determine the Fineness Modulus (F.M.) and the percentage of the fines. The F.M. was determined using Equation (3.1).

$$FM = \frac{\sum \% \text{ of the sample of aggregate retained on each series of sieves}}{100} \quad (3.1)$$

Hydrometer test was done to determine the gradation curve of fly ash used in the model study. In a hydrometer jar (1000 ml), 100 ml deflocculating agent sodium hypophosphite ($NaPO_2H_2$) has been taken. Then #200 sieve passing 50 gm oven dried soil samples has been taken into this jar and water added up to 1000 ml mark. Meniscus correction and zero/reagent correction have been taken.

Table 3.6: Test Scheme to Determine the Properties of Soil Samples

Properties	Name of the Test		Standards/ Methods	Tests performed on	Parameters	Test Place
Index Properties	Grain Size Analysis		ASTM C136, ASTM D422	23 *haor* soils	F.M., % Fines	Geotechnical Laboratory, BUET
				Fly ash		
	Natural Moisture Content		ASTM D2974	6 *haor* soils	ω_u	
				Haor Soil+8.5% fly ash		
	Specific Gravity Test		ASTM D854	23 *haor* soils	G_s	
				Haor Soil+8.5% fly ash		
				Fly ash		
Engineering Properties	Falling Head Permeability Test		ASTM D5084	6 *haor* soils	k	
				Haor Soil+8.5% fly ash		
	Direct Shear Test (CD)		ASTM D3080	6 *haor* soils	Φ	
				Haor Soil+8.5% fly ash		
Chemical Properties	Nutrient Test	pH	ASTM D4972	21 *haor* soils; and *Haor* Soil+8.5% fly ash	pH	SRDI*
		Organic Matter	ASTM D2974		OM	
		Total Nitrogen	Potassium Chloride Extraction		N	
		Potassium	Bray Extraction		K	
		Phosphorus	Ammonium Acetate Extraction		P	
		Sulphur	Barium Sulphate Precipitation Method		S	
		Boron	Extraction with DTPA		B	
		Zinc	Hot Water Extraction		Z	
	Chemical Composition		ASTM C618	Fly ash	% of CaO, SiO, Al_2O_3, Fe_2O_3, MgO, SO_3	BCF*

**SRDI: Soil Resources and Development Institute; BCF: Basundhara Cement Factory*

Natural Moisture Content

Water content or moisture content is required to determine the quantity of water contained in soil. It can be calculated by Equation (3.2).

$$\%\,\text{Moisture Content},\ \omega_u = \frac{\text{Weight of moist soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}} \tag{3.2}$$

Specific Gravity

This test is conducted according to the ASTM D854. Water temperature was noted down since water density varies with temperature. Specific gravity of the soil was calculated by Equation (3.3).

$$G_S = \frac{G_T W_S}{W_S - W_1 + W_2} \quad (3.3)$$

Where, W_1 = weight of pycnometer + water + soil, W_2 = weight of pycnometer + water, G_T = G_S at water temperature T°C.

Falling Head Permeability Test

The coefficient of permeability by falling head permeability test can be calculated using Equation (3.4):

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2} \quad (3.4)$$

Where, a= Cross sectional area of the stand pipe, A= Cross sectional area of the soil sample, h_1= Hydraulic head across sample at beginning of the test, h_2= Hydraulic head across sample at end of the test, L= Length of the soil sample.

$$k_{20} = k_T \frac{\eta_T}{\eta_{20}} \eta \quad (3.5)$$

Equation (3.5) is for the correction of viscosity of water, where η=Viscosity of fluid (water). The void ratio of soil was calculated by Equation (3.6).

$$e = \frac{G_s \gamma_w V_r}{W_s} - 1 \quad (3.6)$$

Where, G_s is the specific gravity of soil solids, W_s is the dry weight of the soil grain and is calculated by the difference between air-dry sample weight and moisture content at the stage of testing, and V_r is the total volume of soil. Permeability of the soils was classified according to Table 3.7 (Lambe, 2014).

Table 3.7: Degree of Permeability of Soils (Lambe, 2014)

Degree of Permeability	Coefficient of Permeability, k (cm/sec)	Degree of Permeability	Coefficient of Permeability, k (cm/sec)
High	Over 10^{-1}	Very Low	10^{-5} to 10^{-7}
Medium	10^{-1} to 10^{-3}	Practically impermeable	Less than 10^{-7}
Low	10^{-3} to 10^{-5}		

Direct Shear Test

Consolidated drained (CD) direct shear tests were conducted on twenty four soil specimens of eight soil samples. Collected soils were crushed by wooden hammer. The remolded soil sample with natural moisture content was placed carefully in the shear box from the ring. The vertical displacement dial gauge was attached to record the vertical deformation with respect to time. Then the preferred normal load was applied (30.97, 61.93 and 123.83 kPa). At first, specimens were kept for consolidation for 1-2 hours in saturated condition. At the mean time horizontal displacement dial gauge was attached. After consolidation, shear was applied.

3.4.2 Nutrient Test

Nutrient analysis of *haor* soils was done from Soil Resource and Development Institute (SRDI) including determining pH, available nitrogen (%), organic matter (%), phosphorus (ppm), potassium (meq/100g of soil), sulphur (ppm), zinc (ppm) and boron (ppm).

pH: Crop yields are normally high in soils with pH values between 6.0 and 7.5. For practical purposes, the soils with a pH value of 6.6–7.5 are considered nearly neutral. So, pH values of the soils were determined to find out the acidity or alkalinity state of *haor* basin.

Nitrogen: Nitrogen is the nutrient responsible for growth and coloring, which makes it vital for grass. Total nitrogen was determined in percentage to evaluate where soil contains enough nutrients, and to define the necessity of fertilizer.

Phosphorus: Phosphorus stimulates root growth and enhances plant vigor early in the plant's life. Phosphorus is most important when grass is first establishing, and remains important as new blades of grass continue to grow. Healthy grass roots are better able to absorb nutrients from the soil so the grass grows faster. This essential nutrient was measured in μg/g (ppm).

Sulphur: The amount of sulphur needed depends on the soil's current pH, the desired pH, the clay or sand content of the soil, and the type of sulphur used. But there may form sulphur toxicity when sulphur is added or applied manually in excessive amount. It was determined in μg/g (ppm).

Potassium: Potassium helps maintain turgor pressure in the cells of the plant, resulting in a positive influence on drought tolerance, cold hardiness, and disease resistance, which was measured in μg/g (ppm). But too much potassium disrupts the uptake of other important nutrients, such as calcium, nitrogen and magnesium, creating deficiencies that usually produce visible effects.

Zinc: Zinc is most available to plants if the soil pH is between 5.5 and 6.5, determined in μg/g (ppm). Most plants uptake sufficient zinc if the pH is between 4.5 and 7.5.

Boron: Boron is a micronutrient that is critical for stem cell differentiation, helping root and blade cells proliferate, nevertheless heavy boron soil concentrations are toxic. This nutrient is measured in μg/g (ppm).

Organic Matter: Organic matter helps the soil to soften making land preparation easy. It helps to increase the moisture holding capacity and retains the nutrient status of soil. Equation (3.7) was used to measure organic matter.

$$OM(\%) = \frac{M_O}{M_d} \tag{3.7}$$

Where, M_o = mass of organic matter and M_d = mass of dry soil.

3.4.3 Microstructural Analyses

The microscopic characterization of the mixture of soil and 8.5% fly ash used in VFM and VFGM was conducted by scanning electron microscope (SEM) imaging. Elemental analysis was done by energy dispersive spectroscopy (EDS). The tests were conducted by JEOLJSM 7600F scanning electron microscope at 5kV. The sample was dried for 24 hours in oven at 110°C in order to remove moisture and coated for 120s before analyses.

3.4.4 Chemical Composition of Fly Ash

Fly ash or flue ash, also known as pulverized fuel ash, is a coal combustion product that is composed of the particulates (fine particles of burned fuel) that are driven out of coal-fired boilers together with the flue gases. Ash that falls to the bottom of the boiler's combustion chamber (commonly called a firebox) is called bottom ash. In modern coal-fired power plants, fly ash is generally captured by electrostatic precipitators or other particle filtration equipment before the flue gases reach the chimneys. Together with bottom ash removed from the bottom of the boiler, it is known as coal ash. Depending upon the source and composition of the coal being burned, the components of fly ash vary considerably, but all fly ash includes substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline), aluminium oxide (Al_2O_3) and calcium oxide (CaO), the main mineral compounds in coal-bearing rock strata. Fly ash material solidifies while suspended in the exhaust gases and is collected by electrostatic precipitators or filter bags. Since the particles solidify rapidly while suspended in the exhaust gases, fly ash particles are generally spherical in shape and range in size from 0.5 µm to 300 µm. SiO_2, Al_2O_3, Fe_2O_3 and occasionally CaO are the main chemical components present in fly ashes. The mineralogy of fly ashes is very diverse. The main phases encountered are a glass phase, together with quartz, mullite and the iron oxides hematite, magnetite and/or maghemite. Other phases often identified are cristobalite, anhydrite, free lime, periclase, calcite, sylvite, halite, portlandite, rutile and anatase.

Table 3.8: Chemical Composition of Fly Ash (According to ASTM C618)

Parameter	Unit	Value
Calcium Oxide (CaO)	%	4.20
Sllicon di-Oxide (SiO_2)		55.80
Aluminium Oxide (Al_2O_3)		25.90
lron Oxide (Fe_2O_3)		6.74
Magnesium Oxide (MgO)		0.712
Sulphuric Anhydride (SO_3)		0.87
Loss on ignition (LOI)		2.92
Moisture (%)		0.34
Blaine	m^2/kg	210
Color	-	Grey

Two classes of fly ash are defined by ASTM C618, Class F fly ash and Class C fly ash. The chief difference between these classes is the amount of calcium, silica, alumina, and iron content in the ash.

For this study, 100 kg of fly ash was collected from Basundhara Cement Factory, located in Narayanganj. The chemical composition of the fly ash is shown in Table 3.8. As the percentage of CaO is low (4.2%), according to ASTM C618-89, the fly ash can be classified as Class F.

3.5 Summary

In this chapter, a brief description about the model study, the selected sites for the evaluation of field performance and laboratory tests is given with detailed pictures. As root soil interaction is very important for bio-engineering work, different model tests were conducted to understand the effect of vegetation to control erosion. The overall work done can be summarized as below:

(i) Four glass models (size 190 cm×60 cm×95 cm) were constructed in terms of conducting a wave tolerance model, to simulate the actual situation of *haor* areas during flood and monsoon period. Half of the models was filled up by *haor* soils by layer by layer compaction with a slope of 1:1.5 (V:H). The soil was brought from Ramrail Upazila, Brahmanbaria which is a *haor* district. Among the four glass models, one was constructed with local soil of *haor* areas (BM); second model was filled up with soil and covered with suitable vegetation (VM). The soil of the third model (VFM) was mixed and compacted with 8.5% fly ash (w/w) as stabilizer and then was covered with vegetation at 20 cm c/c spacing. The fourth model (VFGM) was filled with soil and fly ash mixture, covered with JGT of 600 gsm and vegetation at 20 cm c/c spacing. In these models, wave action was produced after 177 days of vetiver plantation, to observe and compare the sustainability of revetments of *haor* areas during monsoon considering the actual parameters i.e., wave height, wave length and wave velocity. Regular measurements of the tillers were also taken.

(ii) For field study, total 23 sites were selected of five *haor* districts, Brahmanbaria, Habiganj, Kishoreganj, Netrokona and Sunamganj. All the sites have been selected on the basis of topographical, ecological and socio-economic parameters. Collected data included growth measurement, performance of vetiver, growth of other vegetation alongside, soil type, amount of water in soil and soil characteristics, vegetation sample collection, performance of slope (whether erosion has occurred or not, if occurred, how much). Comparative performance evaluation of the existing technologies was investigated and problems in replicating existing technology by local people have been noted as well.

(iii) Laboratory investigation was carried out on 24 soil samples from the selected *haor* sites and models. The laboratory testing program consisted of carrying out specific gravity, moisture content, particle size analysis, permeability test, direct shear test, SEM-EDS analysis and nutrient tests of the samples.

Chapter Four
RESULTS AND DISCUSSIONS

4.1 General

This chapter presents detail test results obtained from the field, model studies and laboratory investigations described in the previous chapter. Both model study and field trials were conducted to investigate the effectiveness of vetiver grass to protect the infrastrcutures of the *haor* region as ecological revetment system using bio-engineering system. Sub-soil characteristics of the *haor* areas have been summarized in this chapter. The results and growth study from the small scale slope model are also authenticated in this chapter with some prevailing literatures.

4.2 Test Results

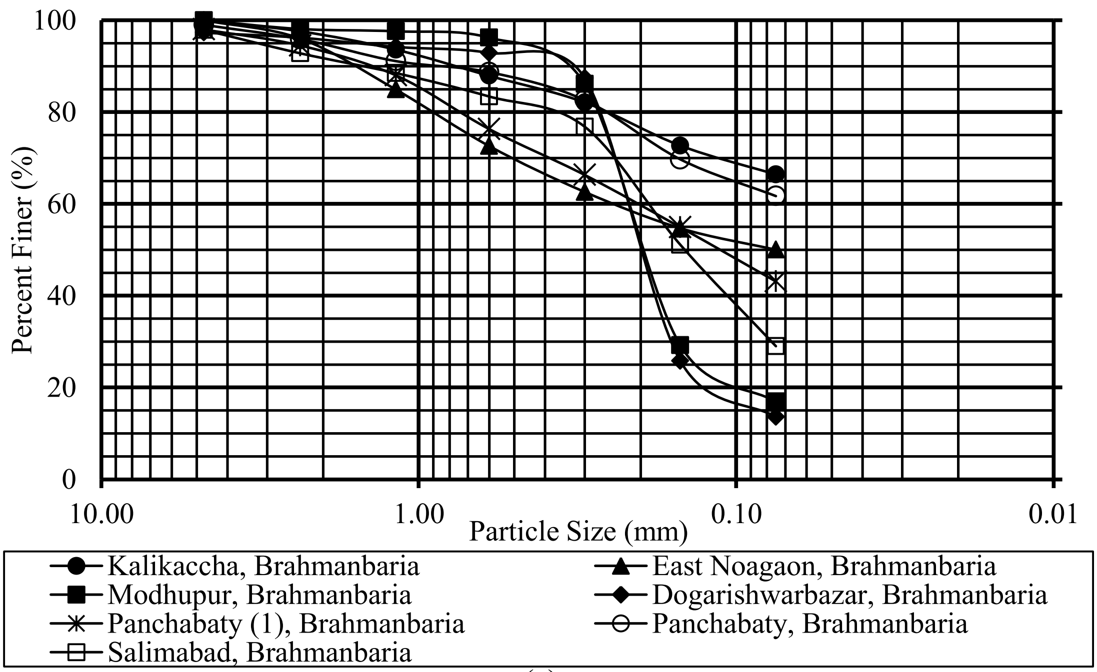
The test results of index, strength and chemical properties of *haor* and model soils are summarized in this section.

4.2.1 Index Properties

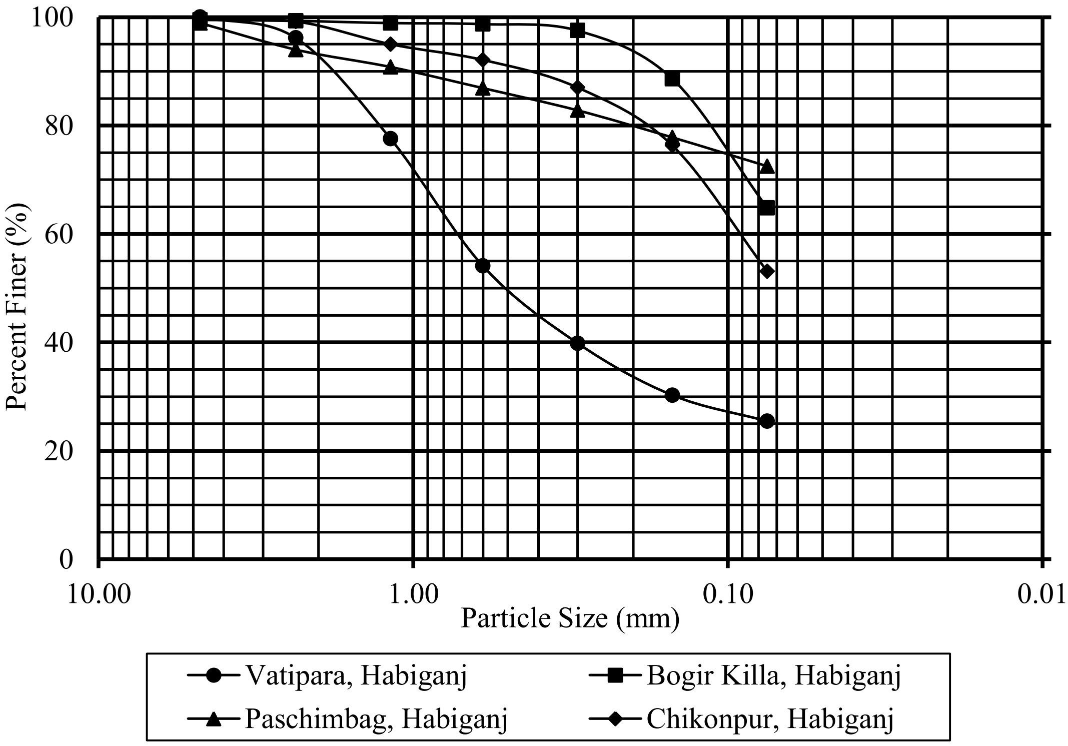
Index properties were done for both field soils and models soils to get the knowledge about the sub-soil properties of the overall *haor* areas.

Field Soils

Figure 4.1 (a) to 4.1 (e) shows the compilation of grain size analysis curves of Brahmanbaria, Habiganj, Kishoreganj, Netrkona and Sunamganj, respectively.

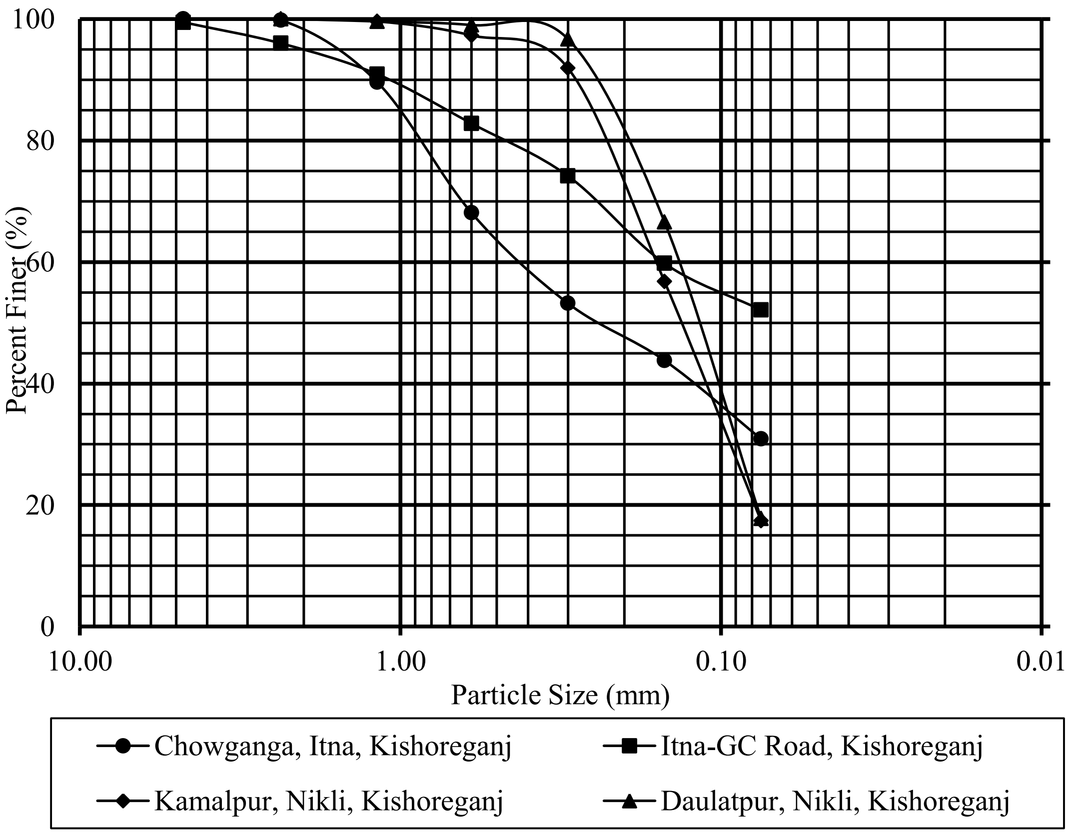


(a)



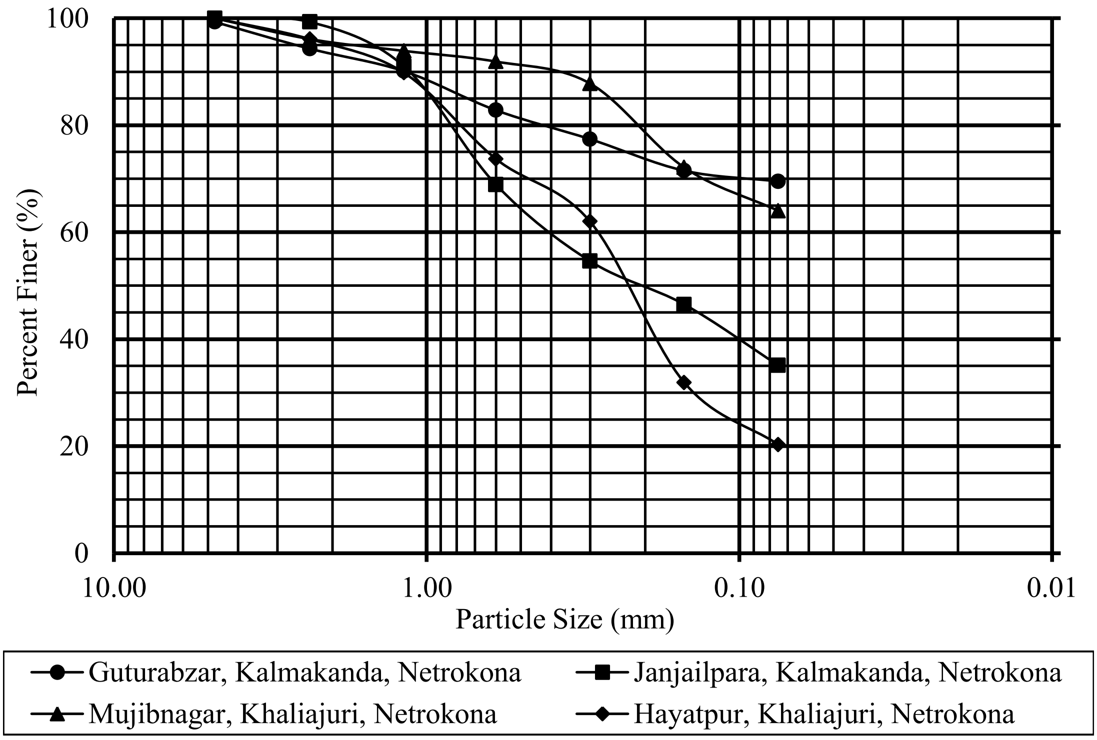
100
80
60
40
20
0
Percent Finer (%)
10.00
1.00
0.10
0.01
Particle Size (mm)
Vatipara, Habiganj
Bogir Killa, Habiganj
Paschimbag, Habiganj
Chikonpur, Habiganj

(b)

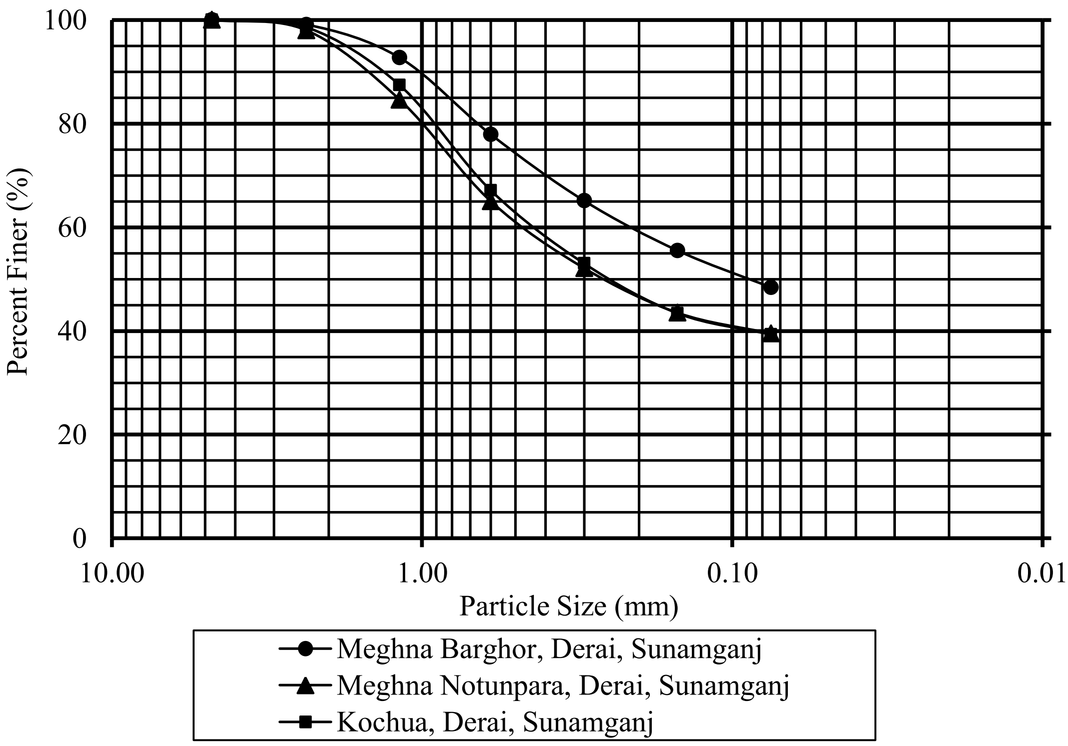


100
80
60
40
20
0
Percent Finer (%)
10.00
1.00
0.10
0.01
Particle Size (mm)
Chowganga, Itna, Kishoreganj
Itna-GC Road, Kishoreganj
Kamalpur, Nikli, Kishoreganj
Daulatpur, Nikli, Kishoreganj

(c)



(d)



(e)

Figure 4.1: Grain Size Analysis of the Soils from (a) Brahmanbaria; (b) Habiganj; (c) Kishoreganj; (d) Netrokona; and (e) Sunamganj

Table 4.1 summarizes the soil type, Fineness Modulus (FM) and specific gravity (G_s) of the soils collected from field study areas.

Table 4.1: Index Properties of *Haor* Soils

District	Site Name	Soil Type*	F.M.	G_s
Brahmanbaria	Kalikaccha, Sarail	Grey Sandy Silt	0.66	2.67
	East Noagaon, Sarail	Brown Silty Sand	1.29	2.62
	Modhupur, Ashuganj	Brown Silty Sand	0.93	2.61
	Dogarishwarbazar, Ashuganj	Brown Silty Sand	1.06	2.56
	Panchabaty (1&2), B. Baria Sadar	Brown Silty Sand	1.22	2.48
	Panchabaty, B. Baria Sadar	Brown Sandy Silt	0.73	2.60
	Salimabad, Bancharampur	Brown Silty Sand	1.10	2.72
Habiganj	Vatipara, Baniachong	Brown Silty Sand	2.02	2.74
	Paschimbag, Azmiriganj	Grey Sandy Silt	0.69	2.68
	Chikonpur, Lakhai	Brown Sandy Silt	0.51	2.60
Kishoreganj	Chowganga, Itna	Brown Silty Sand	1.46	2.51
	Itna-GC Road, Itna	Grey Sandy Silt	0.97	2.66
	Kamalpur, Nikli	Brown Silty Sand	0.55	2.54
	Daulotpur, Nikli	Brown Silty Sand	0.38	2.65
Netrokona	Guturabazar, Kalmakanda	Grey Sandy Silt	0.85	2.75
	Janjailpara, Kalmakanda	Brown Silty Sand	1.40	2.49
	Mujibnagar, Khaliajuri	Brown Sandy Silt	0.58	2.72
	Hayatpur, Khaliajuri	Brown Silty Sand	1.47	2.68
Sunamganj	Meghna Barghor, Derai	Brown Silty Sand	1.10	2.56
	Meghna Notunpara, Derai	Brown Silty Sand	1.57	2.68
	Kochua, Derai	Grey Silty Sand	1.51	2.62

**Classification based on ASTM D422*

Figure 4.2 shows the photographs of all collected soils from five *haor* districts. All graphs and tables indicate the variety and non-uniformity of soil type in *haor* region. It shows that almost all of the soil types are silty sand/sandy silt, i.e., non-plastic, are fine in nature. The more the fine the particles, it is more erodible. Among all the *haor* districts, soils of Sunamganj have been found most coarse, and the soils of Kishoreganj have been found as most fine. The details of the calculation including % finer of course, medium and fine sands are shown in Appendix A.

Model Soils

The model soils were also tested and classified based on ASTM D 422 to determine the index properties of the particular soils. The fineness modulus (FM) and specific gravity (G_s) are listed in Table 4.2. Figure 4.3 presents the combination of the grain size analysis of the model soils and fly ash, where Figure 4.4 shows the photographs of the soil used for model study. It was found that fly ash increased the fineness of the original soil, which helped to reduce the void within the soil particles.

Table 4.2: Index Properties of Model Soils

Model Name	Location	Soil Type	F.M.	G_s
BM, VM	Ramrail	Brown Silty Sand	1.49	2.68
VFM, VFGM		Brown Silty Sand+8.5% Fly Ash	1.36	2.55
Fly Ash			0.11	2.14

Figure 4.2: Visual Photographs of *Haor* Soils

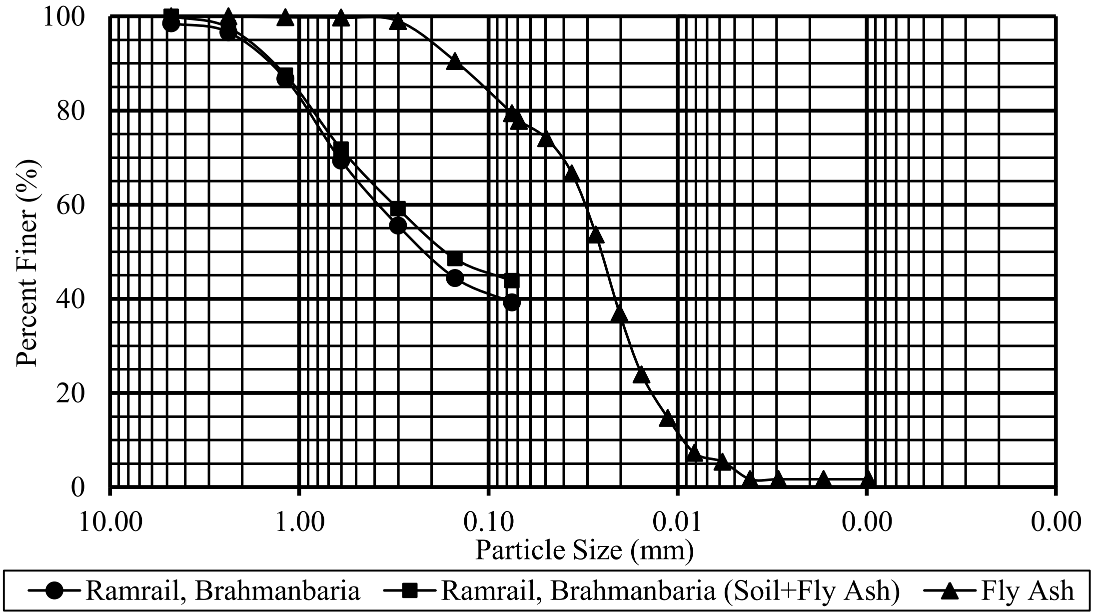


Figure 4.3: Grain Size Analysis of the Model Soils and Fly Ash

Model: BM, VM (Soil from Ramrail) **Model: VFM, VFGM (Ramrail Soil+8.5% Fly Ash)** **Fly Ash**

Figure 4.4: Visual Photographs of Model Soils and Fly Ash

4.2.2 Engineering Properties

Permeability test and direct shear tests (CD) were done for particular selected sites of *haor* soils and model soils to determine the infiltration capacity and shear strength parameters.

Field Soils

Falling head permeability tests were conducted on soils from 5 (five) *haor* districts. The results are summarized in Table 4.3 along with the natural moisture content of soil.

From Table 4.3, it is found that, although most of the soils obtain a low degree of permeability, soils of Sunamganj is the most impermeable soil, where soils of Habiganj is the most permeable soil among all *haor* districts. All strength parameters from the graphs of the *haor* soils are summarized in Table 4.4.

Table 4.3: Permeability Characteristics of *Haor* Soils

Location	Natural Moisture Content, ω_u (%)	State of the soil	Permeability at 20°C, k (cm/sec)	Degree of Permeability	Void Ratio, (e)
Kalikaccha, Sarail, Brahmanbaria	11.35	Loose	1.09×10^{-3}	Low	1.57
		Medium Dense	8.54×10^{-4}	Low	1.36
		Dense	3.97×10^{-4}	Low	1.15
Paschimbag, Azmiriganj, Habiganj	9.36	Loose	1.16×10^{-3}	Low	1.44
		Medium Dense	1.08×10^{-3}	Low	1.30
		Dense	7.79×10^{-4}	Low	1.17
Chowganga, Itna, Kishoreganj	14.19	Loose	2.38×10^{-4}	Low	1.51
Guturabazar, Kalmakanda, Netrokona	16.22	Loose	5.28×10^{-4}	Low	1.52
		Medium Dense	4.14×10^{-4}	Low	1.48
		Dense	1.48×10^{-4}	Low	1.37
Kochua, Derai, Sunamganj	11.52	Loose	8.05×10^{-5}	Very Low	1.49

Table 4.4: Shear Strength Parameters of *Haor* Soils

Location	Moisture Content, ω (%)	Dry Density, γ (kN/m^3)	Normal Stress, σ_n (kPa)	Shear Stress, τ_{max} (kPa)	Cohesion, c (kPa)	Angle of Friction, Φ (°)
Kalikaccha, Sarail, Brahmanbaria	48.1	10.6	30.97	12.52	–	31
	44.0	10.4	61.93	35.47		
	43.2	10.3	123.83	75.01		
Paschimbag, Azmiriganj, Habiganj	36.2	11.9	30.97	12.78	–	28
	35.2	11.5	61.93	31.39		
	35.2	11.4	123.83	66.59		
Chowganga, Itna, Kishoreganj	38.2	12.1	30.97	12.52	–	27
	36.7	12.3	61.93	30.12		
	34.4	12.3	123.83	64.80		
Guturabazar, Kalmakanda, Netrokona	36.8	12.8	30.97	25.19	–	30
	30.4	11.5	61.93	28.91		
	32.4	13.0	123.83	30.81		
Kochua, Derai, Sunamganj	31.2	14.2	30.97	42.71	5.8	36
	32.3	14.1	61.93	38.92		
	30.4	14.5	123.83	37.68		

Figure 4.5 to Figure 4.9 show shear stress vs. shear displacement curves, shear stress vs. normal stress graphs and change of volumetric expansion or reduction with shear displacement of the typical *haor* soils. From Figure 4.5 to Figure 4.9, the graph patterns of all specimens of the *haor* soils indicate the loose consistency of soil, except for the soil under σ_n= 30.97 kPa from Sunamganj.

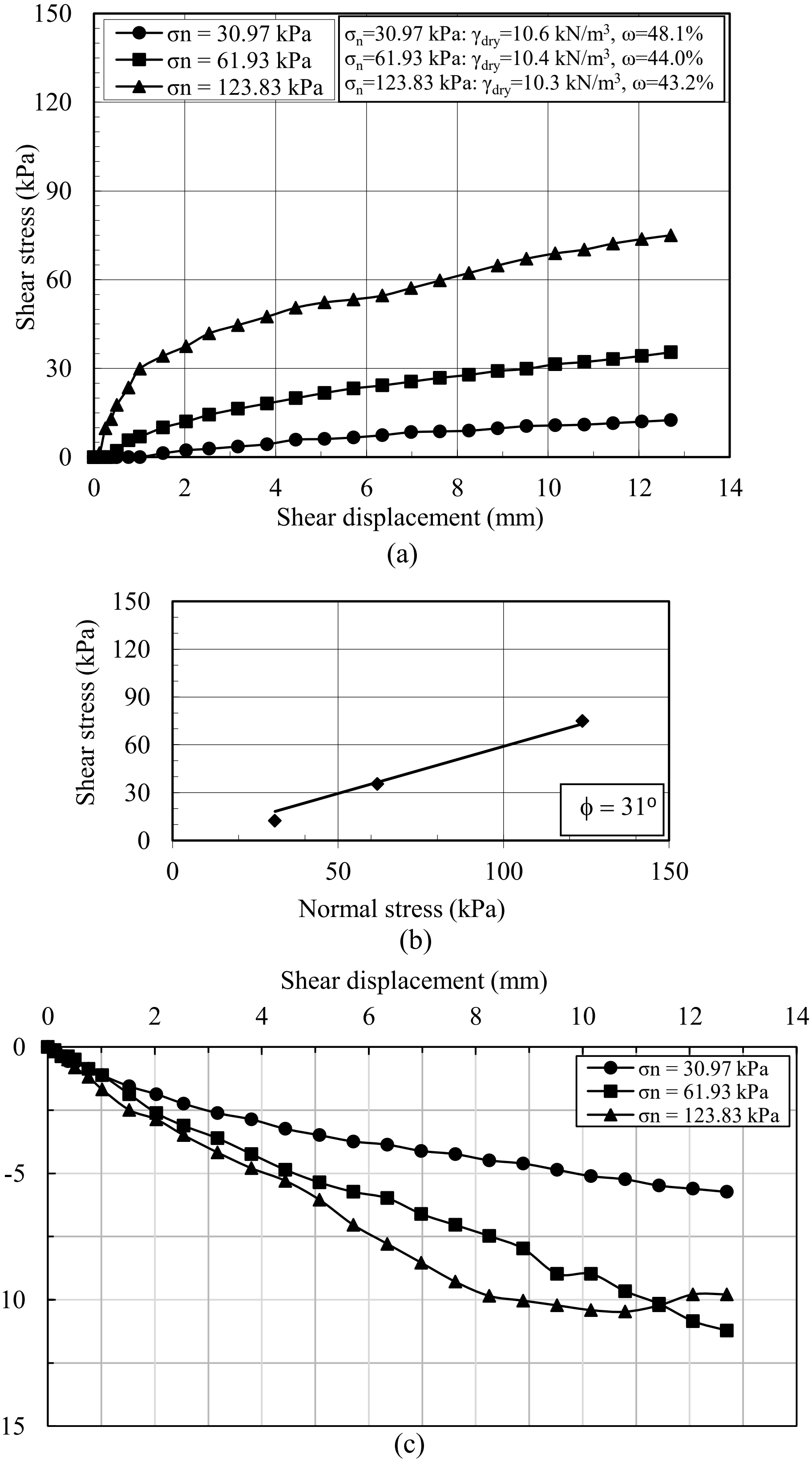
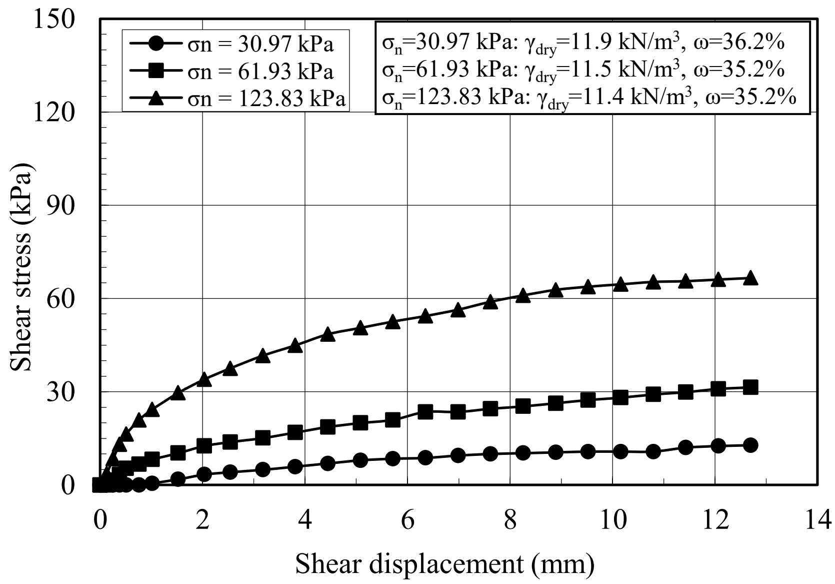
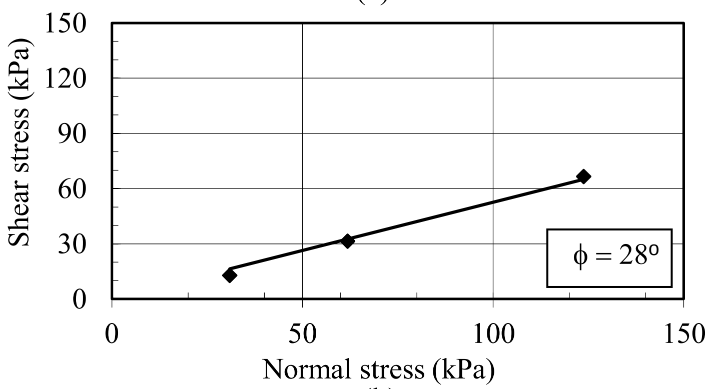


Figure 4.5: Direct Shear Graphs for Soil from Kalikaccha, Sarail, Brahmanbaria: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement



(a)



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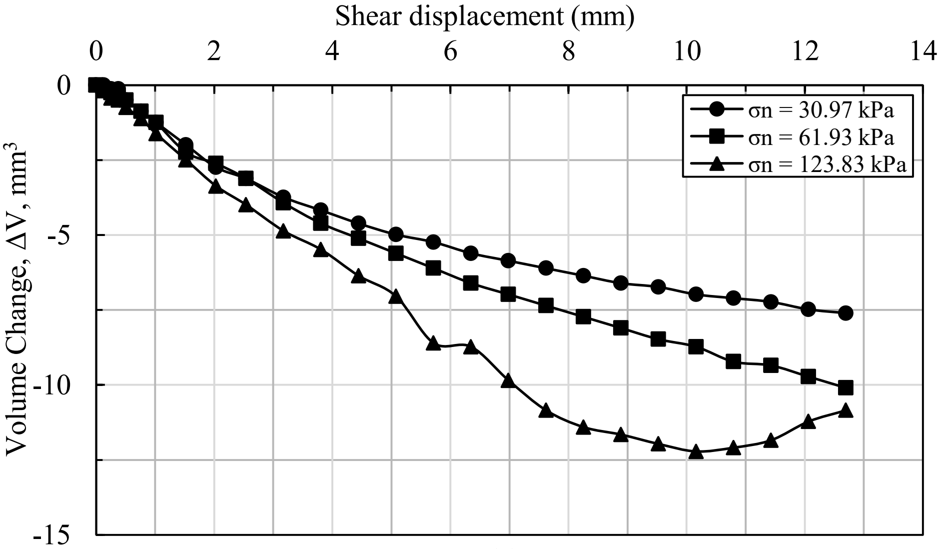
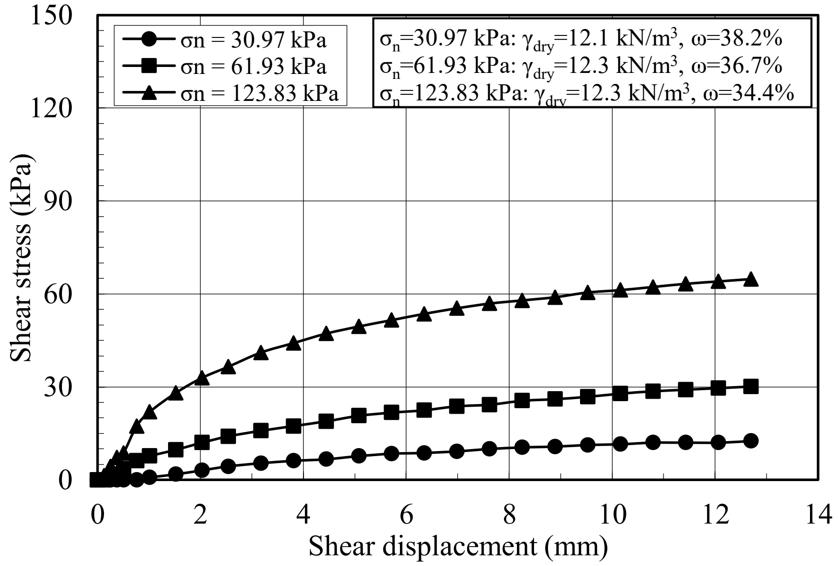
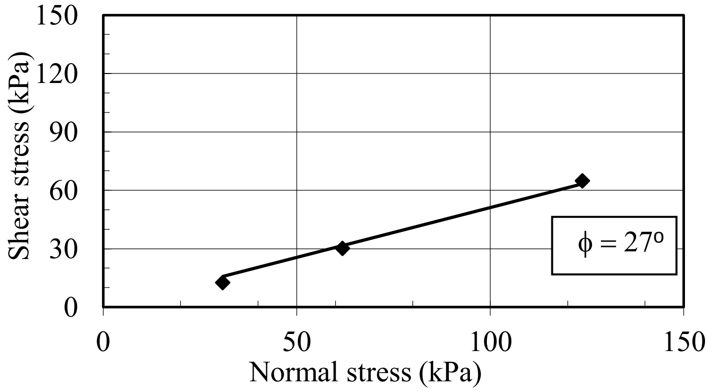


(c)

Figure 4.6: Direct Shear Graphs for Soil from Paschimbag, Azmiriganj, Habiganj: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement



(a)



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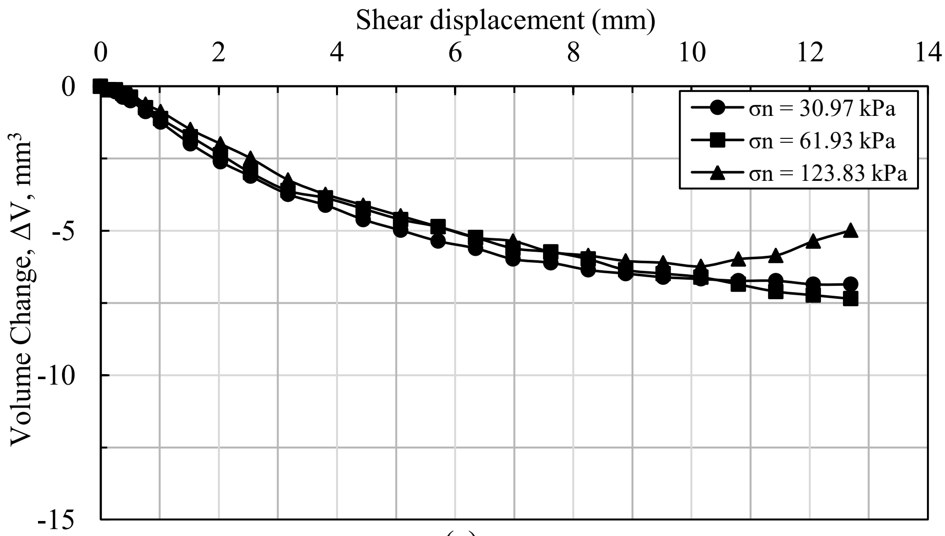
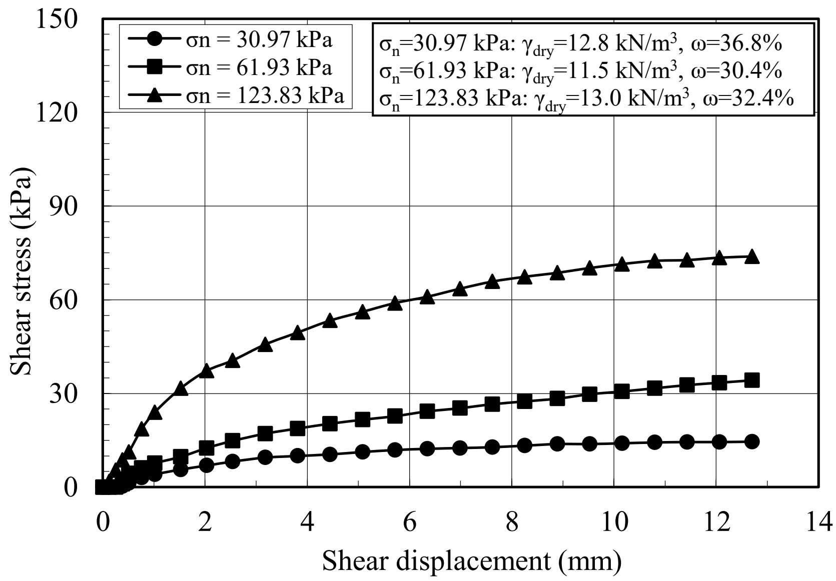
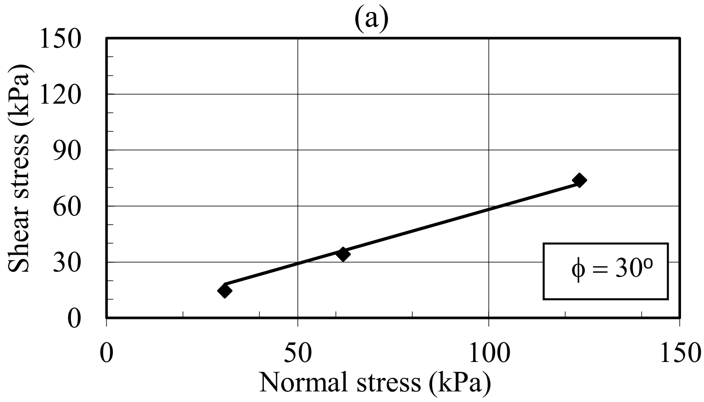


(c)

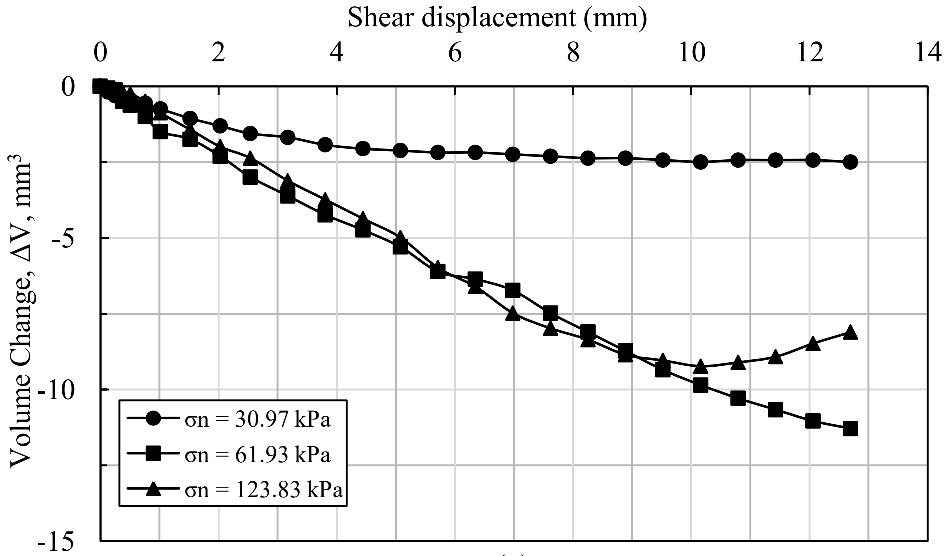
Figure 4.7: Direct Shear Graphs for Soil from Chowganga, Itna, Kishoreganj: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement



(a)



(b)



(c)

Figure 4.8: Direct Shear Graphs for Soil from Guturabazar, Kalmakanda, Netrokona: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement

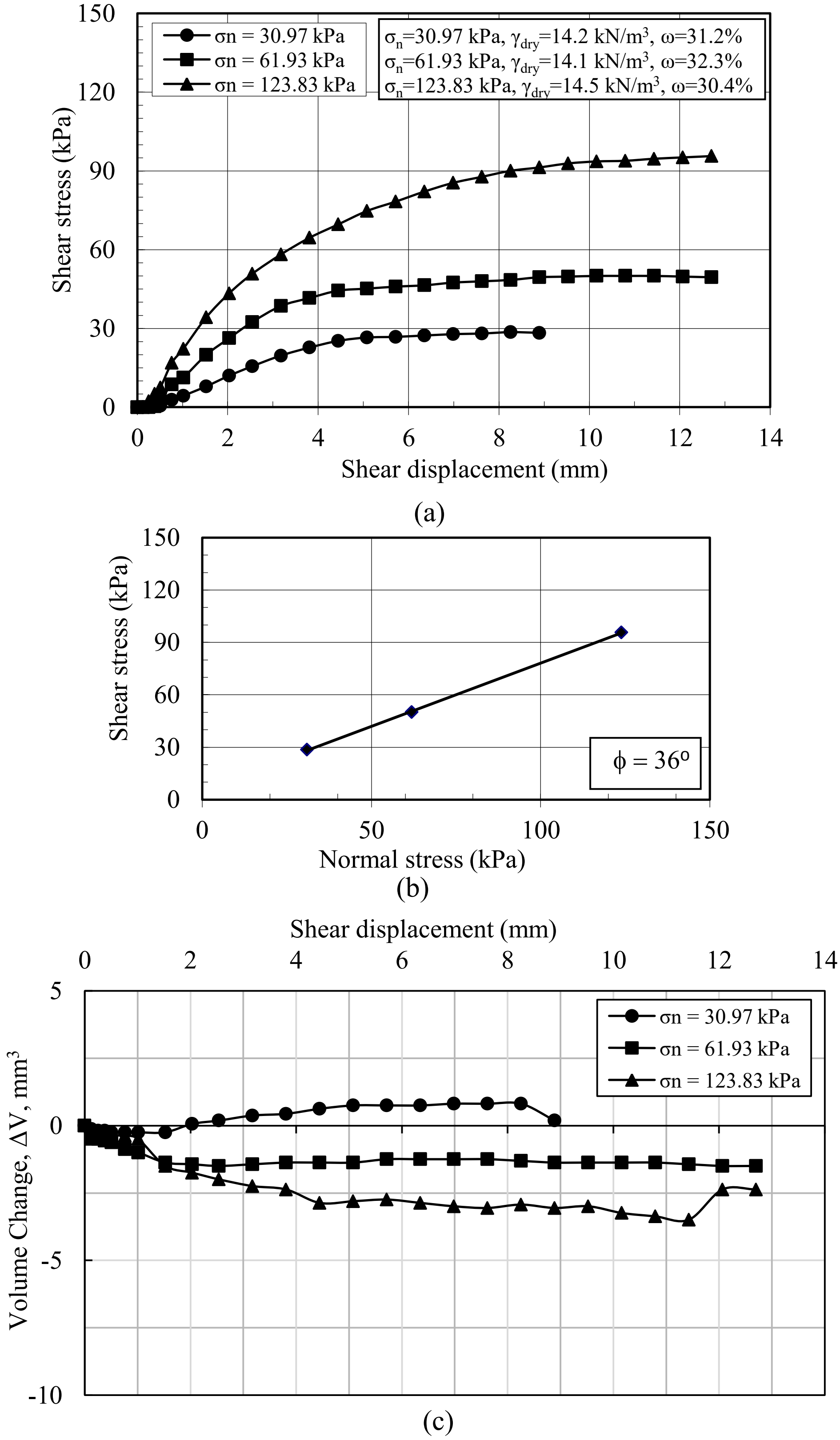


Figure 4.9: Direct Shear Graphs for Soil from Kochua, Derai, Sunamganj: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement

Model Soils

For the model soils, falling head permeability tests were conducted also. The results are summarized in Table 4.5, which shows the change in permeability for adding fly ash as stabilizer.

Table 4.5: Permeability Characteristics of Model Soils

Location	Model Name	Natural Moisture Content, ω_u (%)	State of the soil	Permeability at 20°C, k (cm/sec)	Degree of Permeability	Void Ratio, (e)
Ramrail, Brahmanbaria	BM, VM (Soil Only)	15.65	Loose	6.57×10^{-5}	Very Low	2.09
			Medium Dense	6.41×10^{-5}	Very Low	1.56
	VFM, VFGM (Soil +8.5% Fly Ash)	11.63	Loose	6.55×10^{-5}	Very Low	1.64
			Medium Dense	5.99×10^{-5}	Very Low	1.36

The model soils obtain a very low degree of permeability, and from the experimental data shown in Table 4.5, it can be observed that for mixing 8.5% fly ash, natural moisture content, permeability coefficient and void ratio decreased. All strength parameters from the graphs of the model soils are summarized in Table 4.6. Figure 4.10 and Figure 4.11 show shear stress vs. shear displacement curves, shear stress vs. normal stress graphs and change of volumetric expansion or reduction with shear displacement of the model soils. It is observed from Figure 4.10, Figure 4.11 and Table 4.6 that, adding fly ash increased the shear strength as well as angle of internal friction, which indicates the increase of strength and stability of model soils of VFM and VFGM than that of BM and VM. The increase pattern of shear strength is shown in Figure 4.12.

Table 4.6: Shear Strength Parameters of Model Soils

Location	Model Name	Moisture Content, ω (%)	Dry Density, γ (kN/m³)	Normal Stress, σ_n (kPa)	Shear Stress, τ_{max} (kPa)	Cohesion, c (kPa)	Angle of Friction, Φ (°)
Ramrail, Brahmanbaria	BM, VM (Soil Only)	43.7	10.9	30.97	14.82	–	26
		35.2	11.2	61.93	30.37		
		28.5	11.3	123.83	59.70		
	VFM, VFGM (Soil +8.5% Fly Ash)	34.6	11.6	30.97	13.03	–	28°
		36.2	11.8	61.93	28.33		
		35.8	11.3	123.83	67.35		

For slope stabilization purposes, although 5-15% fly ash can be used (Mahvash et al., 2017), there is a risk of contaminating environment by heavy metals by fly ash. So, fly ash was not mixed in the model soils in a large scale.

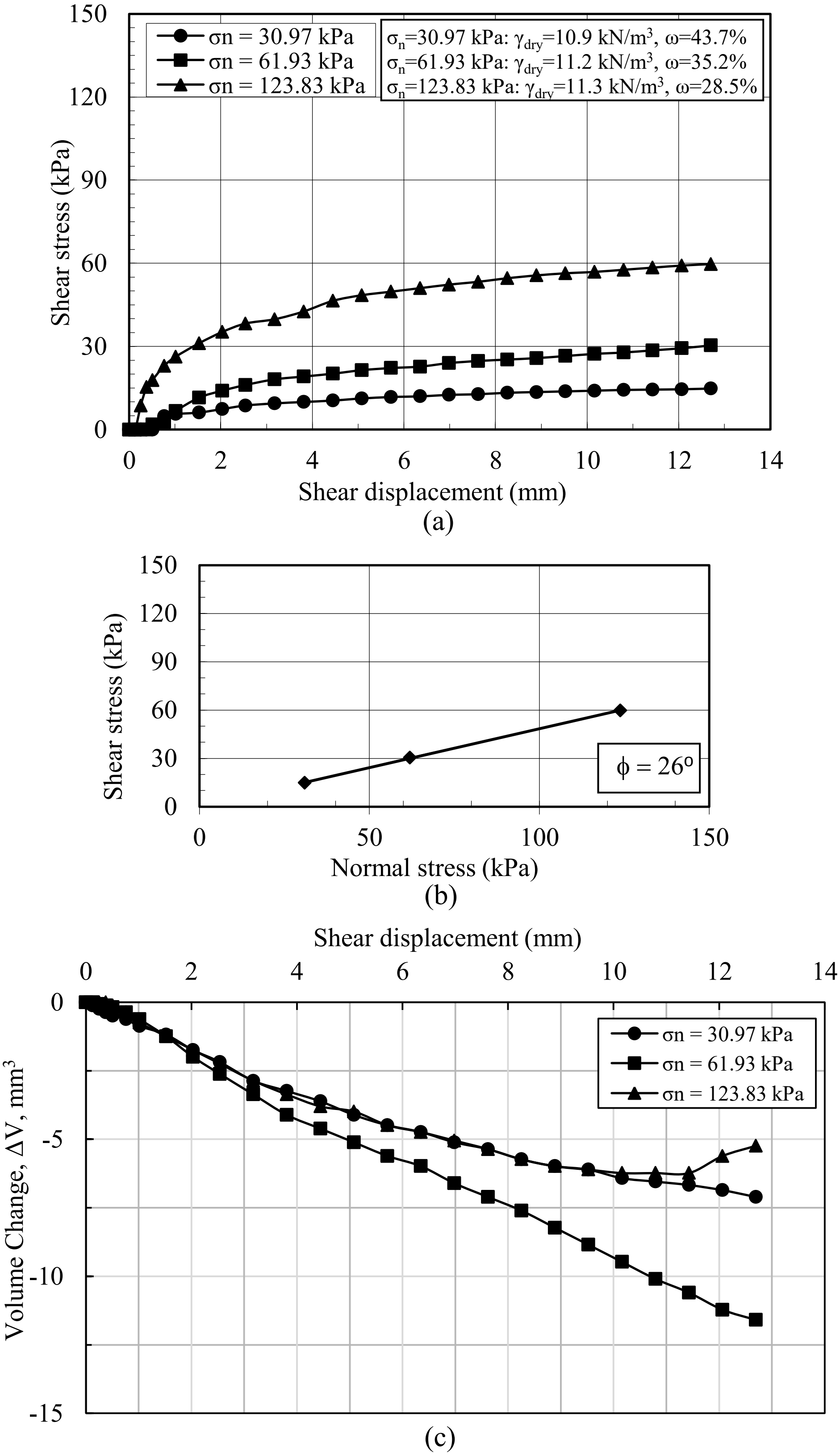


Figure 4.10: Direct Shear Graphs for Soil from Ramrail, Brahmanbaria (Model BM and VM): (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement

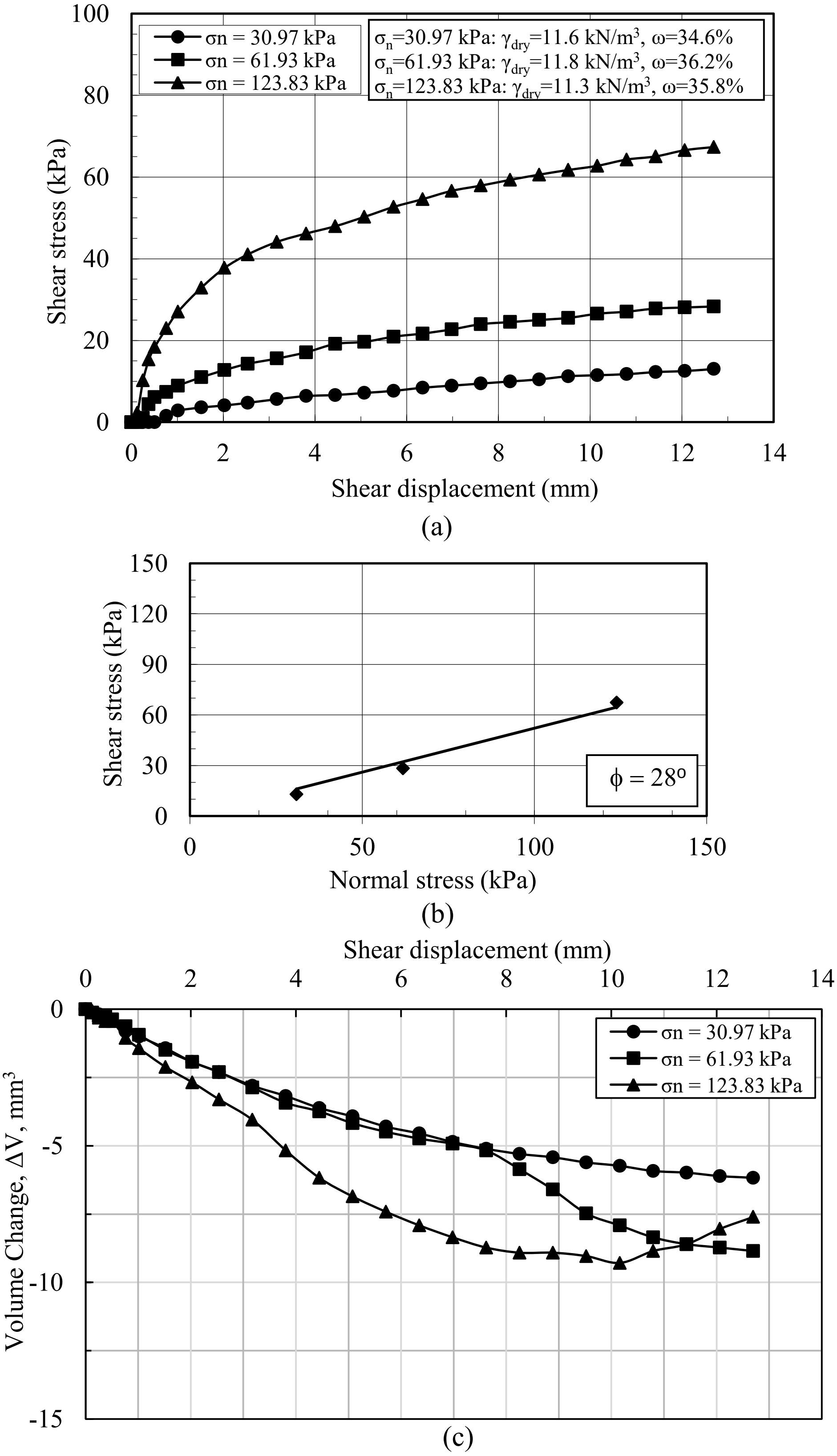


Figure 4.11: Direct Shear Graphs for Soil+8.5% Fly Ash of Model VFM and VFGM: (a) Shear Stress vs. Shear Displacement; (b) Shear Stress vs. Normal Stress; and (c) Volumetric Change vs. Shear Displacement

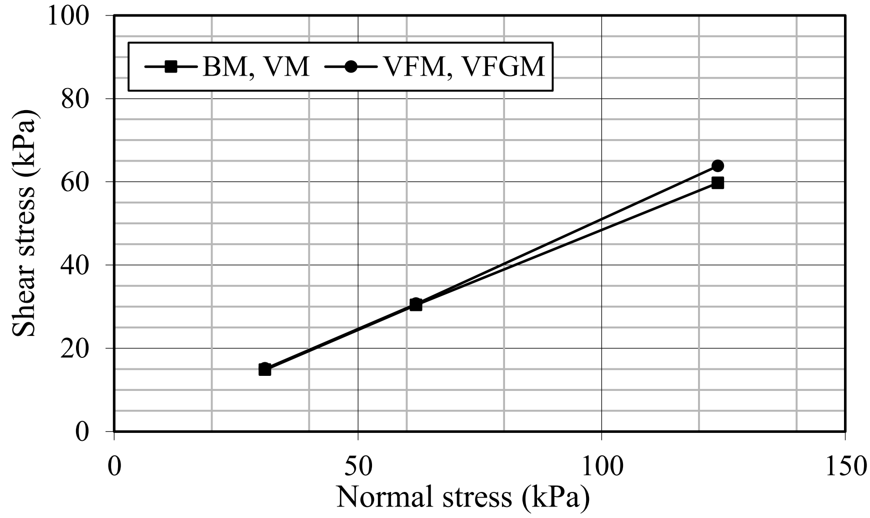


Figure 4.12: Shear Stress vs. Normal Stress of the Four Model Soils

4.2.3 Chemical Properties

Chemical composition is the arrangement, type, and ratio of atoms in molecules of chemical substances, and it is important to realize the change of the properties of particles. So, nutrient tests of *haor* soils were done to determine the fertility, or the expected growth potential of the soil which indicates nutrient deficiencies, potential toxicities from excessive fertility and inhibitions from the presence of non-essential trace minerals.

Nutrients

The 20 (twenty) samples from Brahmanbaria, Habiganj, Kishoreganj, Netrokona, Sunamganj districts and two model soils (soil and soil+8.5% fly ash) were sent to Soil Resource Development Institute (SRDI) to measure the essential elements of soil for proper vegetation growth, i.e. Nitrogen, Phosphorus, Potassium, Sulphur, Zinc, Boron, pH of the soil. These results are shown in Figure 4.13 to Figure 4.16.

Table 4.7: Model Soil Nutrients

Elements	Chemical content of Model Soil		State of Model Soils	Required amount for Proper Vegetation Growth*
	Soil of Model BM, VM	Soil of Model VFM, VFGM		
pH	7.4	8	Alkaline	6.0~7.5
N (%)	0.03	0.04	Low	3.0
K (meq/100g)	0.09	0.09	Very Low	0.32
P (ppm)	31.47	32.49	High	16
S (ppm)	23.64	25.86	Optimum	10~50
Zn (ppm)	0.82	0.77	Low	50
B (ppm)	0.2	0.15	Low	6

**General requirement of vegetation yield according to SRDI*

Table 4.8: *Haor* Soil Nutrients with Required Treatment for Proper Growth of Vegetation

Element	Range	State of *Haor* Soil	Required amount*	Requirements to reach optimum level
pH	4.0-7.8	Acidic-Alkaline	6.0-7.5	Lime addition to reduce acidity
N (%)	0.015-0.365	Very Low-Low	3.0	Organic compost using vegetables coffee grounds
P (ppm)	1.2-104.96	Very Low-High	16	Lime addition
K (meq/100g)	0.09-2.75	Very Low-Very High	0.32	(a) Fruit addition to compost. (b) Gathering the potassium-rich ashes by burning wood once the fire is out (c) Dig 6 to 8 inches beneath the surface of the ground or plant container, then mix coffee grounds into the soil
S (ppm)	0.46-93.56	Low-Very High	10-50	Elemental sulfur addition, also known as "flowers of sulfur," or aluminum sulfate
Zn (ppm)	0.72-10.81	Low-High	50	Compost or organic manure addition
B (ppm)	0.05-3.01	Very Low-High	6	Small amount of boric acid addition (1/2 tsp. per gallon of water) as a foliar spray will do the job, and water the area to move boron into the root zone. Wearing protective clothing, including safety eyewear is recommended.
Organic Matter (%)	0.7-2.9	Low-Medium	2-4	Perennial pasture growing and addition of organic fertilizers.

General requirement of vegetation yield according to SRDI

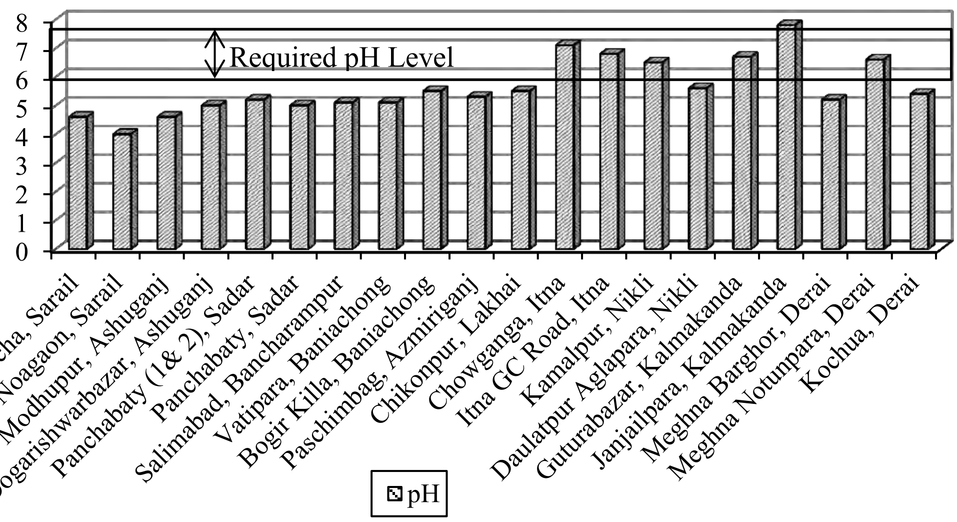


Figure 4.13: pH level of the *Haor* Soils

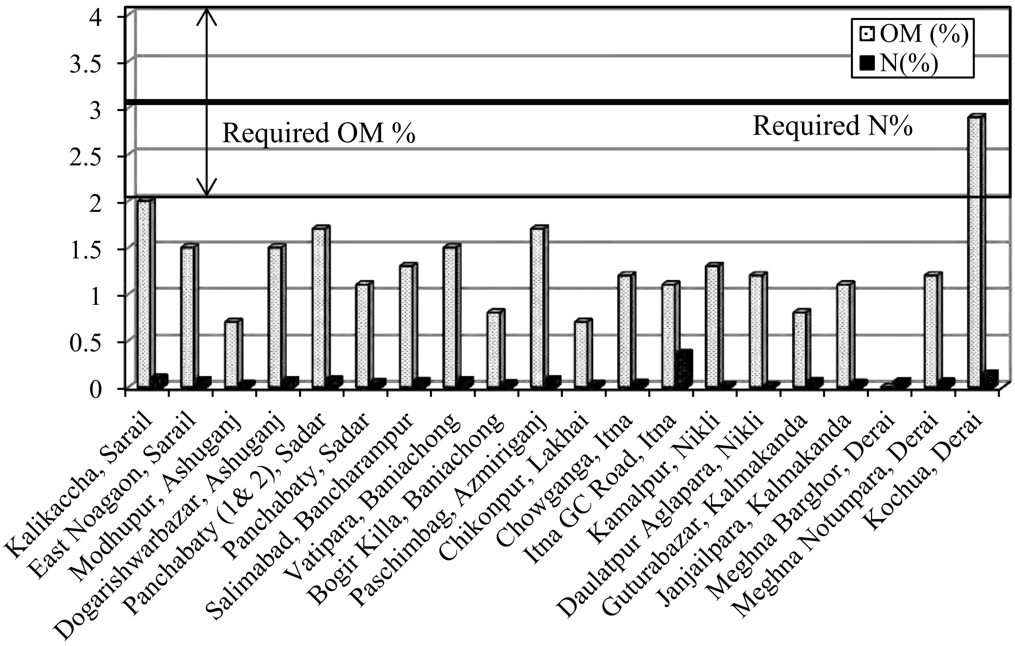


Figure 4.14: Percentage of Organic Matter and Available Nitrogen of the *Haor* Soils

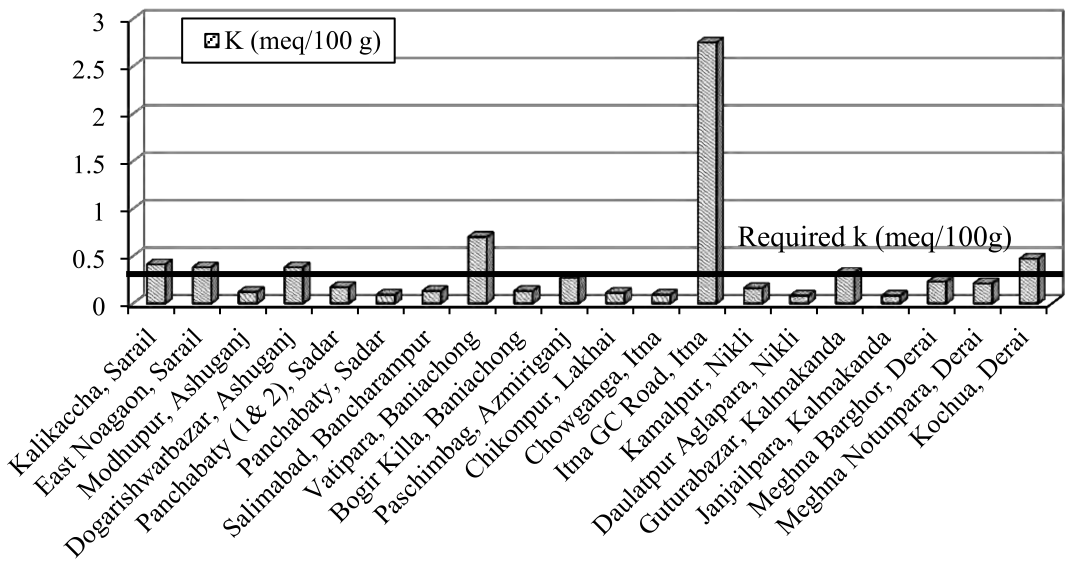


Figure 4.15: Amount of Potassium in meq/100 gm of the *Haor* Soils

Soil nutrients were also determined for the model soils, *haor* soil (Model BM and VM) and the mixture of soil and 8.5% fly ash (Model VFM and VFGM). The results are shown in Table 4.7, which shows the alkaline state of the model soils. The amount of total Nitrogen, Phosphorus and Sulphur increased slightly, where Zinc and Boron reduced by adding fly ash. Figure 4.13 to Figure 4.16 shows amount of nutrients of *haor* soils, which are summarized in Table 4.8 with recommendations of necessary adjustments. From the nutrient analysis of all soils it is observed that, *haor* soils are rich in Phosphorus, Potassium and Sulphur, but contain ample deficiencies in Nitrogen, Zinc, Boron and Organic Matters. Though the nutrients are important for growth of vegetation and should be handled carefully, from field and model study it has been observed that, vetiver can grow excellent despite of the soil nutrients not being in the required range. The graphs show the diversity of soil nutrients in different *haor* areas, which shows the treatment requirements for the proper growth of vegetation. In some cases like plantation of vetiver in dry season and in unfertile soil, locally available organic manure (cow dung, rice husk, coconut dusts) can be applied. Fertilizer recommendation is not suggested when the nutrient values go beyond the optimum level.

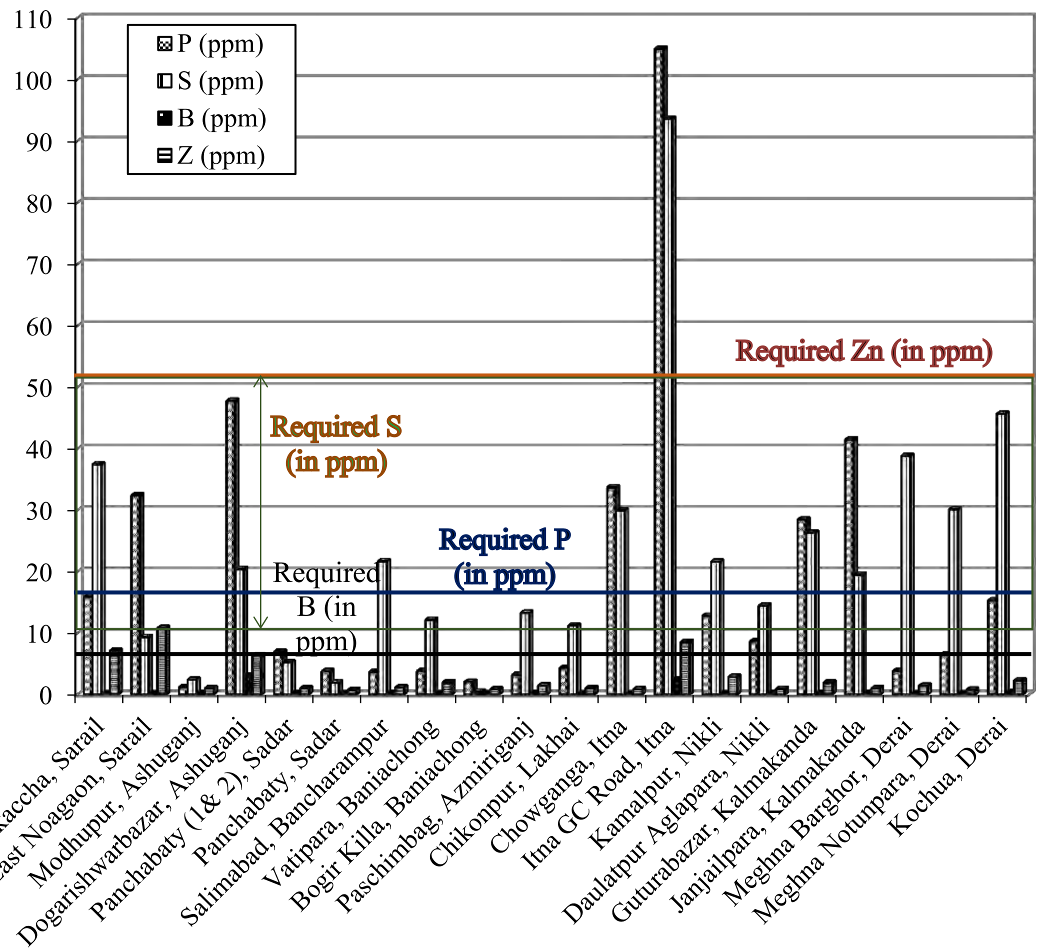
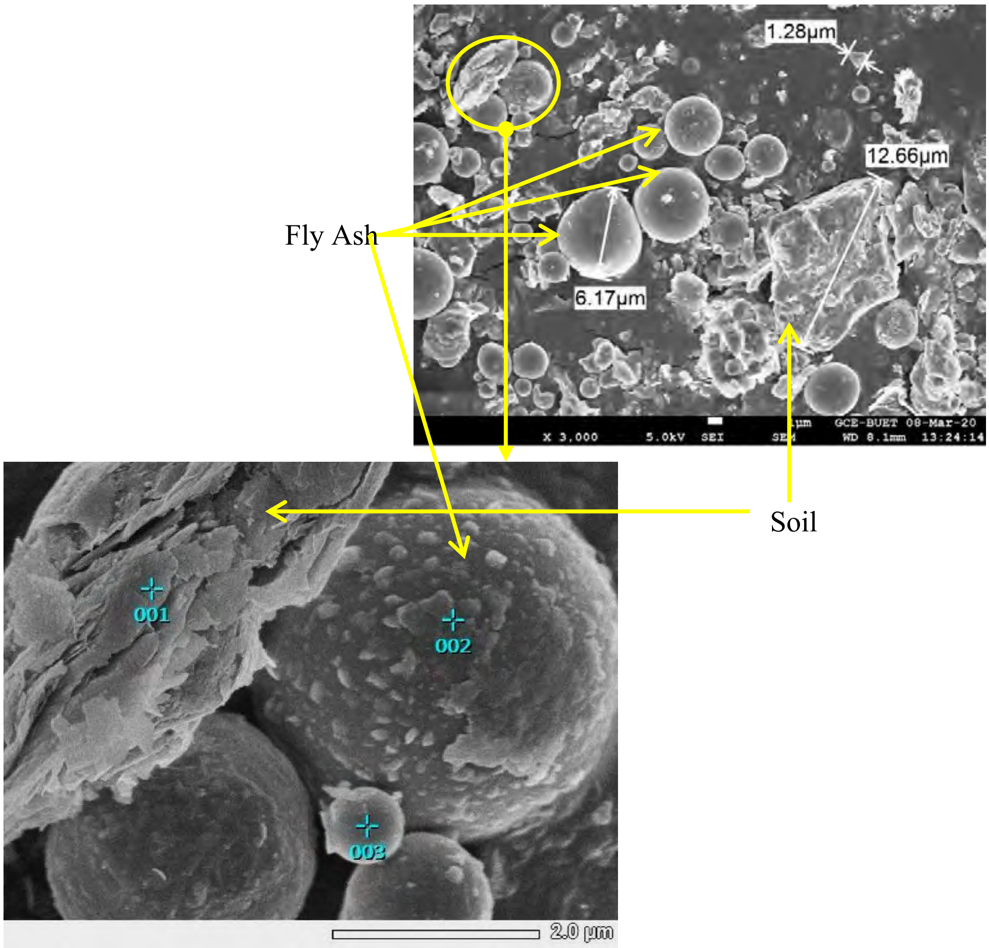


Figure 4.16: Amount of Phosphorus, Sulphur, Boron, and Zinc in ppm of the *Haor* Soils

4.2.4 Microscopic Properties

The microscopic images and elemental analysis of the mixture of soil and 8.5% fly ash (Sample of VFM, VFGM) are shown in Figure 4.17 at different magnifications. Figure 4.17(a) shows the SEM images of soil and fly ash particles. The irregular shapes and protrusions of more angular particles likely prevent tight packing (Miller and Henderson, 2011). From the figure, it is observed that the spherical glass like particles of fly ash fill up the voids and increase the bulk density of soil of the slope. Fly ash is found rich in carbon content by EDS analysis. Since soil-carbon management is an important strategy for improving soil quality and mitigating soil erosion (Agronomy Fact Sheet 91, 2016), it will help to reduce soil erosion.



(a)

pt 001

ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0656

Element	(keV)	Mass%	Sigma	Atom%	K
C K	0.277	10.44	0.07	16.43	3.1820
O K	0.525	49.52	0.22	58.51	53.8521
Mg K	1.253	0.14	0.05	0.11	0.1329
Al K	1.486	9.29	0.15	6.51	9.7630
Si K	1.739	22.72	0.25	15.29	24.8035
S K					
K K*	3.312	2.95	0.15	1.43	3.2846
Ca K	3.690	0.39	0.12	0.18	0.4445
Fe K	6.398	4.55	0.48	1.54	4.5373
As L					
Total		100.00		100.00	

pt 002

ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0706

Element	(keV)	Mass%	Sigma	Atom%	K
C K	0.277	22.55	0.08	32.85	8.8633
O K	0.525	42.88	0.21	46.89	47.4359
Mg K	1.253	0.31	0.06	0.22	0.3617
Al K	1.486	8.21	0.13	5.32	10.1747
Si K	1.739	19.93	0.22	12.41	25.6820
S K					
K K*	3.312	2.49	0.13	1.11	3.2397
Ca K	3.690	0.67	0.11	0.29	0.8855
Fe K	6.398	2.62	0.41	0.82	3.0248
As L	1.282	0.35	0.13	0.08	0.3323
Total		100.00		100.00	

pt 003

ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0724

Element	(keV)	Mass%	Sigma	Atom%	K
C K	0.277	10.60	0.26	16.99	2.9998
O K	0.525	45.46	0.52	54.73	48.5322
Mg K	1.253	0.04	0.05	0.03	0.0412
Al K	1.486	8.61	0.21	6.14	9.3036
Si K	1.739	27.77	0.40	19.04	31.1513
S K					
K K*	3.312	3.19	0.22	1.57	3.5844
Ca K	3.690	0.00	0.11	0.00	0.0054
Fe K	6.398	4.33	0.65	1.49	4.3821
As L					
Total		100.00		100.00	

(b)

Acquisition Parameter
Instrument : 7600F
Acc. Voltage : 10.0 kV
Probe Current: 1.00000 nA
PHA mode : T3
Energy Range : 0 - 20 keV

Figure 4.17: (a) SEM Images of *Haor* Soil stabilized with 8.5% Fly Ash; and (b) Elemental Analysis of *Haor* Soil stabilized with 8.5% Fly Ash

4.3 Small Scale Revetments

Four glass models constructed for wave action propagation purposes (BM, VM, VFM and VFGM) where vetiver tillers were allowed to grow for 172 days, afterwards submerged for 5 days and then wave action was provided to simulate the actual situation of *haor* region during monsoon period and flood. The rainfall and temperature condition within these six months mentioned in Chapter Three indicates that vetiver tillers can grow excellent within this weather.

4.3.1 Growth of Vegetation

Measurements were taken of shoot and root length of the vetiver tillers, as shown in Figure 4.18. Figure 4.19 shows the growth performance of vetiver tillers of 172 days age for the three wave tolerance models.

Figure 4.18: Measurement of Vetiver Tillers of Three Models (VM, VFM, VFGM)

At the beginning, only 3 tillers were sown in one point, which increased to 13, 31 and 28 tillers for VM, VFM, and VFGM, respectively. The root of the tillers reached up to the bottom of the models, and it also formed a matrix with the other tillers in the vicinity. After submergence creation of the four models, the condition of vetiver tillers were similar as before, and no tillers were uprooted and washed away due to wave action. From the growth study, it can be observed that the growth of vetiver for VFGM is the maximum, because the tillers got more nutrients to grow for fly ash, and for JGT, the moisture was preserved with soil when watering was applied. The root of the tillers formed a reinforcing system with soil, which prevented the soil from washing away. So, soil loss was found less where the root matrixes were in a large scale. The shoot matrix also helped to protect the soil from washing away against erosion. The larger the canopy size, the less wave action could hit upon the soil and prevented it from mass movement. The canopy of vegetation (aboveground portion of plants, formed by the collection of individual plant crowns) of all models were measured to determine the total soil area covered by the area. The percentages of vegetation cover area with slope surface area of the three models are shown in

Figure 4.20. The calculation and schematic diagrams of vetiver canopy are shown in Appendix B.

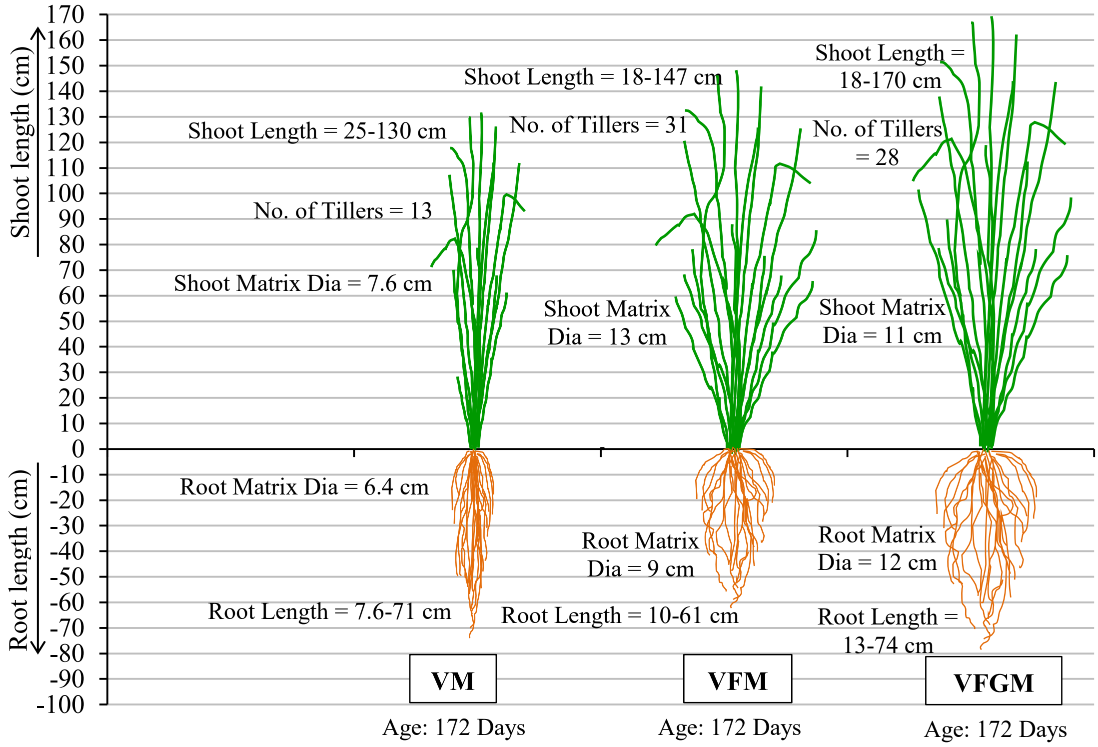


Figure 4.19: Comparison of Vetiver Growth of Wave Tolerance Models

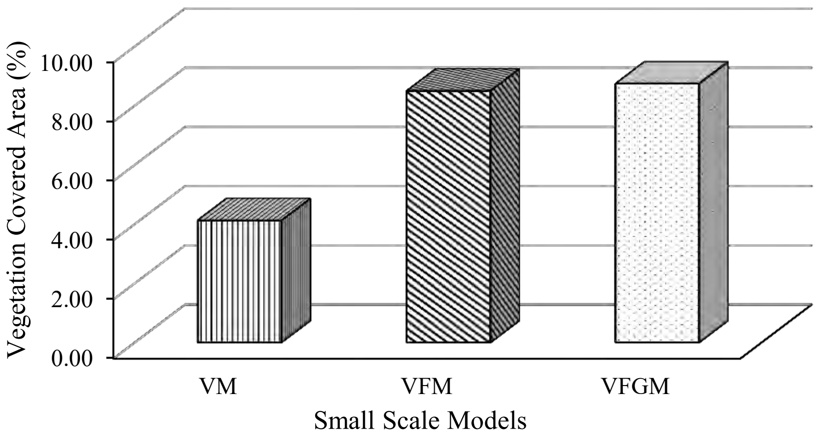


Figure 4.20: Surface Area Covered by Vegetation in Small Scale Models

4.3.2 Wave Tolerance of Small Scale Revetments

Figure 4.21 shows the slope breaking pattern for the four models. The failure pattern was different for the four models which show how the top soil movement occurred due to wave action. Though the top soil erosion occurred for the four models, the slopes were more intact with more protection along with the depth of soil.

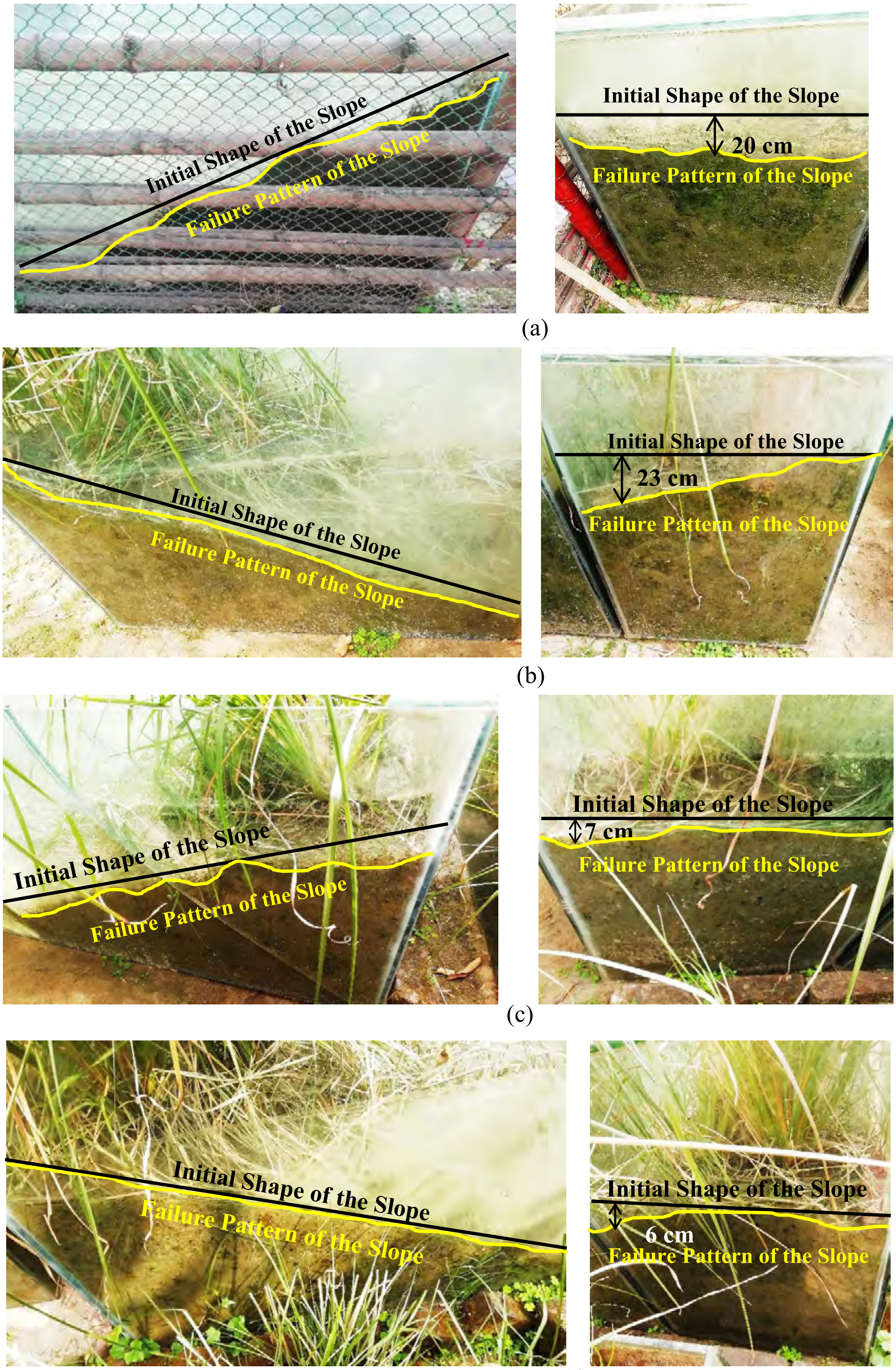


Figure 4.21: Photographs of Slope Deviation due to Wave Action of: (a) BM; (b) VM; (c) VFM; and (d) VFGM

The wave action propagation was continued up to breaking of the slope, which indicates the initial time of loosening the chunks of soil of the slopes by visual interpretation. From the reduction of water level, it represents the percolation and infiltration capability of the models. After 5 days, water infiltrated by 5 cm within the models with no fly ash (BM and VM), where the model with fly ash (VFM) reduced the seepage throughout the soil. Only 0.2 cm percolation was observed for the model with protection of both fly ash and JGT (VFGM), which indicates the moisture preservation of this model.

Table 4.9: Outcomes from Submergence and Wave Action Generation

Model Name	Water Level Reduction after Submergence (cm)	Wave Height (cm)	Wave Velocity (m/s)	Initiation Time of Water being Turbid (sec)	Sediment Ratio in Water (w/w) per 250 mL
BM	5	5-20	0.2-0.3	5	0.019
VM	5			36	0.018
VFM	2.5			47	0.015
VFGM	0.2			63	0.013

Usually the velocity of flow remains from 1 to 2 m/s in the *haor* region of Bangladesh. As small scale models, wave propagation of a height of 5~20 cm and velocity of 0.2-0.3 m/s was possible to provide. The turbidity initiation time of Table 4.9 indicates the starting period when soil started to mix with clean water. At that time, 250 ml mixture of soil and water was collected, and the soil-water ratio was calculated and tabulated as sediment ratio. From Figure 4.22 it is visible that the model without any type of protection (BM) broke quickly with a huge soil loss. The model with vetiver (VM) sustained 15 times higher with 19% less soil loss than that of BM. The model with *haor* soil, 8.5% fly ash and vetiver tiller (VFM) broke 28 times later with 29% less soil loss, and model with *haor* soil, 8.5% fly ash, JGT, and vetiver tiller (VFGM) broke 43 times later with 67% less soil loss than that of BM.

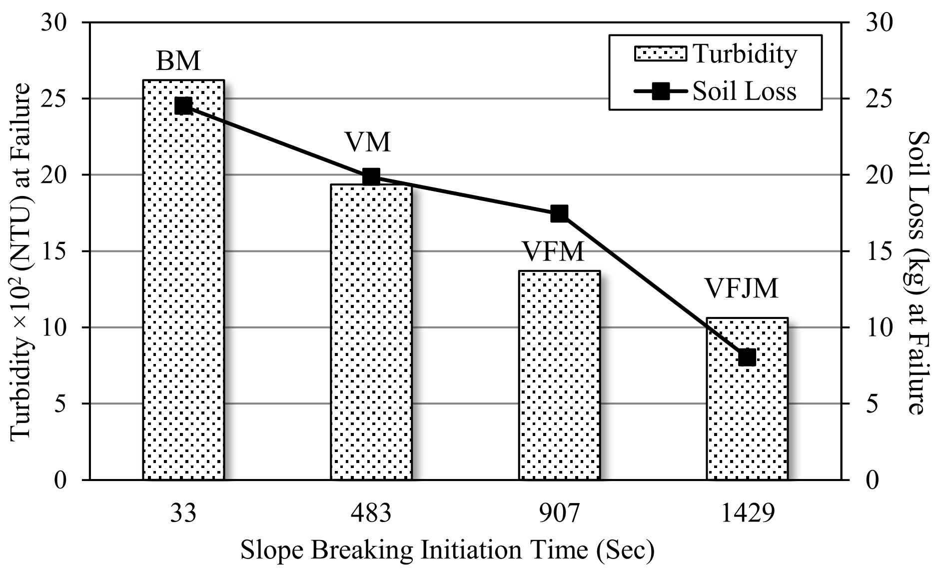


Figure 4.22: Soil Loss and Actual Turbidity of the Models at Failure

Turbidity was measured for the four models by turbidity meter to measure the transparency of water due to the presence of soil particles. The soil and water mixture was collected during the slope breakdown, and 10 ml mixture was diluted with 40 ml distilled water to measure the turbidity by turbidity meter. The results are shown in Figure 4.22.

These imply VFGM as the most stabilized small scale revetment model. After wave generation the damage type was observed as minimal in case of VFGM. It is found that the degree of increasing protection measures increased positive impact on slope protection, which fulfilled the objectives of the study.

4.4 Field Performance

To evaluate the performance of vegetated revetment used in field for road slope protection, embankment and village protection in *haor* areas and simulating the model study outcomes to study the performance of ecological revetment against wave action and submergence, five *haor* districts were visited. The performances of ecological revetment by bio-engineering method is deliberated and outlined in this article.

4.4.1 Soil Erosion Estimation

In every year, erosion is occurred in *haor* region due to surface erosion caused by rainfall and wave action. According to weather data and average annual rainfall (mm) of *haor* districts, soil loss was measured without any type of protection according to USLE (mentioned in Equation 2.1) to determine the rainfall erosion severity of this region. The estimated soil loss amount and erosion category is shown in Table 4.10. The details calculation is shown in Appendix C.

Table 4.10: Soil Loss in *Haor* Region due to Surface Erosion (According to USLE)

District	*Haor* Type	Estimated Soil Loss without protection (tons/(acre)(year))		Erosion Category*
		Silty Sand	Sandy Silt	
Brahmanbaria	Shallow	82	152	Very high
Habiganj	Mid-depth	99	184	Very high
Kishoreganj	Deep	90	167	Very high
Netrokona		103	193	Very high
Sunamganj		130	242	Very high

*(*Tiruneh G.and Ayalew M., 2015)*

From Table 4.10, it is observed that without any type of protection, the erosion measure is very high in these *haor* areas just only for rainfall erosion. So the combined effect of rainfall erosion and wave action turns huge for these areas by washing away the homestead lands, which urges the necessity of sustainable and compatible protection systems to protect the infrastructures of these areas.

4.4.2 Performance of Revetments

The five *haor* districts were visited to monitor the performances of four bio-engineered revetment types (Type I, II, III, IV) against wave fluctuation, submergence and wave action. The details of the design types are described in Chapter Three.

Type I

The main required materials for Type I are treated bamboo and chaliya grass. This type was not implemented in any part of *haor* region, as unavailability of chailya grass and treated bamboo is a major issue for construction. Bamboos have to be treated prior installation which ensures the longevity of it under inundation, as untreated bamboo is durable for maximum 1-2 years only. The durability of bamboo can be increased up to 20 years with treatment and seasoning. But chailya grass is not efficacious in case of preventing soil from erosion. So, during *afal* (wave height 4-8 m), soil erodes with grass and soil, and only bamboo cannot mitigate it. In case of the places where bamboo is not locally available, transportation cost become comparatively high. There is also scarcity of land for bamboo treatment in case of village islands in deep *haor*, surrounded by water. This type can be applied in the low *haor* zone with low water level and low wave actions, and Vetiver, Ikhar or other similar plants can be planted instead of chailya grass for higher protection.

Type II

The main required materials for Type II are vetiver and JGT. This bio-engineering protection was implemented in two sites of shallow and mid-depth *haor* region, Brahmanbaria and Habiganj. In Brahmanbaria, the revetment was maintained properly by caring and watering of the tillers, which resulted to excellent performance of road slope protection, and slope sustained without major structural damage near high water body, (*Kaizzor beel* and *Titas* River). This site survived three monsoon periods, with submergence and high water level, but no wave actions. Growth of vetiver has been found well at this site (Figure 4.23a).

(a) (b)

Figure 4.23: Photographs of Protection Type II; (a) Bancharampur, Salimabad Brahmanbaria; and (b) Bogir *Killa*, Baniachong, Habiganj

From the structural point of view, road shoulder lengths were found insufficient, which catalyzed fragile condition of slopes due to traffic loads. Figure 4.23(b) shows the condition of another implementation of Type II, a *killa* in Habiganj district. In this site, a rare number of vetiver tillers were found, so soil was easily washed away and the submergible road condition is vulnerable. This site also survived three monsoon periods with submergence, but the absence of vetiver shows the differences of slope condition. Regular trimming of vetiver shoots is required up to 30.5 cm height from the base in dry season instead of burning down, which can help local people economically (by selling fodder, fuel) and in case of safety issues. Jute geotextile (JGT) should be installed prior to plantation to prevent early soil erosion, and slope of roads and village islands should be constructed properly with proper compaction, avoiding sand fillings. Not only the slopes but also the road shoulders should be protected by plantation of vetiver grass along the shoulder.

Type III

The main required materials for Type III are vetiver, CC hollow blocks and JGT. This design type was implemented in most part of *haor* region, shallow, mid-depth and deep *haor* zone. Growth of vetiver has been found excellent in every location, which indicates that vetiver can grow easily in *haor* soils with no addition of fertilizers. Figure 4.24 shows two contrast examples of the application of Type III in Brahmanbaria district, which is categorized as shallow depth *haor* zone.

(a) (b)

Figure 4.24: Photographs of Protection Type III; (a) Kalikaccha, Sarail, Brahmanbaria; and (b) Modhupur, Ashuganj, Brahmanbaria

At Kalikaccha, Sarail, Brahmanbaria (Figure 4.24a), vetiver tillers were not maintained properly. As a results, no bonding with soil and protection system resulted in loosening the CC blocks, which eventually lead the slope to fail within a very short time. This site faced 4 monsoon periods, with no wave action and water fluctuation, but only rainfall and surface erosion. Whereas the location denoted in Figure 4.24(b), survived from three monsoons, with wave action, water level fluctuation and also submerged condition, as this site is located beside a branch of the *Meghna* River. For proper maintenance of the ecological revetment, the road slope was found more intact in Modhupur than that of Kalikaccha. In Figure 4.25, the condition of a location of Habiganj is shown, which presents the condition of road slope just after plantation, and the condition after facing a flood. This site is situated beside a river named Barak. Figure 4.25(a) shows the site where slope preparation work and vetiver plantation was completed just before 20 days ago. As the plantation was done in dry season the tillers grew properly. When rainfall and flood occurred, the tillers protected the overall slope by preventing the CC blocks and soils from washing away, which can be observed from Figure 4.25(b).

(a) (b)

Figure 4.25: Photographs of Protection Type III at Vatipara, Baniachong, Habiganj; (a) 20 Days after Plantation (26th January 2019); and (b) After Facing One Flood (11th November 2019)

(a) (b) (c)

Figure 4.26: Photographs of Protection Type III at Chowganga, Itna, Kishoreganj; (a) Slope Condition after Facing One Monsoon; (b) after Facing Two Monsoons; and (c) Slope Condition by Protection with Solid Blocks

Figure 4.26 shows three photographs of same locations of Itna, Kishoreganj, which is a deep *haor* zone and situated beside a river named *Amader Nadi*. The first photograph was taken at 8th March 2019, when the slope was found intact, as the excellent growth of vetiver protected the slope from failing. Figure 4.26(b) shows the slope condition at 8th February 2020, where the vetiver tillers are trimmed and well organized, so even though after facing one more flood, the slope condition was still good. Whereas, Figure 4.26(c) shows the slope condition at the same road, that was constructed by solid blocks. At the same time and after facing similar climatic conditions, the ecological revetment by Type III sustained very well, where the traditional practices by solid blocks made the slope condition vulnerable.

Figure 4.27(a) shows the different socio-economic aspects of vetiver tillers. This magical vegetation not only provides environmental friendly, cost effective and a compatible solution for slope protection, but also supports the locality economically by selling trimmed vetiver shoots as fuel or fodder. Figure 4.27(b) shows a village island of Kishoreganj, which is surrounded by the *Singua* River, where the villagers planted vetiver tillers to protect the homestead lands by their own, and also developed a nursery in their house premises. This village survived from three monsoon period, facing water fluctuation, submergence and high wave action (wave height of 3 m).


(a)


(b)

Figure 4.27: (a) Trimmed Vetiver Selling for Fuel and Fodder; (b) Slope Protection with Vetiver by Villagers in Kamalpur, Nikli, Kishoreganj

Figure 4.28(a) presents a village island protection work in Hayatpur, Khaliajuri, Netrokona, where the block holes were sealed off by mortar instead of planting vetiver. The slope surface was filled by sandy soil, and the slope failed by loosening blocks easily as there was no interaction within the protection system and the soil. This site faced three monsoons, whereas a vetiver source was found at the same village which also faced three monsoon periods with the similar climatic conditions. The vetiver source is surrounded by the *Surma* River, which becomes fully submerged during flood, and wave action is also prominent here. The growth of the tillers are found well, so the road condition is also good as shown as Figure 4.28(b). So, raising more social awareness about ecological revetment system is requisite.


(a)


(b)

Figure 4.28: Site Condition of Hayatpur, Khaliajuri, Netrokona; (a) Slope Condition of the Village Island; (b) Well Condition of the Vetiver Source


(a)


(b)

Figure 4.29: Photographs of Protection Type III; (a) Meghna Natunpara, Derai, Sunamganj; and (b) Kachua, Derai, Sunamganj

Figure 4.29(a) shows the slope condition of Meghna Natunpara village island, Derai, Sunamganj. This village island survived from two monsoons, where inundation occurred up to 1.8 m height from the toe of the slope, and wave action occurs from south-east direction during monsoon. Nevertheless, the growth of vetiver tillers and the slope condition is excellent, and slope failure did not happen, as vetiver tillers were planted and the slope was maintained properly. Figure 4.29(b) shows the Kochua village island condition of the same Upazila and district, which is situated beside the *Dahuk* River. At this site, flood occurred just after placing CC hollow blocks in April 2019, before plantation of tillers in this village slope. Consequently, blocks got unattached to soil due to no plantation of tillers. In this type of cases, it would be better to plant only vetiver without CC blocks, so at least the soil would be prevented from washing away and erosion could be minimized.

For this protection type, the initial design step is to compact soil properly, as not compacted sufficiently soil filling under the CC block caused bearing failure in critical places. In case of vegetation, regular trimming of the vetiver shoot can be accommodating for local people by socio-economic aspect and also it will ensure proper growth of the roots. Plantation of vetiver should be done where holes are open instead of sealing off with mortar. A climber named *Assamlata* is found which straggles over vetiver tufts and other vegetation, and seriously retard their growth, so this type of climbers needs to be removed.

In case of sandy soil, slope should be at least 1:2 (V:H) to withstand. But land scarcity is a big problem in *haor* areas, so it is requisite to maintain the slope ratio as minimum 1:1.5 (V:H), otherwise protection systems become less sustainable. In case of rural roads, shoulder should be maintained properly and can be covered with vegetation. Jute geo-textile (JGT) is recommended to use as filter and early protection of slope instead of synthetic geo-textile, and it should be punched properly to propagate the roots of vegetation within soil properly.

Interlocking CC blocks have structural difficulties at the time of constructing the slopes, so this type of blocks should be revised and redesigned as square shaped hollow blocks. Mix ratio of CC blocks have been found insufficient in many places, which is suggested to be at least 1:2:4. Thickness of the CC blocks should be at least 100 mm in case of shallow and mid-depth *haor*, and 150 mm in case of deep *haor*s according to the LGED officials and field engineers. Stair system should be constructed at a regular interval of the slope which ensures undisturbed movement of human and animals.

As weather is irregular in *haor* areas, implementation of the protection system in due time is difficult, so the grasses cannot take enough time to grow. The cattle also feed on newly borne vetiver tillers. So, proper maintenance is very much required, like fencing and engaging people to observe the site for at least 3 months with appropriate wages. Nursery should be developed and prepared at least 120 days prior to plantation which should be on raised land and with sufficient rain protection cover. In harvesting seasons, finding and engaging labors in slope protection works is difficult. In case of emergency situation, when time is limited for construction and labors are difficult to find, contractors and specialists are required to engage and the protection work should be granted before one year of the construction.

Type IV

RCC pole and vetiver grass are the main materials required for design Type IV. This system can be applied in the acute sections of deep *haor* zone with high water level and high waves up to 4-8 meters, but this type is economically not feasible in case of construction compared to other bio-engineered protection measures. In case of placing RCC poles on slopes, a grade beam is needed to be constructed under the poles. But during rainfall and flooding, water enters through the slope area and thus soil erodes. Eventually, the grade beam shifts downward and cause huge settlement. From these different aspects of construction difficulties and as a cost intensive measure, this type was not implemented in any part of *haor* region.

4.4.3 Growth of Vegetation in *Haor* Districts

By observing survival of the grasses, condition of slope and determining shoot and root length of the tillers, growth of vetiver tillers is found excellent in all districts. Figure 4.30 shows vetiver measurements in *haor* districts, and Figure 4.31 presents the growth data of vetiver tillers in Brahmanbaria.

Figure 4.30: Measurement of Vetiver Grass at *Haor* Districts

In Brahmanbaria, the range of maximum of shoot length of vetiver was found as 122-178 cm after 4 years, and 66-168 cm after 2-3 years. The tillers could not be uprooted properly, so actual measurement of root was not possible. The maximum root length possible to uproot was found 36 cm.

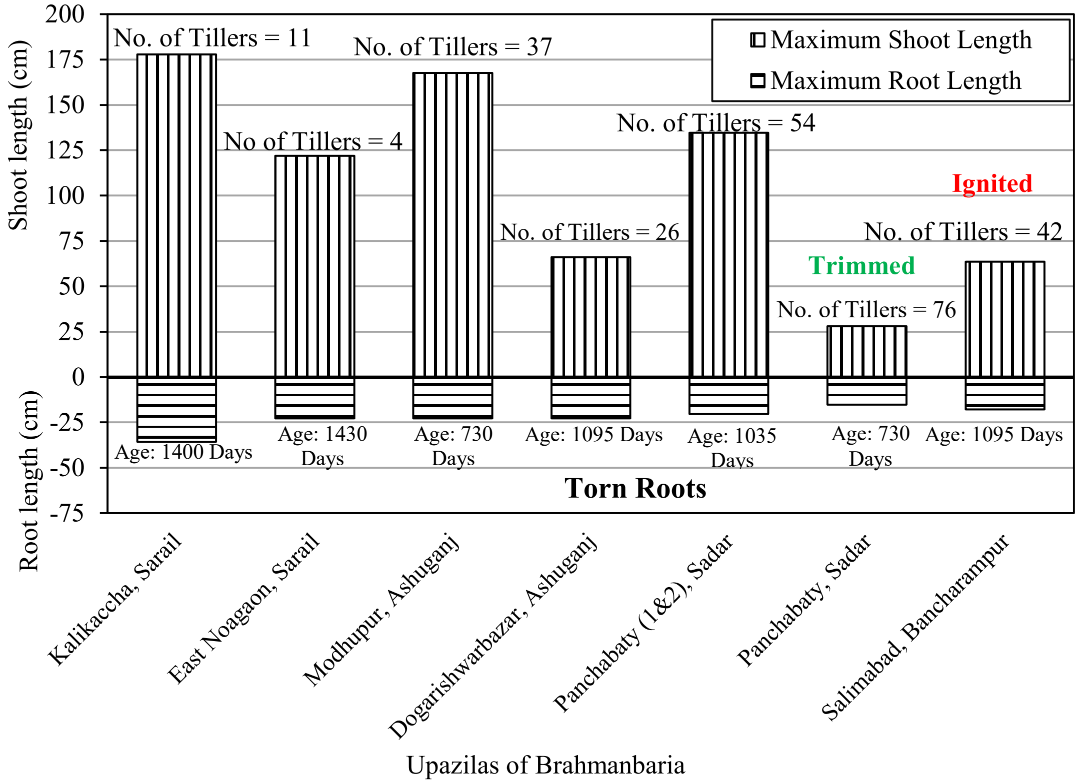


Figure 4.31: Growth of Vegetation in Brahmanbaria (Shallow *Haor*)

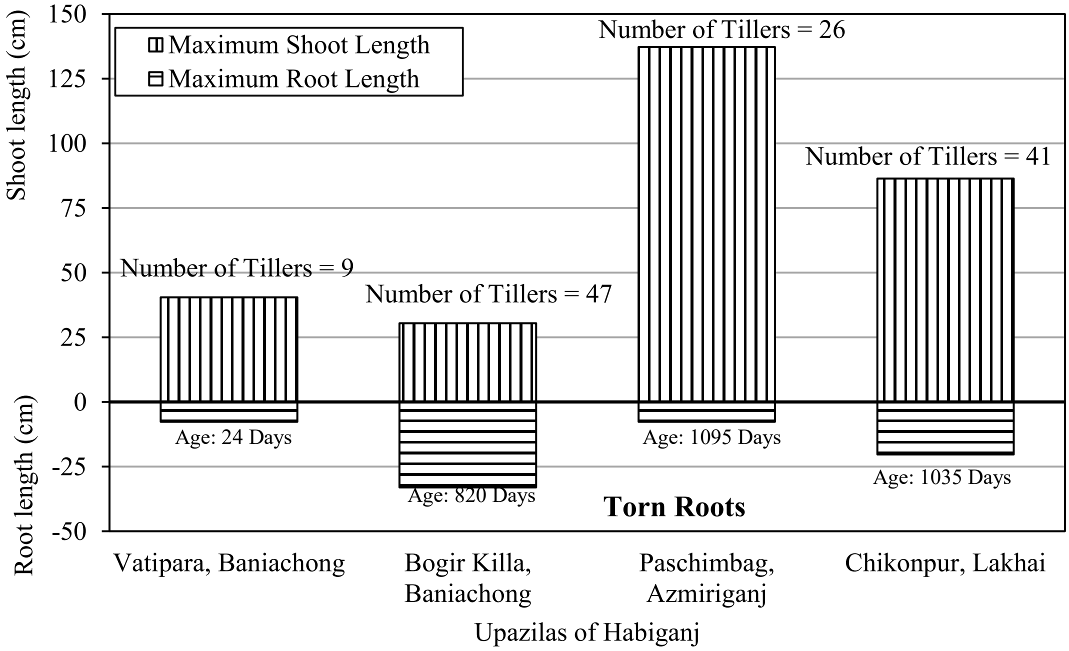


Figure 4.32: Growth of Vegetation in Habiganj (Mid-depth *Haor*)

Figure 4.32 and Figure 4.33 present the growth data of vetiver tillers in Habiganj and Kishoreganj. In Habiganj, the range of maximum of shoot length of vetiver was found as 86-137 cm after 3 years. At Bogir *killa*, very few numbers of vetiver were found poor site maintenance was observed, so the tillers did not grow properly. Root length of vetiver was possible to measure up to 33 cm. In Kishoreganj, the range of maximum of shoot length of vetiver was measured as 107-132 cm. The actual measurement of root was not possible for not uprooting the tillers due to strong bondage with soil. The torn root length of the tillers was measured up to 23 cm. The ages of the tillers were 1-4 years for Kishoreganj.

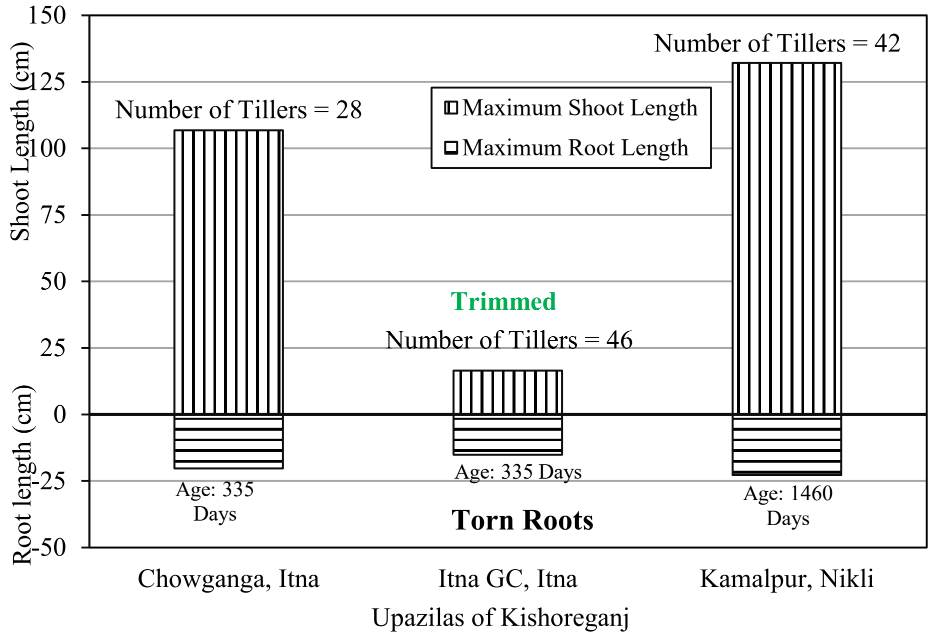


Figure 4.33: Growth of Vegetation in Kishoreganj (Deep *Haor*)

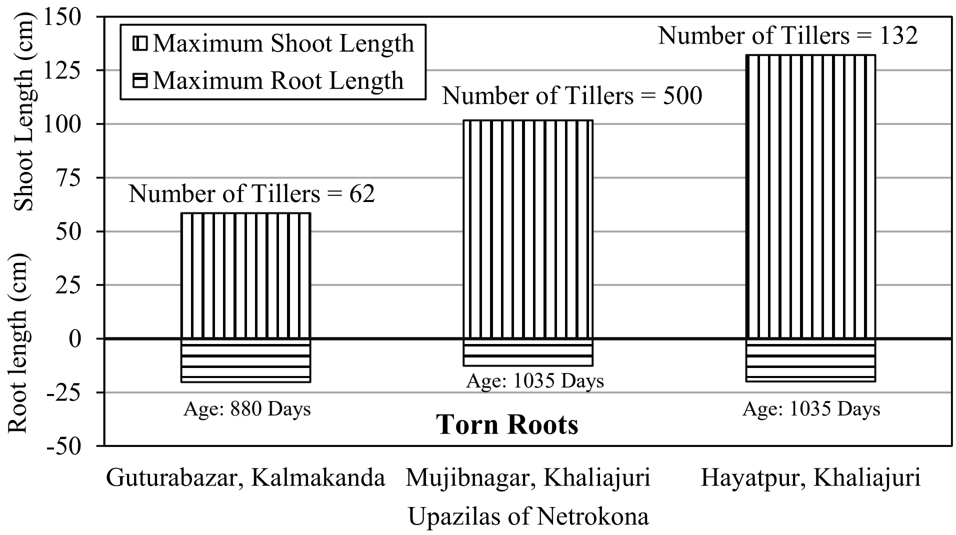


Figure 4.34: Growth of Vegetation in Netrokona (Deep *Haor*)

Figure 4.34 and Figure 4.35 present the growth data of vetiver tillers in Netrokona and Sunamganj. In Netrokona, the maximum of shoot length of vetiver was ranged within 58-132 cm for 2-3 years. In Sunamganj, maximum of shoot length of vetiver was found as 89 cm after 1.5 years, and the root length was possible to measure up to 28 cm. The details measurement data is shown in Appendix D.

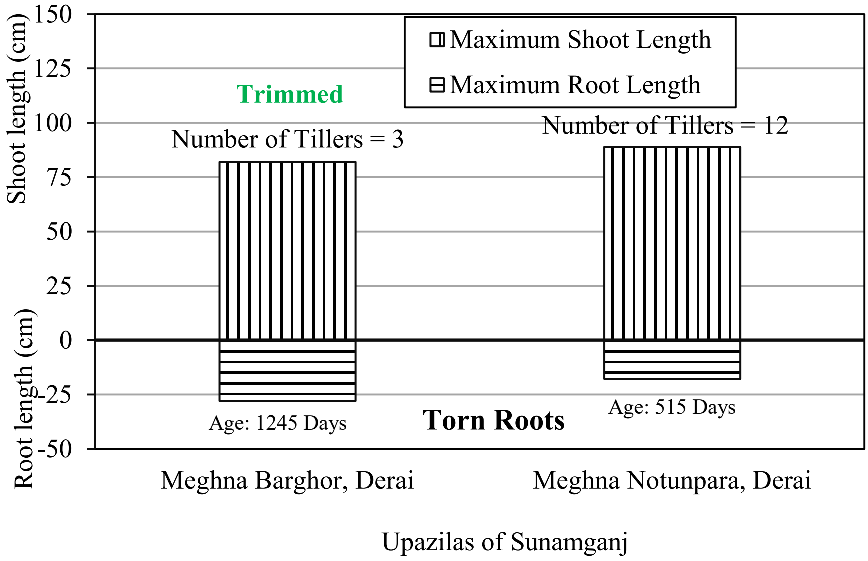


Figure 4.35: Growth of Vegetation in Sunamganj (Deep *Haor*)

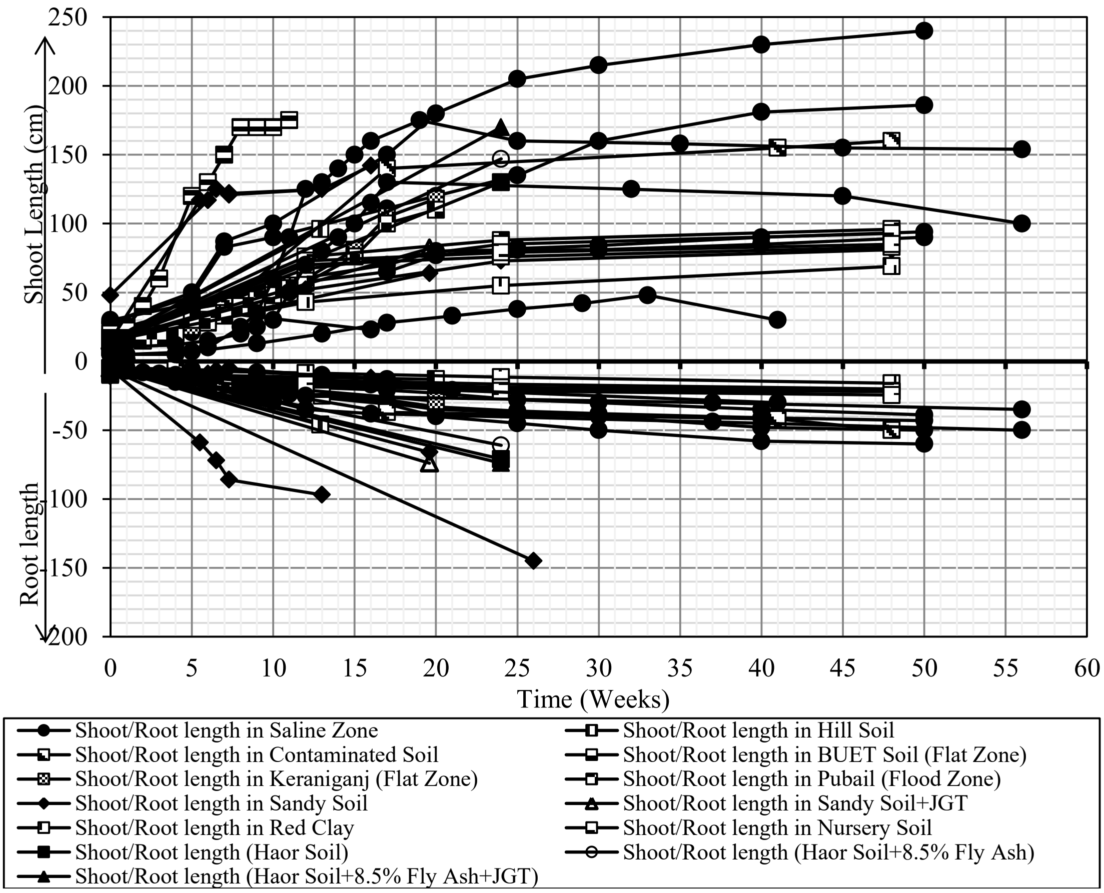


Figure 4.36: Comparative Pattern of Vetiver Growth in Different Studies

Figure 4.36 shows the comparative study of the growth performances of vetiver by other researchers all over the country including the model performances from this study. As the tillers were unable to be torn from field in *haor* areas, the growth study is not included in this comparison. This figure will help to idealize the growth pattern of vetiver in all types of soil in Bangladesh depending on the climatic factors.

4.4.4 Cost Estimation

According to the rate schedules of LGED for Cumilla, Sylhet, Narayanganj and Mymensingh zones (LGED, 2019), cost analysis for construction materials and total cost estimation including labor, guide wall and maintenance was done. The details calculations of the cost analysis of the four different types of ecological revetments are shown in Appendix E. Table 4.11 shows the total construction cost, including material, labor and maintenance cost.

Table 4.11: Comparison of Total Cost of Different Protection Methods per m^2

District	Total Cost in BDT for Slope Construction (per m^2)				
	Type I	Type II	Type III	Type IV	CC Solid Block+SGT
Brahmanbaria	305	47	990	6258	3493
Habiganj	305	47	923	6272	3355
Kishoreganj	292	47	977	6161	3440
Netrokona	292	47	983	6191	3594
Sunamganj	305	47	923	6272	3355

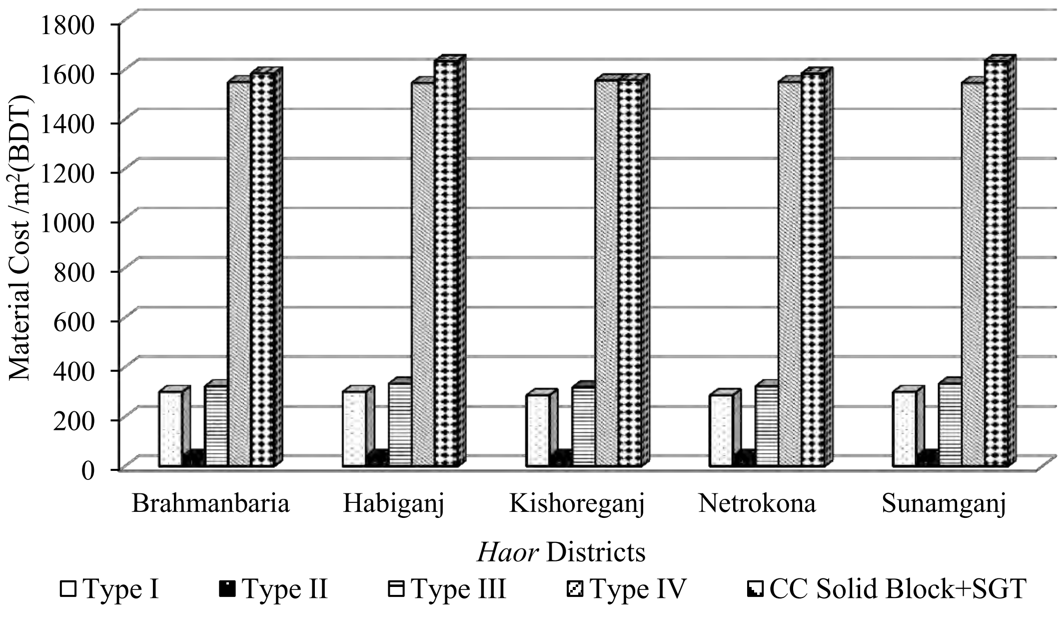


Figure 4.37: Material Cost Comparison per m^2

Figure 4.37 shows the cost comparison of the construction materials. From field study, Type II and Type III are found suitable in case of sustainable, environmental friendly and compatible solution. In case of cost benefit analysis, the graphs and figures show that, in case of slope protection and cost effectiveness, both Type II and

Type III are efficacious than traditional practices of slope protection by solid blocks. Type II and III are found subsequently 99% and 73% low-cost than that of the traditional practices of slope protection by CC solid blocks. Although design Type I is cheaper comparing to the conventional practices, it is found unfeasible for *haor* infrastructure protections by means of construction and transportation. Design Type IV is not only inapplicable in *haor* areas, but also a costly protection type.

From the topographical study, not only in *haor* areas, ecological revetment can be applied throughout the whole country as well as the world with similar climatic condition and sub-soil characteristics. Soil bio-engineering methods can be applied in tropical, subtropical and temperate zones whereas the plants are able to grow well. This technology can be applicable for protection of road sector and slope beside river or water body facing wave action and submergence.

4.5 Summary

Performances of ecological revetment by bio-engineering method were evaluated through laboratory investigations, small scale models and field trials in *haor* areas. Results obtained from the investigations are summarized below:

(i) Index properties, shear strength parameters, permeability properties, microscopic analysis and nutrient contents were tested of 23 *haor* soils and 1 stabilized soil from models collected from 5 *haor* districts. *Haor* soil type is classified as silty sand/sandy silt, and most of the soils are acidic. F.M. of the soils are found within 0.55-1.57, and the angles of internal friction vary between 27^{o} and 36^{o}. The coefficient of permeability (k) of the soils ranges within 8.05×10^{-5}-1.16×10^{-3} cm/sec, which specifies very low to low degree of permeability of *haor* soils. From nutrient tests, it was estimated that Phosphorus, Potassium and Sulphur contents are adequate in *haor* soils, but the soils lack of maximum essential nutrients, i.e., Nitrogen, Organic Matter, Boron, and Zinc. From the SEM and EDS analyses, it is observed that the spherical particles of fly ash fill up the voids of the irregular angular *haor* soil particles which consequently increase soil density.

(ii) From the performances of the model study it is found that, VM sustained 15 times longer period with 19% less soil loss than that of BM, and VFM sustained 28 times greater duration with 29% less soil loss, and VFGM broke 43 times later duration with 67% less soil loss than that of BM. Turbidity was found as 2620, 1935, 1370, and 1060 NTU for BM, VM, VFM and VFGM, respectively. It implies that VFGM is the most stabilized revetment model.

(iii) Growth of tillers is excellent in both model and field study, which ensured that vetiver can grow well in *haor* soil without fertilizers. The maximum shoot and root length of vetiver in the model soils was measured subsequently as 130–170 cm and 61–74 cm in 172 days. Within the same period, the number of tillers per point grew between 13 and 31 per point from 3 tillers. The percentages of covered area by vegetation were determined as 4.1%, 8.5% and 8.7% for VM, VFM and VFGM, respectively. The maximum shoot length and number of vetiver tillers from the selected field trial locations were found within 58–178 cm and 42-500 for 2-3 years, respectively. It was possible to measure up to a maximum root length of 36 cm of the tillers. Some vegetation such as Ikhar, Dholkolmi, Koroch, Bonnya Hijal, Pitali, can be planted with vetiver for a holistic approach of ecological revetments in *haor* areas.

(iv) Design Type II and III are found as the most feasible and cost-effective as ecological revetments among four design schemes of Type I, II, III and IV to protect the *haor* infrastructures against submergence and wave action. The cost estimation indicates that design Type II and III are 99% and 73% cheaper than that of CC solid blocks. It is observed from the field trials that proper compaction of soil, slope ratio according to the soil type, mix ratios of CC blocks are found as important parameters for slope stabilization. Mix ratio of CC blocks needs to be increased to at least 1:2:4 and thickness of the CC hollow blocks can be 100-150 mm depending on the depth and wave action of *haor*. Punched jute geo-textile (JGT) is recommended to use instead of synthetic geo-textile for appropriate propagate the roots of vegetation within soil.

An advantage of dense green cover is by protecting bank surface from erosion which also prevents soil mixing into the water and keeping the water clean, which is also found from model study by performing turbidity test. From the above discussions, ecological revetment system by bioengineering method can be said as sustainable, eco-friendly, cost effective and compatible solution for protecting *haor* infrastructures against submergence and wave action.

Chapter Five
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The overviews and observations of the study to evaluate the performance of ecological revetment in *haor* areas based on the synopsis of model study, field trials and experimental program are concluded below.

(i) *Haor* soils are classified as grey/brown silty sand/sandy silt and acidic to alkaline. Specific gravity (G_s) of *haor* soils range vary between 2.48 and 2.74, natural moisture content range within 9.4%-16.2%, and F.M. are found as 0.55-1.57. The angles of internal friction of the soils vary between 27^o and 36^o. The coefficient of permeability (k) was determined within 8.05×10^{-5} - 1.16×10^{-3} cm/sec, which designates very low to low degree of permeability of *haor* soils. Phosphorus, Potassium and Sulphur contents are found adequate in *haor* soils, but the soils lack of maximum essential nutrients, i.e., Nitrogen, Organic Matter, Boron, and Zinc. From the microscopic analyses of the model sample it is observed that the spherical fly ash increase soil density by filling up the voids within the irregular angular soil particles.

(ii) Without any accumulation of fertilizers or composts, vetiver grows well in *haor* soil. In 172 days the maximum shoot and root length of vetiver grown in the model soils were measured within 130–170 cm and 61–74 cm. In the same age, the number of tillers increased to 13-31 nos. per point from 3 tillers. The percentages of vegetative covered area are determined as 4.1%-8.7% in the three models, VM, VFM and VFGM. It is found that the maximum shoot length and number of vetiver tillers from the field trials range within 58–178 cm and 42-500, respectively in 2-3 years of age. For a sustainable ecological revetment to protect the *haor* infrastructures, some vegetation i.e., Ikhar, Dholkolmi, Koroch, Bonnya Hijal, Pitali, can be planted along with vetiver. From the study in field trial locations it is found that, a climber named "Assamlata" is required to remove if found as it hinders the growth of slope protective vegetation.

(iii) The model investigations show that VM sustained by 15 times higher duration with 19% less soil loss than that of BM. VFM sustained 28 times greater duration with 29% less soil loss and VFGM sustained 43 times longer duration with 67% less soil loss than that of BM. By means of turbidity and damage type of slope, VFGM can be concluded as the most stabilized small scale revetment model among the four models.

(iv) Type II and III are found as most suitable and cost-effective as ecological revetments among four design schemes of Type I, II, III and IV according to the *haor* perspectives. Cost comparison of the ecological revetments and traditional methods indicate that Type II and III are 99% and 73% cheaper than that of conventional practices by CC solid blocks. It is observed from the field trials that some important parameters i.e., proper soil compaction, adequate slope ratio, mix ratio and thickness of CC blocks, trimming of vetiver, fencing needs to be maintained to avoid sliding and bearing failure, and to get better performance in case of stability and protection against wave actions in *haor* areas.

From the overall research, it can be concluded that the current study will be useful for slope protection purposes in dynamic and adverse situations like *haor* areas as well as the similar topographic areas by ecological revetment in a sustainable, cost effective and compatible way.

5.2 Recommendations

This research was conducted for comparative study to design ecological revetment for protecting *haor* infrastructures of Bangladesh such as submerged road, village, killa, river bank. The studies that can be conducted in future in order to capture all the problems encountered in the field during the design and implementation of bioengineered slope stabilization are shown below.

(i) Tri-axial tests and consolidation tests can be conducted for better understanding of the strength deformation and compressibility behavior of the rooted soils.

(ii) In situ direct shear test, Standard Penetration Test (SPT), Dynamic Cone Penetrometer (DCP), compaction tests can be performed in field to quantify the added shear strength to the soil by the root.

(iii) Before wave action propagation, 5 days of submergence has been observed. Further study can be continued to observe the longevity of vetiver under submergence. Wave action can be applied for more cycles after model maintenance to determine the withstanding capacity of vetiver against wave.

(iv) Analysis for durability and sustainability can be done, i.e., finite and infinite slope stability model for estimating factor of safety, bearing capacity, sliding and overturning of rooted soil slopes.

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APPENDIX A
HAOR SOIL PROPERTIES

Haor Soil Properties

District	Site Name	Soil Color	Soil Type	G_s	% Course Sand	% Medium Sand	% Fine Sand	∑ % Sand	% Silt	F.M.
Brahmanbaria	Kalikaccha, Sarail	Grey	Sandy Silt	2.67	3.52	11.86	18.12	33.50	66.50	0.66
	East Noagaon, Sarail	Brown	Silty Sand	2.62	7.39	25.85	16.77	50.01	49.99	1.29
	Modhupur, Ashuganj	Brown	Silty Sand	2.61	2.05	7.64	73.41	83.10	16.90	0.93
	Dogarishwarbazar, Ashuganj	Brown	Silty Sand	2.56	1.71	5.90	76.09	83.70	16.30	1.06
	Panchabaty (1&2), B. Baria Sadar	Brown	Silty Sand	2.48	5.48	22.05	27.37	54.90	45.10	1.22
	Panchabaty, B. Baria Sadar	Brown	Sandy Silt	2.60	4.56	9.29	23.44	37.29	62.71	0.73
	Salimabad, Bancharampur	Brown	Silty Sand	2.72	6.41	11.94	50.55	68.90	31.10	1.10
Habiganj	Vatipara, Baniachong	Brown	Silty Sand	2.74	9.52	44.70	20.31	74.53	25.47	2.02
	Bogir Killa, Baniachong	Brown	Sandy Silt	2.68	0.32	1.18	33.20	34.70	65.30	0.18
	Paschimbag, Azmiriganj	Grey	Sandy Silt	2.68	5.88	8.52	12.01	26.41	73.59	0.69
	Chikonpur, Lakhai	Brown	Sandy Silt	2.60	1.58	8.79	36.03	46.40	53.60	0.51
Kishoreganj	Chowganga, Itna	Brown	Silty Sand	2.51	3.31	37.28	28.51	69.10	30.90	1.46
	Itna-GC Road, Itna	Grey	Sandy Silt	2.66	5.01	16.68	25.66	47.35	52.65	0.97
	Kamalpur, Nikli	Brown	Silty Sand	2.54	0.19	5.66	76.75	82.60	17.40	0.55
	Daulotpur, Nikli	Brown	Silty Sand	2.65	0.12	2.22	79.86	82.20	17.80	0.38
Netrokona	Guturabazar, Kalmakanda	Grey	Sandy Silt	2.75	6.28	13.37	10.15	29.80	70.20	0.85
	Janjailpara, Kalmakanda	Brown	Silty Sand	2.49	3.23	36.21	25.46	64.90	35.10	1.40
	Mujibnagar, Khaliajuri	Brown	Sandy Silt	2.72	4.57	5.92	25.51	36.00	64.00	0.58
	Hayatpur, Khaliajuri	Brown	Silty Sand	2.68	5.82	27.30	46.58	79.70	20.30	1.47
Sunamganj	Meghna Barghor, Derai	Brown	Silty Sand	2.56	2.85	26.71	22.03	51.59	48.41	1.10
	Meghna Notunpara, Derai	Brown	Silty Sand	2.68	6.09	36.44	17.98	60.51	39.49	1.57
	Kochua, Derai	Grey	Silty Sand	2.62	4.82	36.31	19.58	60.71	39.29	1.51

Model Soil Properties

Location	Model Name	Soil Color	Soil Type	G_s	% Course Sand	% Medium Sand	% Fine Sand	∑ % Sand	% Silt	F.M.
Ramrail, Brahmanbaria	BM, VM (Haor Soil)	Brown	Silty Sand	2.68	4.92	32.33	22.05	59.30	40.70	1.49
	VFM, VFGM (Soil + 8.5% Fly ash)	Greyish Brown	Silty Sand+Fly ash	2.55	5.48	30.13	20.59	56.20	43.80	1.36

APPENDIX B
VEGETATIVE COVER AREA

Vegetation Cover Area of Protected Slope Models after Six Months

Calculation of % Covered Area:

Model Name	Σa (cm)	b (cm)	Total Vegetation Covered Area of 10 Tillers, (cm^2)*	% of Surface Area Covered
VM	86.6	4	272	4.1
VFM	102	7	561	8.5
VFGM	104.9	7	577	8.7

**The covered area by vegetation was assumed as elliptical surface*

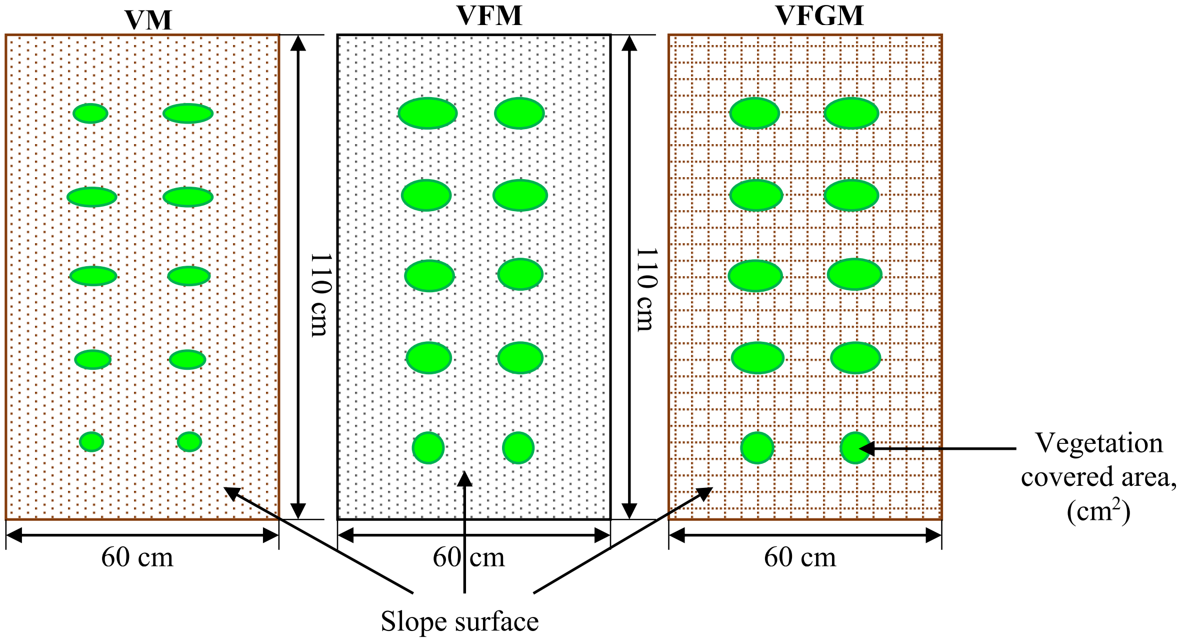


Figure: Schematic Diagram of Vegetative Covered Area on Slope Surface (According to True Scale)

APPENDIX C
SOIL LOSS ESTIMATION

Calculation of Soil Loss in Different Haor Districts of Bangladesh

Districts	Rainfall erosion index, R (100 ft×tons/acre×in/hr)	Soil erodibility factor, K (tons/acre per unit of R)		Slope length and steepness factor, LS	Vegetative Cover Factor, C	Erosion Control Practice Factor, P	Soil Loss, A (tons/(acre)(year))		Soil Loss, A (tons/(hectare)(year))		Category*
		Silty Sand	Sandy Silt				Silty Sand	Sandy Silt	Silty Sand	Sandy Silt	
Brahmanbaria	50.11163337	0.22	0.41	9.24360039	1	0.8	82	152	201	375	Very high
Habiganj	60.60517039	0.22	0.41	9.24360039	1	0.8	99	184	244	454	Very high
Kishoreganj	55.02350176	0.22	0.41	9.24360039	1	0.8	90	167	221	412	Very high
Netrokona	63.50763807	0.22	0.41	9.24360039	1	0.8	103	193	255	476	Very high
Sunamganj	79.91774383	0.22	0.41	9.24360039	1	0.8	130	242	321	599	Very high

(*Tiruneh G.and Ayalew M., 2015)

1. Rainfall erosion index

R (in MJmmha^{-1} h^{-1} year^{-1})= 81.5+0.38P (for 340<P<3500 in mm) (Jain, M.K. and Das, D, 2010)

Districts	R (in MJmmha^{-1} h^{-1} year^{-1})	R in (100 ft×tons/acre×in/hr)
Brahmanbaria	852.9	50.11163337
Habiganj	1031.5	60.60517039
Kishoreganj	936.5	55.02350176
Netrokona	1080.9	63.50763807
Sunamganj	1360.2	79.91774383

1 (100 ft×tons/acre×in/hr) = 17.02 (MJmmha^{-1} h^{-1} year^{-1}) (Foster et. al., 1981)

Districts	P in mm	Reference
Brahmanbaria	2030	https://en.climate-data.org/asia/bangladesh/chittagong-division/brahmanbaria-1012611/
Habiganj	2500	https://www.thebangladesh.net/rainfall-map-of-bangladesh.html
Kishoreganj	2250	https://en.climate-data.org/asia/bangladesh/rangpur-division/kishoreganj-969604/
Netrokona	2630	https://en.climate-data.org/asia/bangladesh/dhaka-division/netrokona-970055/
Sunamganj	3365	https://en.climate-data.org/asia/bangladesh/sylhet-division/sunamganj-970062/

2. Soil erodibility factor

From triangular nomograph to determine K, most of the haor soils are silty loam/sandy loam

For silty loam, K = 0.41
For sandy loam, K = 0.22
For very fine sandy loam, K = 0.41

(for <2% Organic Matter Content)

Reference: www.omafra.gov.on.ca/english/engineer/facts/12-051.htm

3. Slope length and steepness factor

$$LS = \left(\frac{65.41 \times s^2}{s^2 + 10,000} + \frac{4.56 \times s}{\sqrt{s^2 + 10,000}} + 0.065\right)\left(\frac{l}{72.5}\right)^m$$

s= 66.66666667 (for slope 1:1.5 (V:H)

l (in ft) = 12

m= 0.5

(0.2for slopes <1%, 0.3 for slopes 1 to 3%, 0.4 for slopes 3.5 to 4.5%, and 0.5% for slopes>5%

4. Vegetative cover factor

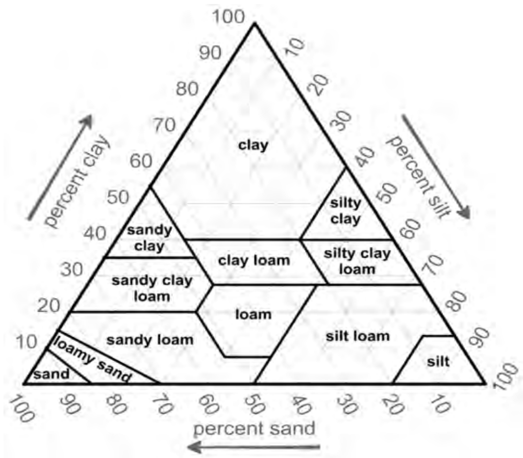
C factor for no vegetative cover =1.0

(Jackson, K. et. al., 1986)

5. Erosion control practice factor

P factor for Loose to 12 in depth = 0.8

(Jackson, K. et. al., 1986)



APPENDIX D
FIELD STUDY DATA

1.

Location	Sarail, Brahmanbaria	
Name of the site	Kalikaccha UP-Bariura Bazar Road, Part 1 and 2	
GPS	N24°3’20”, E91°8’51”	
Date of plantation/Construction	March, 2015	
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED	
Date of monitoring	14/01/2019	
Design Type	Type III, CC block (450×450mm) with hole (125mm dia) +stepped brickwall	
Investigation of Shoot	Sample minimum shoot length	35.6 cm
	Sample maximum shoot length	177.8 cm
	Overall range of shoot	35.6~177.8 cm
	Shoot/stem width	5 mm
	Diameter of the bush	71.1 cm
	No. of tillers grown in one point	11
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	35.6 cm
	Root matrix diameter	10.2 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Faded green
	Leaf color	Faded green
Other vegetation grown alongside		Mojjoa/Ikhor, Dholaguiya/Chikan, Telakucha, Kash, Durba, Kul/Boroi, Verenda,
Length of the vetiver planted strip		180 m
Length of the strip in which vetiver has grown well		18 m

2.

Location	Sarail, Brahmanbaria	
Name of the site	East Noagaon Village	
GPS	N24°5’27”, E91°8’5”	
Date of plantation/Construction	February, 2015	
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED	
Date of monitoring	14/01/2019	
Design Type	Type III, CC block (450×450mm) with hole (125mm dia)	
Investigation of Shoot	Sample minimum shoot length	38.1 cm
	Sample maximum shoot length	121.9 cm
	Overall range of shoot	38.1~121.9 cm
	Shoot/stem width	5 mm
	Diameter of the bush	40.6 cm
	No. of tillers grown in one point	4
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	22.9 cm
	Root matrix diameter	2.5 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Faded green
	Leaf color	Faded green
Other vegetation grown alongside		Mojjoa/Ikhar, Kash
Length of the vetiver planted strip		75 m
Length of the strip in which vetiver has grown well		20 m

3.

Location	Ashuganj, Brahmanbaria
Name of the site	Modhupur Temohoni – Lalpur GC Road
GPS	N24º0’31.79”, E90º59’26.32”
Date of plantation/Construction	January, 2017
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED
Date of monitoring	14/01/2019

Design Type	Type III, CC block (450×450mm) with hole (125mm dia)	
Investigation of Shoot	Sample minimum shoot length	35.6 cm
	Sample maximum shoot length	167.6 cm
	Overall range of shoot	35.6~167.6 cm
	Shoot/stem width	4 mm
	Diameter of the bush	12.7 cm
	No. of tillers grown in one point	37
Investigation of Root	Single root diameter	1.5 mm
	Sample maximum root length	22.9 cm
	Root matrix diameter	20.3 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green, Faded yellow
	Leaf color	Green
Other vegetation grown alongside		Durba
Length of the vetiver planted strip		180 m
Length of the strip in which vetiver has grown well		100 m

4.

Location	Ashuganj, Brahmanbaria
Name of the site	Dogarishwar Bazar Road
GPS	N24º0’6”, E91º0’38”
Date of plantation/Construction	February, 2016
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED
Date of monitoring	14/01/2019

Design Type	Type III, CC block (450×450mm) with hole (125mm dia) + Palisade wall	
Investigation of Shoot	Sample minimum shoot length	22.9 cm
	Sample maximum shoot length	66.1 cm
	Overall range of shoot	22.9~66.1 cm
	Shoot/stem width	4 mm
	Diameter of the bush	35.6 cm
	No. of tillers grown in one point	26
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	22.9 cm
	Root matrix diameter	15.2 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Brown, Faded yellow
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		200 m
Length of the strip in which vetiver has grown well		100 m

5.

Location	Brahmanbaria Sadar, Brahmanbaria
Name of the site	Panchabaty – Akhaura Bazar Road, Part 1 and 2
GPS	N23°52’47”, E91°8’28.61”
Date of plantation/Construction	20 March, 2016
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED
Date of monitoring	15/01/2019

Design Type	Type III, CC block with hole	
Investigation of Shoot	Sample minimum shoot length	25.4 cm
	Sample maximum shoot length	134.6 cm
	Overall range of shoot	25.4~134.6 cm
	Shoot/stem width	6 mm
	Diameter of the bush	38.1 cm
	No. of tillers grown in one point	54
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	20.3 cm
	Root matrix diameter	12.7 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		620 m
Length of the strip in which vetiver has grown well		Not continuous

6.

Location	Brahmanbaria Sadar, Brahmanbaria
Name of the site	Panchabaty – Akhaura Bazar Road
GPS	N23°52’38”, E91°9’20”
Date of plantation/Construction	January, 2017
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED
Date of monitoring	15/01/2019

Design Type	Type III, CC block (175×175 cm) with hole (75 mm dia)	
Investigation of Shoot	Sample minimum shoot length	10.2 cm
	Sample maximum shoot length	27.9 cm
	Overall range of shoot	10.2~27.9 cm
	Shoot/stem width	3 mm
	Diameter of the bush	17.8 cm
	No. of tillers grown in one point	76
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	15.2 cm
	Root matrix diameter	12.7 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		540 m
Length of the strip in which vetiver has grown well		110 m

Brahmanbaria

7.

Location	Bancharampur, Brahmanbaria
Name of the site	North west side bridge, Salimabad
GPS	N23°44’7”, E90°49’47”
Date of plantation/Construction	January, 2016
Nursery location of Vetiver tiller collection	Karaikandi (Brahmanbaria); Araihajar (Narayanjgonj)
Date of monitoring	15/01/2019

Design Type	Type II	
Investigation of Shoot	Sample minimum shoot length	15.2 cm
	Sample maximum shoot length	63.5 cm
	Overall range of shoot	15.2~63.5 cm
	Shoot/stem width	2 mm
	Diameter of the bush	38.1 cm
	No. of tillers grown in one point	42
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	17.8 cm
	Root matrix diameter	12.7 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green, Faded yellow
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		500 m
Length of the strip in which vetiver has grown well		Not continuous

Habiganj

1.

Location	Baniachong, Habiganj
Name of the site	Vatipara village, Baniachong
GPS	N24°27'25", E91°22'21"
Date of plantation/Construction	January 2, 2019
Nursery location of Vetiver tiller collection	Local
Date of monitoring	26/01/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (110mm dia)	
Investigation of Shoot	Sample minimum shoot length	12.7 cm
	Sample maximum shoot length	40.5 cm
	Overall range of shoot	12.7~40.5 cm
	Shoot/stem width	3 mm
	Diameter of the bush	5.1 cm
	No. of tillers grown in one point	9
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	7.6 cm
	Root matrix diameter	3.8 cm
	Sample minimum root length	3.6 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Brown
	Leaf color	Brown
Other vegetation grown alongside		Koroch
Length of the vetiver planted strip		80 m
Length of the strip in which vetiver has grown well		Not continuous

2.

Location	Baniachong, Habiganj
Name of the site	Bogir Killa, Kagapasha Union, Baniachong
GPS	N24°34'31", E91°23'57"
Date of plantation/Construction	October 2016
Nursery location of Vetiver tiller collection	Local
Date of monitoring	26/01/2019

Design Type	Vetiver with geo-textile	
Investigation of Shoot	Sample minimum shoot length	12.7 cm
	Sample maximum shoot length	30.5 cm
	Overall range of shoot	12.7~30.5 cm
	Shoot/stem width	3 mm
	Diameter of the bush	15 cm
	No. of tillers grown in one point	47
Investigation of Root	Single root diameter	1.5 mm
	Sample maximum root length	33 cm
	Root matrix diameter	17.8 cm
	Sample minimum root length	5 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Green/Faded Yellow
	Leaf color	Green/Faded Yellow
Other vegetation grown alongside		Dholkolmi
Length of the vetiver planted strip		-
Length of the strip in which vetiver has grown well		-

3.

Location	Azmirigonj, Habiganj
Name of the site	Paschimbag-Azmiriganj Road, Azmiriganj, Habiganj
GPS	N24º30'47", E91º18'40"
Date of plantation/Construction	2016
Nursery location of Vetiver tiller collection	Local
Date of monitoring	26/01/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (100mm dia)	
Investigation of Shoot	Sample minimum shoot length	25.4 cm
	Sample maximum shoot length	137.2 cm
	Overall range of shoot	25.4~137.2 cm
	Shoot/stem width	3 mm
	Diameter of the bush	43.2 cm
	No. of tillers grown in one point	26
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	7.6 cm
	Root matrix diameter	10.2 cm
	Sample minimum root length	3.8 cm
Investigation of Leaf	Inflorescence	Yes, purple
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		300 m
Length of the strip in which vetiver has grown well		24 m

4.

Location	Lakhai, Habiganj
Name of the site	Chikonpur, Lakhai
GPS	N24º16'57", E91º13'9"
Date of plantation/Construction	March 2016
Nursery location of Vetiver tiller collection	Nasirnagar, HILIP, LGED
Date of monitoring	27/01/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (110mm dia)	
Investigation of Shoot	Sample minimum shoot length	20.3 cm
	Sample maximum shoot length	86.4 cm
	Overall range of shoot	20.3~86.4 cm
	Shoot/stem width	3 mm
	Diameter of the bush	71.1 cm
	No. of tillers grown in one point	41
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	20.3 cm
	Root matrix diameter	8.9 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes, purple
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Potato, Fola ghash
Length of the vetiver planted strip		-
Length of the strip in which vetiver has grown well		18.3 m

Kishoreganj

1.

Location	Itna, Kishoreganj	
Name of the site	Chowganga-Chandrapur Road, Itna	
GPS	N24°31'16", E90°57'19"	
Date of plantation/Construction	April, 2018	
Nursery location of Vetiver tiller collection	Local haor	
Date of monitoring	08/03/2019	
Design Type	Type III, CC block (400×400mm×75mm) with hole (100mm dia) and geojute	
Investigation of Shoot	Sample minimum shoot length	20.3 cm
	Sample maximum shoot length	106.7 cm
	Overall range of shoot	20.3 ~106.7 cm
	Shoot/stem width	3 mm
	Diameter of the bush	40.6 cm
	No. of tillers grown in one point	28
Investigation of Root	Single root diameter	1.5 mm
	Sample maximum root length	20.3 cm
	Root matrix diameter	10.2 cm
	Sample minimum root length	5.08 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Muktapati
Length of the vetiver planted strip		675 m
Length of the strip in which vetiver has grown well		282 m

2.

Location	Itna, Kishoreganj	
Name of the site	Laimpasha village, Itna-Azmiriganj GC Road	
GPS	N24°33'41.3", E91°12'8.6"	
Date of plantation/Construction	May, 2018	
Nursery location of Vetiver tiller collection	Badla union, Itna	
Date of monitoring	12/04/2019	
Design Type	Type III, CC block (450×450mm×75mm) with hole (110mm dia)	
Investigation of Shoot	Sample minimum shoot length	15.3 cm
	Sample maximum shoot length	16.5 cm
	Overall range of shoot	15.3 ~16.5 cm
	Shoot/stem width	1 cm
	Diameter of the bush	53.34 cm
	No. of tillers grown in one point	46
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	15.2 cm
	Root matrix diameter	10.2 cm
	Sample minimum root length	2.5 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		No other vegetation
Length of the vetiver planted strip		154 m
Length of the strip in which vetiver has grown well		117 m

3.

Location	Nikli, Kishoreganj
Name of the site	Kamalpur village, Nikli
GPS	N24°20’21.88”, E90°56’58.37”
Date of plantation/Construction	2015
Nursery location of Vetiver tiller collection	Local haor
Date of monitoring	08/03/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (100mm dia) and Type II (vetiver only)	
Investigation of Shoot	Sample minimum shoot length	20.3 cm
	Sample maximum shoot length	132.1 cm
	Overall range of shoot	20.3 ~132.1 cm
	Shoot/stem width	3 mm
	Diameter of the bush	40.7 cm
	No. of tillers grown in one point	42
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	22.9 cm
	Root matrix diameter	12.7 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Jiga
Length of the vetiver planted strip		Not continuous
Length of the strip in which vetiver has grown well		62 m

4.

Location	Nikli, Kishoreganj
Name of the site	Daulatpur-Aglapara, Nikli
GPS	N24°15’40”, E90°56’33.6”
Date of Construction	April, 2016
Date of monitoring	11/04/2019
Design Type	Type III, CC block (450×450mm×75mm) with hole (100mm dia)
No vetiver tillers are found in this site	
Other vegetation grown alongside	No other vegetation

1.

Location	Kalmakanda, Netrokona
Name of the site	Borkhapon UP Office-Guturabazar Road
GPS	N25º2'23.40", E90º54'10.5"
Date of plantation/Construction	October, 2016
Nursery location of Vetiver tiller collection	Local haor
Date of monitoring	25/05/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (150mm dia) and geotextile	
Investigation of Shoot	Sample minimum shoot length	17.8 cm
	Sample maximum shoot length	58.4 cm
	Overall range of shoot	17.8 ~58.4 cm
	Shoot/stem width	20 mm
	Diameter of the bush	15 cm
	No. of tillers grown in one point	62
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	20.3 cm
	Root matrix diameter	10.2 cm
	Sample minimum root length	3.8 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Water hyacinth
Length of the vetiver planted strip		850 m
Length of the strip in which vetiver has grown well		Not continuous

2.

Location	Kalmakanda, Netrokona
Name of the site	Janjailpara
GPS	N25º1'26.84", E90º55'30.75"
Date of Construction	September, 2017
Date of monitoring	23/05/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (100mm dia)
No vetiver tillers are found in this site	
Other vegetation grown alongside	No other vegetation

3.

Location	Khaliajuri, Netrokona
Name of the site	Mujibnagar
GPS	N24°41'5.22", E91°9'55.09"
Date of plantation/Construction	April, 2017
Nursery location of Vetiver tiller collection	Hayatpur Nayahati, Khaliajuri
Date of monitoring	09/02/2020

Design Type	Type III, CC block (450×450mm×80mm) with hole (110mm dia)	
Investigation of Shoot	Sample minimum shoot length	15.2 cm
	Sample maximum shoot length	101.6 cm
	Overall range of shoot	15.2 ~101.6 cm
	Shoot/stem width	10 mm
	Diameter of the bush	38.1 cm
	No. of tillers grown in one point	500
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	12. 7 cm
	Root matrix diameter	10 cm
	Sample minimum root length	3.0 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Local Vegetables
Length of the vetiver planted strip		780m
Length of the strip in which vetiver has grown well		6-7 bushes are alive only

4.

Location	Khaliajuri, Netrokona
Name of the site	Hayatpur
GPS	N24°39'10.11", E91°11'20.47"
Date of plantation/Construction	April, 2017
Nursery location of Vetiver tiller collection	Hayatpur Nayahati, Khaliajuri
Date of monitoring	09/02/2020

Design Type	Type III, CC block (450×450mm×80mm) with hole (110mm dia)	
Investigation of Shoot	Sample minimum shoot length	15.2 cm
	Sample maximum shoot length	132.1 cm
	Overall range of shoot	15.2 ~132.1 cm
	Shoot/stem width	12 mm
	Diameter of the bush	55.9 cm
	No. of tillers grown in one point	132
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	20 cm
	Root matrix diameter	6 cm
	Sample minimum root length	2.5 cm
Investigation of Leaf	Inflorescence	No
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		-
Length of the vetiver planted strip		250 m
Length of the strip in which vetiver has grown well		6 bushes are alive only

Sunamganj

1.

Location	Derai, Sunamganj
Name of the site	Meghna Barghor, Derai
GPS	N24°50’20”, E91°16’49”
Date of plantation/Construction	March, 2016
Nursery location of Vetiver tiller collection	Vatipara union, Habiganj
Date of monitoring	30/08/2019

Design Type	In-situ CC block (1000×1000mm×100mm) with hole (75 mm dia) and wire mesh	
Investigation of Shoot	Sample minimum shoot length	45.7 cm
	Sample maximum shoot length	82 cm
	Overall range of shoot	45.7~82 cm
	Shoot/stem width	10 mm
	Diameter of the bush	5.3 cm
	No. of tillers grown in one point	3
Investigation of Root	Single root diameter	2 mm
	Sample maximum root length	27.9 cm
	Root matrix diameter	5 cm
	Sample minimum root length	6.4 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Mango, Jackfruit, Lemon, Koroch
Length of the vetiver planted strip		Not continuous
Length of the strip in which vetiver has grown well		10 m

2.

Location	Derai, Sunamganj
Name of the site	Meghna Notunpara, Derai
GPS	N24°50’36.95”, E91°17’24.72”
Date of plantation/Construction	March, 2018
Nursery location of Vetiver tiller collection	Vatipara union, Habiganj
Date of monitoring	30/08/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (90mm dia) with Jute geotextile	
Investigation of Shoot	Sample minimum shoot length	38.0 cm
	Sample maximum shoot length	89.0 cm
	Overall range of shoot	38.0~89.0 cm
	Shoot/stem width	6 mm
	Diameter of the bush	7.6 cm
	No. of tillers grown in one point	12
Investigation of Root	Single root diameter	1 mm
	Sample maximum root length	17.8 cm
	Root matrix diameter	6.4 cm
	Sample minimum root length	5.1 cm
Investigation of Leaf	Inflorescence	Yes
	Shoot/stem color	Green
	Leaf color	Green
Other vegetation grown alongside		Water hyacinth
Length of the vetiver planted strip		Not continuous
Length of the strip in which vetiver has grown well		62 m

3.

Sunamganj

Location	Derai, Sunamganj
Name of the site	Kochua, Derai
GPS	N24°46'42.94", E91°23'1.1"
Date of Construction	March, 2019
Date of monitoring	30/08/2019

Design Type	Type III, CC block (450×450mm×75mm) with hole (90mm dia) with geotextile
No vetiver tillers are found in this site	
Other vegetation grown alongside	No other vegetation

APPENDIX E
COST ANALYSES

Cost analysis of Type I

Brahmanbaria:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Borak Bamboo	75 mm dia @ 300 mm	m	39	156
Grass turfing	m^2	m^2	5	5
Jute geotextile	500 gsm	m^2	29	29
Bamboo pegs	6.1×1.1 cm @ 300 mm	number	10	80
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	271.878
			With 10% Profit of Contractor =	299.0658

Labor Cost		
Unskilled labor	per day	480

Kishoreganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Borak Bamboo	75 mm dia @ 300 mm	m	36	144
Grass turfing	m^2	m^2	5	5
Jute geotextile	500 gsm	m^2	29	29
Bamboo pegs	6.1×1.1 cm @ 300 mm	number	10	80
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	259.878
			With 10% Profit of Contractor =	285.8658

Labor Cost		
Unskilled labor	per day	470

Habiganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Borak Bamboo	75 mm dia @ 300 mm	m	39	156
Grass turfing	m^2	m^2	5	5
Jute geotextile	500 gsm	m^2	29	29
Bamboo pegs	6.1×1.1 cm @ 300 mm	number	10	80
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	271.878
			With 10% Profit of Contractor =	299.0658

Labor Cost		
Unskilled labor	per day	470

Netrokona:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Borak Bamboo	75 mm dia @ 300 mm	m	36	144
Grass turfing	m^2	m^2	5	5
Jute geotextile	500 gsm	m^2	29	29
Bamboo pegs	6.1×1.1 cm @ 300 mm	number	10	80
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	259.878
			With 10% Profit of Contractor =	285.8658

Labor Cost		
Unskilled labor	per day	470

Sunamganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Borak Bamboo	75 mm dia @ 300 mm	m	39	156
Grass turfing	m^2	m^2	5	5
Jute geotextile	500 gsm	m^2	29	29
Bamboo pegs	6.1×1.1 cm @ 300 mm	number	10	80
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	271.878
			With 10% Profit of Contractor =	299.0658

Labor Cost		
Unskilled labor	per day	470

Cost analysis of Type II
All Haor Districts

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Vetiver	2m × 1 m grid pattern @ 25 cm c/c spacing	tiller	0.2	6
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	36.878
			With 10% Profit of Contractor =	40.5658

Labor Cost		
Skilled labor	per day (Brahmanbaria, Habiganj, Sunamganj)	550
	per day (Kishoreganj)	545
	per day (Netrokona)	560

Recommended Design Type Cost Analysis:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
Vetiver	@ 25 cm c/c spacing	tiller	0.2	9.6
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	40.478
			With 10% Profit of Contractor =	44.5258

Cost analysis of Type III

Brahmanbaria:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
CC Block	Block Size 450×450×75mm, hole dia 150 mm,mix ratio 1:2:4	per block	52.164	257.6
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	430	
	25 mm down graded brick chips	m^3	3198	
Vetiver	@ 450 mm c/c spacing	tiller	0.2	5.4
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	293.878
			With 10% Profit of Contractor =	323

Labor Cost		
Unskilled labor	per day	480
Skilled labor	per day	550
Mason	per day	635

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	817.4

Kishoreganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
CC Block	Block Size 450×450×75mm, hole dia 150 mm,mix ratio 1:2:4	per block	52.164	253.25
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	400	
	25 mm down graded brick chips	m^3	3103	
Vetiver	@ 450 mm c/c spacing	tiller	0.2	5.4
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	289.528
			With 10% Profit of Contractor =	318

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	545
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	797.5

Habiganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
CC Block	Block Size 450×450×75mm, hole dia 150 mm,mix ratio 1:2:4	per block	53.9	266
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	460	
	25 mm down graded brick chips	m^3	3400	
Vetiver	@ 450 mm c/c spacing	tiller	0.2	5.4
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	302.278
			With 10% Profit of Contractor =	333

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	861.4

Netrokona:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
CC Block	Block Size 450×450×75mm, hole dia 150 mm,mix ratio 1:2:4	per block	52.164	257.6
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	440	
	25 mm down graded brick chips	m^3	3192	
Vetiver	@ 450 mm c/c spacing	tiller	0.2	5.4
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	293.878
			With 10% Profit of Contractor =	323

Labor Cost				
Unskilled labor	per day			480
Skilled labor	per day			550
Mason	per day			635

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	818.1

Sunamganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
CC Block	Block Size 450×450×75mm, hole dia 150 mm,mix ratio 1:2:4	per block	53.9	266
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	460	
	25 mm down graded brick chips	m^3	3400	
Vetiver	@ 450 mm c/c spacing	tiller	0.2	5.4
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	302.278
			With 10% Profit of Contractor =	333

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	861.4

Cost analysis of Type IV

Brahmanbaria:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
RCC Pole	@ 600 mm c/c spacing			1341.5
	10 mm rebar and 8 mm tie	m	227.18	
	Concrete work (mix ratio 1:1.5:3)	m	443.57	
Vetiver	@ 250 mm c/c spacing (horizontally), @ 1000 mm c/c spacing (vertically)	tiller	0.2	9.6
U-hook	10 BWG wire reinforcement, @500 mm c/c	per number	9.019333	27.058
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	1409.036
			With 10% Profit of Contractor =	1,550

Labor Cost		
Unskilled labor	per day	480
Skilled labor	per day	550
Mason	per day	635

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	817.4

Kishoreganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
RCC Pole	@ 600 mm c/c spacing			1346.8
	10 mm rebar and 8 mm tie	m	230.89	
	Concrete work (mix ratio 1:1.5:3)	m	442.5	
Vetiver	@ 250 mm c/c spacing (horizontally), @ 1000 mm c/c spacing (vertically)	tiller	0.2	9.6
U-hook	10 BWG wire reinforcement, @500 mm c/c	per number	9.019333	27.058
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	1414.336
			With 10% Profit of Contractor =	1,556

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	545
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	797.5

Habiganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
RCC Pole	@ 600 mm c/c spacing			1338.3
	10 mm rebar and 8 mm tie	m	223.44	
	Concrete work (mix ratio 1:1.5:3)	m	445.7	
Vetiver	@ 250 mm c/c spacing (horizontally), @ 1000 mm c/c spacing (vertically)	tiller	0.2	9.6
U-hook	10 BWG wire reinforcement, @500 mm c/c	per number	9.019333	27.058
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	1405.836
			With 10% Profit of Contractor =	1,546

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	861.4

Netrokona:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
RCC Pole	@ 600 mm c/c spacing			1341.5
	10 mm rebar and 8 mm tie	m	227.18	
	Concrete work (mix ratio 1:1.5:3)	m	443.6	
Vetiver	@ 250 mm c/c spacing (horizontally), @ 1000 mm c/c spacing (vertically)	tiller	0.2	9.6
U-hook	10 BWG wire reinforcement, @500 mm c/c	per number	9.019333	27.058
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	1409.036
			With 10% Profit of Contractor =	1,550

Labor Cost				
Unskilled labor	per day			480
Skilled labor	per day			550
Mason	per day			635

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	818.1

Sunamganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m² (BDT)
Materials Cost				
RCC Pole	@ 600 mm c/c spacing			1338.3
	10 mm rebar and 8 mm tie	m	223.44	
	Concrete work (mix ratio 1:1.5:3)	m	445.7	
Vetiver	@ 250 mm c/c spacing (horizontally), @ 1000 mm c/c spacing (vertically)	tiller	0.2	9.6
U-hook	10 BWG wire reinforcement, @500 mm c/c	per number	9.019333	27.058
Jute geotextile	500 gsm	m^2	29	29
Maintenance Cost				
Urea	per hectare	kg	45	0.9
TSP	per hectare	kg	30	0.978
			Total Cost=	1405.836
			With 10% Profit of Contractor =	1,546

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550
Mason	per day	640

Item	Specification	Cost/m (BDT)
Toe Wall	1st class brick, mix ratio 1:4	861.4

Cost analysis of Conventional Practice by Solid Blocks

Brahmanbaria:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
CC Block	Block Size 500×500×300mm, mix ratio 1:2:4	per block	279.7	1381.24
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	430	
	25 mm down graded brick chips	m^3	3198	
Geotextile	(Grade II-DF-30-2.0 mm thick)	m^2	60	60
			Total Cost=	1441.24
			With 10% Profit of Contractor =	1,585

Labor Cost		
Unskilled labor	per day	480
Skilled labor	per day	550

Kishoreganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
CC Block	Block Size 500×500×300mm, mix ratio 1:2:4	per block	274.7	1356.7
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	400	
	25 mm down graded brick chips	m^3	3103	
Geotextile	(Grade II-DF-30-2.0 mm thick)	m^2	60	60
			Total Cost=	1416.7
			With 10% Profit of Contractor =	1,558

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	545

Habiganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
CC Block	Block Size 500×500×300mm, mix ratio 1:2:4	per block	288.7	1425.8
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	460	
	25 mm down graded brick chips	m^3	3400	
Geotextile	(Grade II-DF-30-2.0 mm thick)	m^2	60	60
			Total Cost=	1485.8
			With 10% Profit of Contractor =	1,634

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550

Netrokona:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
CC Block	Block Size 500×500×300mm, mix ratio 1:2:4	per block	279.4	1379.8
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	440	
	25 mm down graded brick chips	m^3	3192	
Geotextile	(Grade II-DF-30-2.0 mm thick)	m^2	60	60
			Total Cost=	1439.8
			With 10% Profit of Contractor =	1,584

Labor Cost				
Unskilled labor	per day			480
Skilled labor	per day			550

Sunamganj:

Item	Specification	Unit	Unit Cost (BDT)	Cost/m^2 (BDT)
Materials Cost				
CC Block	Block Size 500×500×300mm, mix ratio 1:2:4	per block	288.7	1425.8
	Portland composite cement	bag	440	
	Local Sand (#200 passing not more than 15%)	m^3	460	
	25 mm down graded brick chips	m^3	3400	
Geotextile	(Grade II-DF-30-2.0 mm thick)	m^2	60	60
			Total Cost=	1485.8
			With 10% Profit of Contractor =	1,634

Labor Cost		
Unskilled labor	per day	470
Skilled labor	per day	550