CHARACTERIZATION OF SOIL-ROOT SYSTEM TO DETERMINE STABILITY OF VEGETATED SLOPES

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ABSTRACT
Protection of embankments is of paramount importance from Bangladesh's context. Every year, slope instability related damages upset people's lives in many parts of the country. The conventional methods used for slope protection are generally temporary solutions and require large, long-term investment. Alternatively, plantation of vetiver grass can be a very cost-effective and innovative solution for the protection of banks/slopes. In this study, to evaluate the performance of vetiver grass in slope protection, direct shear tests were conducted on both bare and rooted soil samples. Samples were prepared with different root lengths varying from 1.25-5 cm with varying water content of 15% - 30%. Root content was 3% of the dry weight of soil. It has been found that both shear stress and strain largely depend on root length. From slope stability analyses, it has been found that vetiver grass is able to increase factor of safety of embankment slope up to 2.66 times to that of bare soil.

Keywords: Bio-engineering, bare soil, slope stability, rooted soil, vetiver

INTRODUCTION
Bangladesh is a low-lying deltaic country. The geographical characteristics have made the country vulnerable to different natural hazards. Due to lack of adequate mangrove forests and absence of coastal embankment, Bangladesh is the fifth most natural disaster prone country in the world, according to the World Risk Report (FE Report. 2012). The major disasters that are generally encountered are flood, cyclone and storm surge, flash flood, drought, tornado, riverbank erosion and landslide. These are recurrent natural hazards, causing loss of lands, agriculture and houses. It also destroys embankments, other hydraulic structures and livelihood along coastlines and estuaries. Often, landslides cause long-term economic disruption, population displacement, and negative effects on the natural environment. Each year, slope failures produce extensive property damage and result in loss of life. These numerous issues elucidates the vitality of earth slopes' protection to minimize the losses that occur every year.
There are different approaches to deal with slope instability, depending on needs, risks and available funds. Stabilization measures to fully remediate landslides according to the standard of practice often take time to investigate, design and construct and above all become expensive, particularly for developing and least developed countries like Bangladesh. Significant stabilization measures might be required to protect critical facilities such as dams, expensive structures and primary highway routes. However, there are situations where full stabilization is impractical due to size of landslide, excessive cost, and highly dense foothill settlement, environmental and ownership restrictions. Hence, the challenge is to develop an optimal treatment that is cost-effective.
Plantation of vetiver system along the slopes is a very effective and low-cost solution for slope protection (Verhagen et al., 2008, Islam et al., 2013b, Badhon, 2015). Vetiver not only serves the purpose of slope protection but also add 'green environment', reducing pollution. Vetiver grass is native to tropical and subtropical India. It has a dense structured deep root system capable of reaching 2.5–4 m (Islam et al., 2013a, 2013b) and its roots are very strong with high tensile strength of 75 MPa. In addition, it is highly tolerant to extreme soil conditions including prolonged drought, flood, submergence, extreme temperature (-10 to 48^{o}C), and a wide range of soil acidity and alkalinity (pH: 3 to 10.5). It has also been reported to be highly tolerant to soil salinity, sodicity, acidity, and presence of Al, Mn and heavy metal ions in the soil (Islam et al., 2013b). Bangladesh Water Development

Board, BWDB (2000) found vetiver grass to be very common in about 40% of the total land area of Bangladesh. Vetiver grass has wider applications due to its unique morphological, physiological and ecological characteristics that highlight its adaptability to a wide range of environmental and soil conditions. The most impressive characteristic of the vetiver grass is its root system. Islam et al. (2013a) conducted in-situ shear tests on vetiver rooted soil system and found that the shear strength and effective soil cohesion of vetiver rooted soil matrix are respectively 2.0 and 2.1 times that of the bare soil. To evaluate the performance of vetiver grass in slope protection, several laboratory tests were conducted on vetiver rooted soil. The objective was to determine the strength of vetiver rooted soil and to observe the change in shear strength, deformation, cohesion and angle of internal friction in comparison to bare soil.

METHODOLOGY

Laboratory direct shear tests were conducted to determine the shear strength and failure strain of vetiver rooted soil matrix and soil without root. Vetiver grasses were collected from a naturally grown source in Pubail, Gazipur and then roots were obtained from uprooted vetiver grass. Soil for making samples was also collected from the same place.

Laboratory Tests

A detailed laboratory investigation was carried out to determine the physical and index properties of the soil samples collected from Pubail. The laboratory testing program consisted of carrying out specific gravity, moisture content and particle size analysis. All the tests were conducted according to ASTM standards. Direct shear tests were conducted in Consolidated Undrained (CU) condition on reconstituted soil samples. Tests were conducted on both bare and root mixed composite soil samples collected from the Pubail region of Bangladesh. The tests were performed on samples prepared with different root lengths (1.25 cm, 2.54 cm and 5 cm) with same root content (3% of dry weight of soil). Samples were prepared at two different moisture contents (15% and 30%). Normal stresses were arbitrary selected in the range between 10.83 kPa and 20.12 kPa.

Preparation of Reconstituted Soil Samples

At first, roots were collected and then preserved in the refrigerator (at 4ºC) with arbitrary moisture content to keep the roots fresh. Then, roots were chopped to the desired length (1.25 cm, 2.54 cm, 5.0 cm). Collected soil samples were air dried and crushed to powder by wooden hammer. Next, water (amount corresponding to 15% and 30% moisture content respectively) was added to the dry soil. Chopped vetiver roots were randomly mixed with the wet soil. The soil was then compacted by a wooden rod inside a probing ring (size of 63.5 mm diameter and 25.4 mm height) from a falling height of 100 mm. The compaction was done in three layers with 25 blows being applied to each layer. The prepared samples were kept in a desiccator to keep the moisture content constant. Direct

(a) (b) (c)

Fig. 1: (a) 5 cm long chopped vetiver root, (b) root mixed soil, (c) soil sample inside the shear ring.

shear test was conducted on those prepared specimens according to the ASTM standards. Fig. 1 shows the photographs of different stages of reconstituted soil sample preparation.

Test Set-up

The remolded soil sample was placed in the shear box from the ring. Then, the desired normal load was applied. Normal stresses were arbitrarily selected in the range from 10.87 kPa to 20.12 kPa. Vertical displacement dial gauge was attached to record the vertical deformation with respect to time. Enough time (about 1 hour) was allowed for consolidation before applying the shear force. When two consecutive vertical deformation dial readings were the same, shear force was applied to the soil sample with a constant strain rate of 0.75 to 1.25 mm/min. The lateral deformation was recorded by a lateral constant strain rate of 0.75 to 1.25 mm/min via the means of a lateral displacement dial gauge of 25 mm capacity. The applied shear force was recorded by a load dial gauge of 2.22 kN capacity.

RESULTS AND DISCUSSIONS

Index Properties of Soils

The specific gravity of the soil sample collected from Pubail region is 2.68. Natural moisture content is 10%. Dry unit weight of the soil samples varies from 15.67-17.37 kN/m^3 at 15% moisture content and 17.23-17.87 kN/m^3 at 30% moisture content. Clay, silt and sand fractions of the soils have been determined according to ASTM D 422. Fig. 2 shows grain size distribution of Pubail soil samples. From Fig. 2, it is seen that clay, silt and sand content of the soil are respectively 24%, 60%, 16%. Liquid limit is 44%, plastic limit is 21% and plasticity index is 23%. It is found that Pubail soil is Lean clay and the designated group symbol according to ASTM D 2487 is CL (inorganic clays of low to medium plasticity or silty clay).

Strength Properties of Soils

Test result of the soil samples in different root length is presented in the Table 1 and Table 2. Typical shear stress vs shear strain and shear stress vs normal stress graphs are presented in Fig. 3a and Fig. 3b, respectively. Variation of angle of internal friction and cohesion are presented in Fig. 4 and Fig. 5. From the test results, it is observed that for 15% moisture content, the peak shear stress of vetiver rooted soil matrix varies from 33.57 kPa to 69.63 kPa and peak shear strain of vetiver rooted soil matrix varies from 1.65 to 5.66 mm.

For 30% moisture content, it is observed that the peak shear stress of vetiver rooted soil matrix varies from 15.78 kPa to 34.74 kPa and peak shear strain varies from 6.48 mm to 10.03 mm. In case of 30% moisture content, though, the peak shear stress is lower than that of soil samples for 15% moisture content but peak shear strain is quite higher. This means, for higher moisture content, soil sample tends to display more ductility.

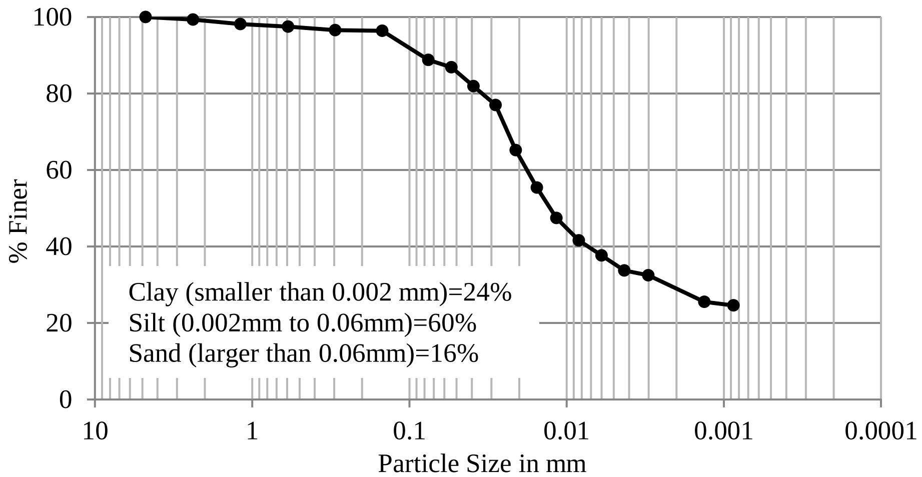

Fig. 2: Particle size distribution of soil sample collected from Pubail region

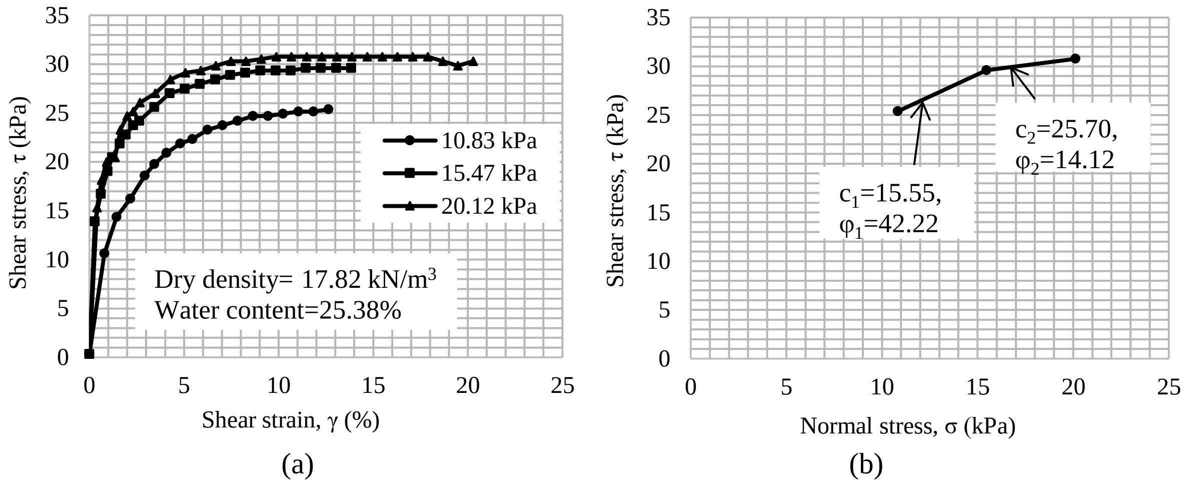

Fig. 3: (a) Shear stress vs shear strain for specimens prepared with 1.25 cm root length; (b) shear stress vs normal stress for specimens prepared with 1.25 cm root length

Table 1: Comparison of shear strength and shear deformation of reconstituted bare and rooted soil

σ_n	Moisture content= 15%								Moisture content=30%							
	Bare soil		1.25 cm root length		2.54 cm root length		5 cm root length		Bare soil		1.25 cm root length		2.54 cm root length		5 cm root length	
	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}	τ_{max}	δ_{hf}
10.8	42.9	1.7	38.3	9.7	33.6	4.7	51.8	3.4	24.2	9.6	25.4	8.0	28.0	6.9	15.8	10.0
15.5	46.2	2.6	49.0	2.6	52.8	5.7	66.8	2.9	29.1	9.7	29.6	7.3	34.7	6.5	20.2	9.8
20.1	56.5	1.9	53.7	1.9	57.9	3.6	69.6	3.7	34.3	9.7	30.8	6.3	31.2	6.5	21.6	9.8

Note: σ_n =Normal Stress in kPa; τ_{max} = Peak Shear stress in kPa; δ_{hf} = Horizontal Failure Deformation in mm

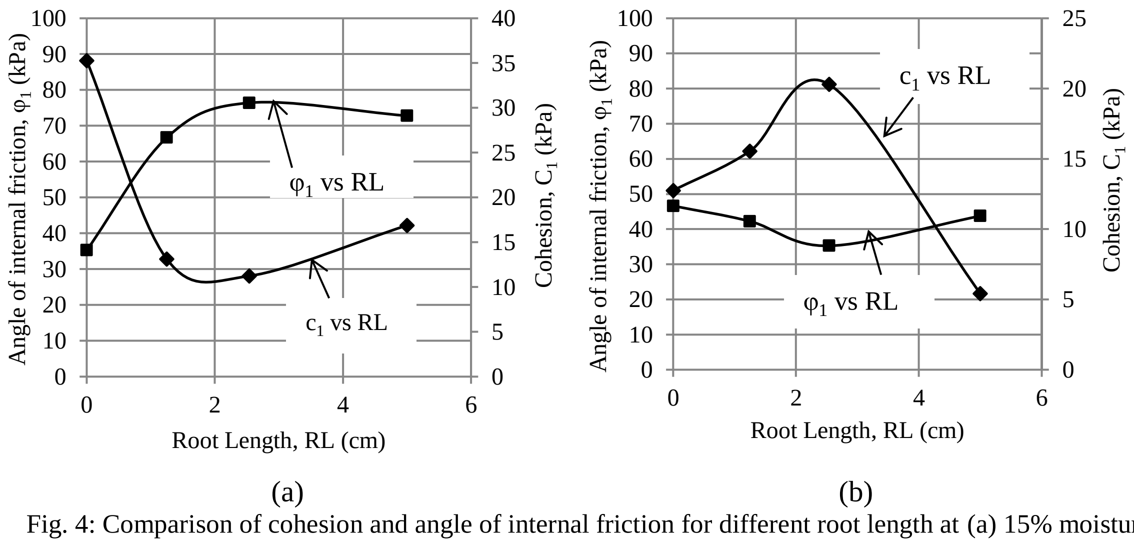

Fig. 4: Comparison of cohesion and angle of internal friction for different root length at (a) 15% moisture content (b) 30% moisture content

It is seen that for 30% water content, maximum shear stress almost increases with the increase in root length for all three normal loads except for the case of normal load of 10.83 kPa and for 2.54 cm root length, maximum shear stress decreases in comparison to bare soil.

However, for 15% water content maximum shear stress increases up to root length 2.54 cm but decreases for root length 5 cm. This may occur due to the failure of soil samples in a predetermined failure plane. As root is arbitrarily placed in soil sample, root may be positioned in vertical, horizontal or inclined direction in failure plane. Also, there is a possibility that there is no root in the failure plane. The above mentioned reasons might explain why shear strength varies.

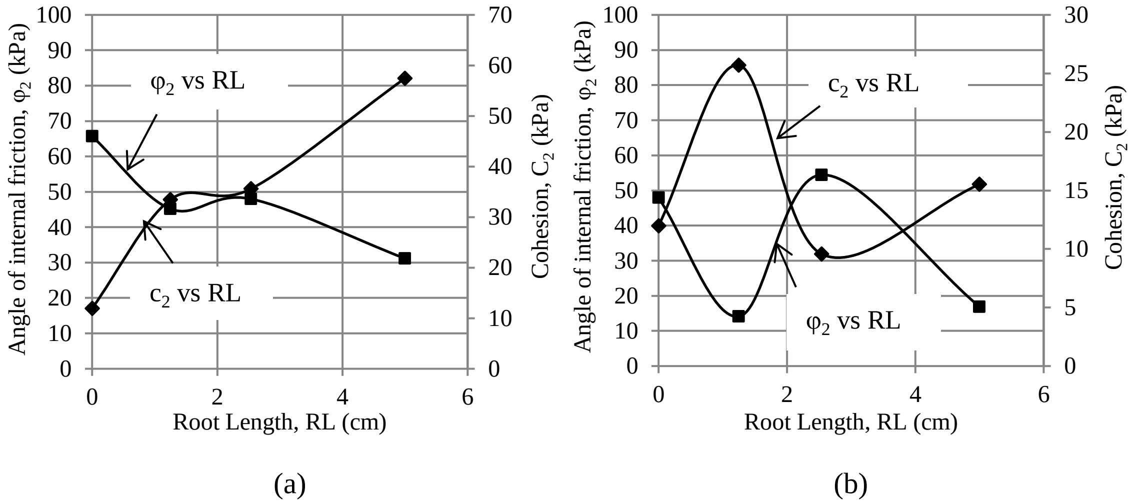

Fig. 5: Comparison of cohesion and angle of internal friction for specimens prepared with different root length at (a) 15% moisture content (b) 30% moisture content

Therefore, it is clear that the presence of root content significantly affects the strength of soil. Shear stress, deformation, cohesion and angle of internal friction of a soil matrix varies with the variation in root length. The shear strength of a rooted soil matrix depends on the interaction between the soil and the roots and the distribution of roots on the soil matrix. At a certain plane in a rooted soil matrix, the shear force is resisted by the soil and the roots. The performance of the rooted soil matrix depends on the critical combination of soil and roots on the failure plane. The critical combination also varies with root content, root ratio and root position. This is the reason the shear stress, deformation, cohesion and angle of internal friction of a soil matrix varies. It expounds on the fact that the root content and the length of roots in the soil mix have a major effect on the shear strength of soil.

Estimation of Slope Stability

Slope stability for a typical rural road section has been analyzed using Coppin and Richards's method (Coppin et al. 1990) for obtained by laboratory direct shear tests on reconstituted soil samples.

For bare soil, $FS = \frac{c' + (\gamma z - \gamma_w h_w)\cos^2\beta\tan\varphi'}{\gamma z \sin\beta\cos\beta}$

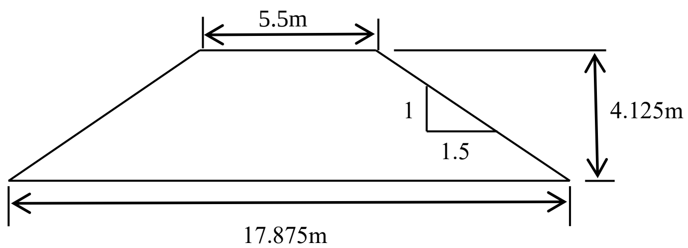

Fig. 6: LGED rural road section through hills, Road Type B (LGED, 2005)

Table 2: Parameters used for stability analysis

Parameter	Unit	Value
Vertical height of soil above slip plane	m	1
Slope angle, β	degree	34
Unit weight of water, γ	kN/m³	9.8
Vertical height of ground water table above slip plane, h_w	kN/m²	–
Surcharge due to weight of vegetation, W	kN/m²	0.1
Vertical height of groundwater table above the slip plane with the vegetation, h_v	m	0
Tensile root force acting at the base of the slip plane, T	kN/m	0.4
Angle between roots and slip plane, θ	degree	–
Wind loading force parallel to the slope, D	kN/m	0.1

For rooted soil, $FS = \frac{(c'+c_R')+ [\{(\gamma z-\gamma_w h_v)+W\}\cos^2\beta+ T\sin\theta]\tan\varphi'+T\cos\theta}{\{(\gamma z+W)\sin\beta+D\}\cos\beta}$

Table 3: Factor of safety of embankment slope on the basis of reconstituted soil samples test results

Moisture content=15%			**Moisture content=30%**		
Root Length (cm)	Factor of Safety	Times higher	Root Length (cm)	Factor of Safety	Times higher
---	4.8	---	---	3.3	---
1.25	6.5	1.35	1.25	4.0	1.21
2.54	6.7	1.39	2.54	2.5	0.76
5.00	12.8	2.66	5.00	6.1	1.85

CONCLUSIONS

Slope failure due to erosion is a common problem in Bangladesh. Plantation of vetiver system along the slope is an alternative green solution to the problem. In order to characterize the soil-root system to determine the stability of vegetated earth slopes, several laboratory investigations has been carried out in this study. The main findings of the study are as follows:

(1) Direct shear tests were conducted on reconstituted samples for 3% root content for varying root length and varying water content under different normal stresses. Test results show that shear strength and deformation of rooted soil changes with root length significantly in comparison to that of bare soil.

(2) From the obtained cohesion and angle of internal friction, the stability of embankment slopes was estimated. From the analyses, it has been found that the factor of safety of embankment slope increases with the increase of root length.

Therefore, it can be said that the vetiver grass plantation is a very effective and low cost green solution to slope stability related problems.

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