Geotech Geol Eng (2022) 40:3267–3286
https://doi.org/10.1007/s10706-022-02092-y

ORIGINAL PAPER

# Mechanical Effect of Vetiver Grass Root for Stabilization of Natural and Terraced Hill Slope

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Received: 29 September 2020 / Accepted: 27 February 2022 / Published online: 8 March 2022

**Abstract** This paper studies the role of vetiver grass (*Vetiveria zizanoides*) on the stability of hill slopes through physical and numerical modeling. Vetiver plantation in nutrient-deficient poorly graded sand with silt in a glass model, showing mean root growth of 0.42 m and increase in tillers (shoots) from 3 to 15 after six months, advocates its survival in unfavorable soil conditions. Finite element analysis shows, for the sand/silt, existing 15 m high bare natural slopes are stable up to a slope angle of 30° with a factor of safety of 1.01 and crest deformation of 37.2 mm. Covering the whole slope with vetiver yields a higher factor of safety of 1.17 and nearly 10 mm lower crest deformation as the root zone depth reaches 3.0 m. However, as this positive impact of root's mechanical reinforcement is inhibited beyond the threshold angle of 33.3° yielding factor of safety of 1.06, terraced slopes in combination with vetiver are considered. Compared to sand/silt, vetiver performs better in sandy silt in reducing chances of shallow slope failure at the same geometry of natural slope. This study recommends vetiver as a sustainable and cost-effective approach for restoration of hill slopes along with reducing the risk of shallow slope failures and eventually landslides.

**Keywords** Factor of safety · Hill slope stability · Vetiver · Landslide · Terraced slope

## 1 Introduction

Landslide is a common and third most crucial natural disaster, caused by movement of rock, earth or debris down a slope as the stability of the slope is disturbed and the gravity force exceeds the shear strength, e.g. the resisting force of the soil, while being the most significant one in hilly environments causing major loss of lives and infrastructures (Highland and Bobrowsky 2008; Chen et al. 2017; Abedin et al. 2020). Rainfall induced landslides have been prominent in many countries in Asia, like India, Nepal, Japan, China, Taiwan (Shrestha et al. 2017; Rabby and Li 2019). Bangladesh has also been added to the set as the life loss and property damage during the recent landslides, especially the one of 2017, has been alarming compared to the previous ones. Along with this natural factor, human interventions, deforestation and land cover changes have accelerated the risk of the landslide which demands a sustainable solution.

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Shallow slide prevention in mountainous regions along with erosion reduction has been achieved through the use of vegetation (Gray and Sotir 1996; Kokutse et al. 2016; Temgoua et al. 2016; Rey 2018) as an eco-friendly, cost-effective and viable solution. Vegetation has also reduced permanent slope movement by 61% compared to bare conditions (Liang et al. 2015). Among different vegetations, although grasses have been good agents to reduce erosion, their effect on slope stability has not been studied much owing to their fibrous shallow roots holding the soil in a horizontal pattern (Mickovski et al. 2007). Vetiver grass (*Vetiveria zizanoides*) is an exception in this regard due to its thin, long and fibrous roots that penetrate vertically deep into soil up to 3–4 m (Truong et al. 1995; Hellin and Haigh 2002) and interacts with it. Vetiver grass has thus been gaining popularity in imparting slope stability in tropical and sub-tropical countries (World Bank 1990; Islam et al. 2020). Laboratory investigations (Islam et al. 2010; Islam and Badhon 2020), field trials (Mickovski et al. 2007; Islam and Hossain 2013; Teerawattanasuk et al. 2014; D'Souza et al. 2019) and numerical modeling studies (Islam et al. 2020; Tsige et al. 2020) have been performed to quantify the mechanical and hydrological effects of vetiver roots on soil reinforcement, thus slope stability. The majority of mechanical soil reinforcement provided by the roots is via the additional cohesion coming from mobilized tensile strength of the roots (Wu 1976; Wu et al. 1979; Nguyen et al. 2018; Islam and Badhon 2020). This mechanical property depends on root architecture, root diameter and root area ratio (Mattia et al. 2005; De Baets et al. 2008; Islam and Badhon 2020) which further varies with the vetiver's growth. Therefore to implement a measure such as vetiver for safeguarding slope stability at a particular soil and climatic condition, its growth and further sustainability need to be studied and ensured.

Previous studies show that vetiver grows well in the tropics (Hengchaovanich 1998) but its growth varies with water content, longer summer months, dry climate, etc. In the case of Bangladesh, the morphological studies of vetiver report excellent growth of vetiver in *haor* regions which is the local name of the wetland ecosystem in the northeastern part of Bangladesh (Islam et al. 2013, 2020). Physically it is a bowl or saucer-shaped shallow depression which is also known as a back swamp (Alam and Hasan 2010). However, growth variability has been found at different sites due to salinity, submergence, rainfall intensity and nutrient content. Also, clay-rich soil shows lower growth of vetiver than sandy soil (Islam et al. 2013; Islam 2019). So, for using vetiver as a reinforcing agent at any location, its growth cannot be inferred and requires site-specific results.

The use of vetiver has been established for protecting the slopes of the embankment, but its use is still being explored in hill slope protection of Bangladesh, especially for the hills of Chattogram which are formed of sandstone and shale (Reimann 1993). Though small landslides have hit the Chattogram Hill Districts (CHD) of Bangladesh during the last three decades, two major ones took place in the last 14 years. Following the one of 2007, the threats of rainfall induced landslides have been sensed during the one of 2017. Being triggered by heavy rainfall of 610 mm over eight consecutive days, it caused 159 fatalities and 88 injuries (Ahmed et al. 2018). Among 730 mapped landslides of CHD, 208 have occurred in the Chattogram district alone (Rabby and Li 2019). Particularly, the urbanized center of Chattogram district, Chattogram City Corporation area, where increasing intensities of rainfall have been accompanied with intensive hill cutting, illegal housing at steep hill slopes and destruction of the vegetative cover has become vulnerable to landslides. These landslides in Chattogram contain more than 80% sand and fines and are classified as "earth slides" according to the classification of Cruden and Varnes (1996) and Cruden and Vandine (2013). Despite being addressed as a major disaster, the studies previously conducted in Chattogram region focuses on the planning aspects, causes and mapping of landslide (Ahmed 2015; Rahman et al. 2017). Whereas stability analysis of the hills via the use of engineering and non-engineering methods is quite scarce. Even though conventional measures may solve the problem partially, slope instability can result due to a lack of environmental planning and conservation measures (Nordin 1995). Hence to reduce the risk of landslide, insight involving the application of sustainable methods for slope stability is essential along with focusing on measures that address conservation of the environment. Vetiver plantation can be such an option for ensuring the stability of these hills.

Khan et al. (2012) reported these landslides in CHD to be mostly shallow which has been further bolstered by field investigation conducted by Ahmed (2015). Limited studies by Islam (2018) and Aziz et al. 2020) have tried to investigate the growth of vetiver in nutrient deficit hilly soil of Chattogram. Whereas Elahi et al. (2019) and Islam et al. (2020) have studied the effect of varying root depth of vetiver on slope stability by finite element modeling at some particular slope angles. The slope geometries, e.g. slope height and slope angle, have a prominent and sometimes overriding effect on the stability of slope even after vegetation has been used (Chok et al. 2015; Kokutse et al. 2016; Islam 2018). Recommendations or quantification have not been obtained from previous studies regarding the slope angle till which the natural hills can be safe at the bare condition and until which vetiver can be effective in providing stability. Slope failure being a large deformation problem accompanied by toe movement and crest settlement, numerical investigations have also come to different conclusions about the best distribution pattern of vegetation by which maximum safety can be achieved. The result may depend on vegetation type, slope condition and the numerical simulation of reinforcement. Vegetation only at the slope surface (Naghdi et al. 2013), only on the toe (Habibah et al. 2014), or at the slope and toe together (Chok et al. 2015) may provide the best results of reinforcement.

Considering the mentioned variations and contradictions, field trials will involve both time and monetary investment to a great extent. Thus this study plans a comprehensive way to investigate the possibilities of vetiver in imparting stability to hill slopes through small scale model study as well as finite element (FE) modeling. Firstly, the study attempts to monitor the growth and root morphology of vetiver in the local hilly soil of Chattogram to be certain about its development and sustainability under prevailing nutrient and soil conditions. Later parameters hinged on root conditions are used in the FE modeling which further aims to evaluate the efficacy of vetiver in slope stabilization alongside proposing a range of slope angle till which vetiver can provide sufficient stability to the natural slopes. Focusing on the impact of slope geometry in determining the factor of safety (FS) of slopes, it further recommends ways to augment the effect of vetiver by applying it in combination with terraced slopes and ensure stability. These combined results from practical growth study and numerical analysis shall shed light on maintainable and eco-friendly protective measures like vetiver plantation that can be practiced by the professionals and development authorities of urban built-up hilly areas like Chattogram where excessive rainfall accompanied with human interventions have accelerated the occurrences of landslide.

## 2 Materials and Methods

### 2.1 Study Area

The study has been conducted for a hill located at the core urbanized part of Chattogram city which is known as Chattogram City Corporation (CCC) area as shown in Fig. 1. The hill is locally known as *Berma Haji* hill (latitude 22°21′30.8″ N, longitude 91°49′10.6″ E). The weather in Chattogram is humid with mean temperatures varying between 32.5° and 13.5° (BBS 2011). The average annual rainfall is 3378 mm showing an upward shift in the last five decades since 1960 (Ahmed et al. 2018). Dihing Formation, Dupi Tila Formation, Tipam Sandstone, Bhuban and Boka Bil Formation of Tertiary period make up the hilly deposits of CCC and alternating beds of siltstone, sandstone and shales are present in the sediments (Brammer 2012). This alteration of shale and sandstone makes the soil structure unstable and thus increases the susceptibility to landslides (Islam et al. 2014, 2017; Haque et al. 2018). Few landslides have already occurred in the vicinity of the selected hills (Ahmed 2015).

### 2.2 Characterization of Topography

From field investigations performed in 2020, collected contour maps and previous literature, it has been observed that the slope angle of the hills of Chattogram varies between 20° and 70° with slope height varying between 15 and 20 m (Islam et al. 2014). From field observation, it was noticeable that nearly vertical cuts are also present at some parts of the hills.

### 2.3 Soil Properties

In-situ field density tests have been carried out in the site according to the sand cone method of ASTM D-1556. Soil samples have been collected

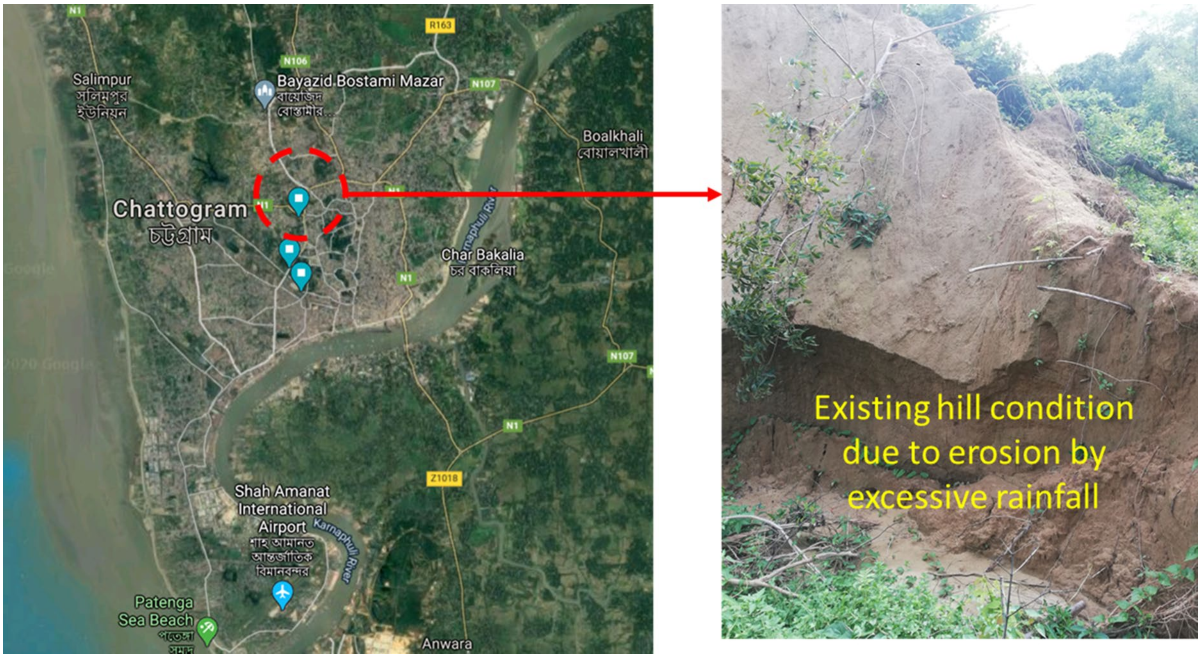


**Fig. 1** **a** Location of soil collection (Berma Haji hill) and **b** Photograph showing the present situation of the hill (eroded by heavy rainfall)

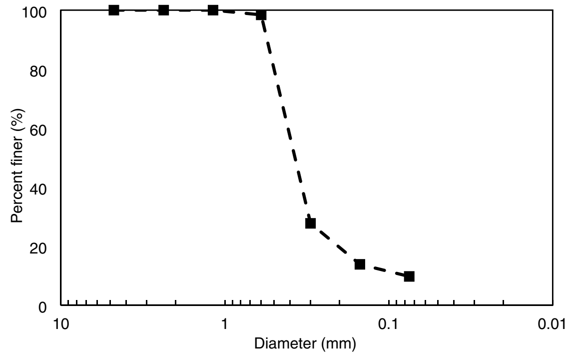


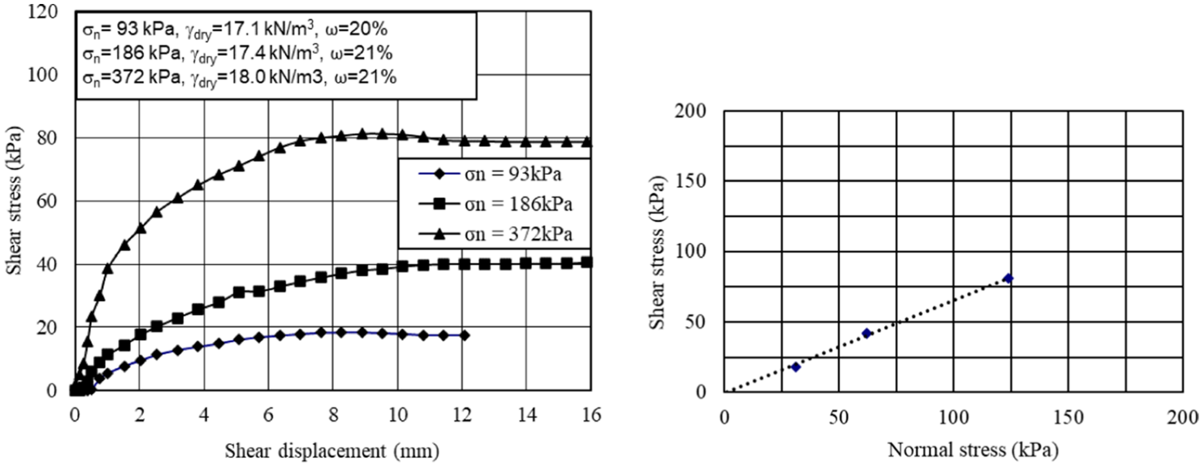
**Fig. 2** Grain size distribution curve of the collected soil sample from Berma Haji hill

from the field for conducting grain size distribution following ASTM C136, as shown in Fig. 2, and according to the Unified Soil Classification System (USCS), the soil was found to be poorly graded sand with silt (SP-SM). Previous study reported that mostly the hilly soil is characterized as silty sands, silty or clayey fine sand or mixtures of sand and silt with high permeability and low capacity of moisture retention (Ahmed and Dewan 2017). The soil erosion ($\mathrm{tha}^{-1}\ \mathrm{y}^{-1}$) has been calculated using the Universal Soil Loss Equation (USLE) where the erosion depends on rainfall erosivity index, soil erodbility factor, vegetative cover, slope length and steepness, and erosion control practice (Goldman and Jackson 1986). Considering no vegetative cover and the annual rainfall of Chattogram ($r = 3378$ mm) the soil erosion was found to be 567 $\mathrm{tha}^{-1}\ \mathrm{yr}^{-1}$ which represents a very severe erosion class. This rainfall-driven erosion increases the threat of landslides in the study area. Besides, the eroded soil load from the hills causes congestion of the drainage system. This ultimately results in water-logging of the city during monsoon which is considered as a secondary effect of the erosion of hills (Islam et al. 2017).

The chemical properties have also been tested, and the results are presented in Table 1. The pH suggests the soil is slightly acidic. The organic content, TN, phosphorus and potassium all are very low according to the classification of BARC (2005). N, P and K are called primary nutrients because of their large requirement and Sulfur is called a secondary nutrient (BARC 2005). So, there is a deficiency of all three primary nutrients in the soil.

**Table 1** Chemical properties of soil

| pH | Organic matter (%) | Total Nitrogen (%) | Potassium (K) meq/100 gm | Phosphorus (P) ppm | Sulfur (S) ppm | Boron (B) ppm | Zinc (Zn) ppm |
|---|---|---|---|---|---|---|---|
| 6.2 | 0.06 | 0.003 | 0.09 | 1.03 | 10.30 | 0.13 | 0.80 |



**(a)** **(b)**

**Fig. 3** **a** Shear stress versus shear displacement graph; **b** Mohr–Coulomb failure envelope obtained from direct shear test

Shear strength parameters, cohesion (*c´*) and angle of internal friction (*φ´*), were obtained from consolidated drained (CD) direct shear test following ASTM D3080. The test has been conducted with reconstituted samples, where the water content was kept close to natural moisture content ($\omega_n$). The Mohr–Coulomb failure envelope is shown in Fig. 3. Due to the presence of sand and silt the soil has a high internal angle of friction of 33° while the cohesion is nearly zero. Hydraulic conductivity (*k*) and specific gravity ($G_s$) have been obtained via ASTM D5084 and ASTM D854 respectively. The obtained values are stated in Table 2. Young's modulus (E) and Poisson ratio have been obtained from Bowels (2012) that states the range of Young's modulus from 5 to 20 MPa for sand with silt. At a moisture content of 10%, Mouazen et al. (2002) reported the Young's modulus of sandy loam close to 15 MPa for a dry density of 17.65 kN/m$^3$. As the dry density and natural moisture content of the poorly graded sand with silt used in this study ($\omega_n = 10.23\%$, $\gamma_{dry} = 17.17$ kN/m$^3$) are close to that reported by Mouazen et al. (2002), $E = 15 \times 10^3$ kPa has been considered here. The soil has been considered as homogenous.

**Table 2** Soil parameters obtained from the field, laboratory test and literature

| Soil property | Values |
|---|---|
| Natural moisture content, $\omega_n$ (%) | 10.23 |
| Dry density, $\gamma_{dry}$ (kN/m$^3$) | 17.17 |
| Saturated density, $\gamma_{sat}$ (kN/m$^3$) | 20.6 |
| Angle of internal friction, φ´ (°) | 33 |
| Cohesion, c´ (kPa) | 0 |
| Co-efficient of permeability, k (m/s) | $4.64 \times 10^{-5}$ |
| Specific gravity, $G_s$ | 2.65 |
| Young's modulus E (kPa) | $15 \times 10^3$ |
| Poisson ratio, *ν* | 0.3 |

## 2.4 Selection of Vegetation

The vegetation of the hills of Chattogram is characterized by semi-evergreen (deciduous) to tropical evergreen and was dominated by tall trees belonging to dipterocarpaceae, euphorbiaceae, lauraceae, leguminosea and rubiaceae (Chowdhury 2012). However, the shifting cultivation has resulted in coarse grasses, bamboos and regrown shrubs. Fallow hill slopes are created by the destruction of vegetation that is burned hence making the hills vulnerable to erosion and in the long run at risk of landslides. The general soil of the hills of Chattogram is also low in organic content and nutrients (Hassan et al. 2017). Steep slopes accompanied by heavy rainfall and erodible soil make cultivation more challenging. The selection of vegetation thus needed consideration regarding growth, survival rate, longevity, nutrient demand, and successional dynamics.

The physiological and morphological characteristics of *Vetiveria zizanioides* (L.) Nash, reclassified as Chrysopogon *zizanioides* (L.) Roberty, locally known as vetiver or "*binna* grass" makes it suitable considering the aforementioned factors. Vetiver can adapt to soils with pH varying between 3.0 and 10.5 (Truong and Loch 2004) and the collected soil's pH is also within this range. It can sustain extreme climatic conditions, temperature ranging from −20 to 55 °C and thrive under rainfall ranging between 300 and 6000 mm per year (Truong and Loch 2004) while regaining top growth fast after rainfall (Smith and Srivastava 1989). Instead of being invasive, vetiver is a pioneering plant growing in hostile conditions under nutrient constraints (Truong and Loch 2004). It further provides micro-climates for the growth of indigenous plants. For all these, vetiver can be suitable for hills of Chattogram and thus this study aims to investigate its mechanical reinforcing effects on the hills.

## 2.5 Growth Study of Vetiver

The growth of vetiver needs to be satisfactory in the hilly soil for reinforcing the slopes. A trapezoidal glass model of 900 mm × 600 mm × 150 mm was prepared with the soil of Berma haji hill to observe the growth. To facilitate drainage and prevent stagnation of infiltrated water, circular holes with a diameter of 2.54 cm were created at the base of the glass model which was placed above a 150 mm thick sand bed. The sand bed connected to the bottom of the model helped to rapidly drain the water escaping from the holes. The model has a slope of 1H:1.33 V where vetiver tillers have been planted in a square pattern with a 5 × 4 matrix as shown in Fig. 4. The c/c spacing between the tillers was 15 cm. The plantation was done in December 2018 which is characterized as the dry season in Bangladesh. Hence right after plantation, the plants were watered daily for 2 weeks.

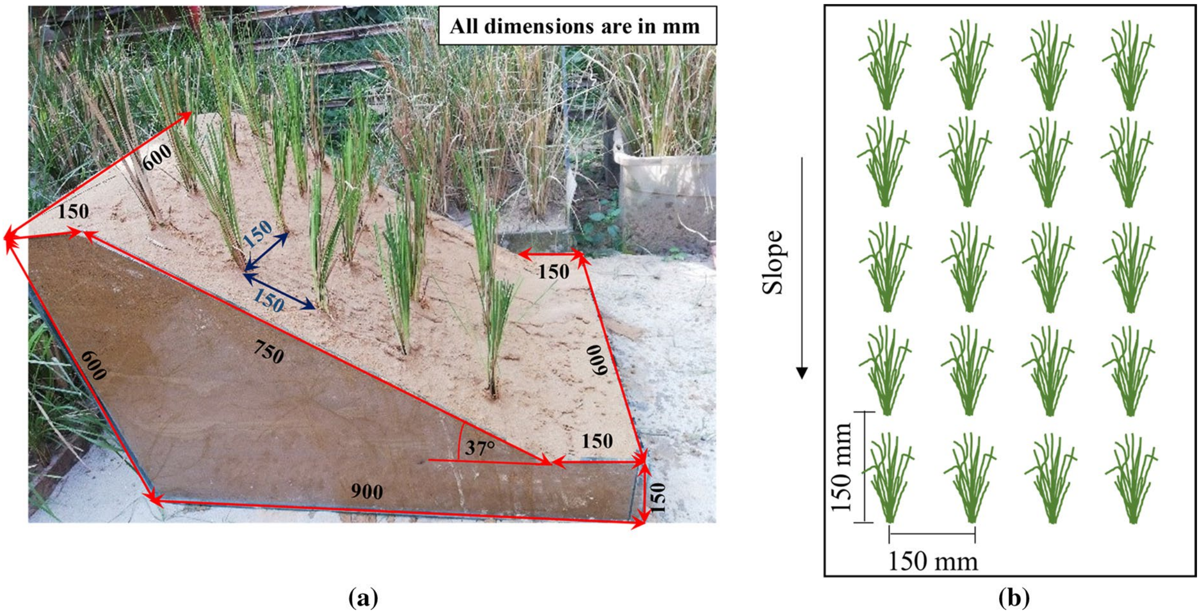


**Fig. 4** **a** Side view of glass model with vetiver tillers; **b** Schematic diagram of the arrangement (top view) of vetiver tillers

Throughout the 6 months, they have been watered in absence of natural rainfall. During the rainy season, no additional watering has been done. Though vetiver grass is tolerant of extreme climatic conditions, growth is hampered when under shade (Truong and Loch 2004). Hence, the models were kept exposed to sunlight under an open sky. In barren hill slope, there will be no shading from other plants and thus the model set up imitated the field scenario. After proper nurturing, measurements of root diameter and root lengths were taken after 6 months of the plantation.

Though the soil is unbecoming for plants intolerant of nutrient deficiency, vetiver's ability to sustain nutrient stress advocated for its growth in the glass models. After 6 months of the plantation, measurements show that the diameter of roots varied between 1.76 and 3.3 mm. The mean root diameter was obtained as 2.90 mm. The length of roots varied from 0.39 to 0.48 m with a mean length of 0.42 m while the mean shoot length was 0.702 m. The number of tillers per point increased from 3 to 15 on average.

## 2.6 Finite Element Modeling

2D finite element modeling has been performed using commercially available software PLAXIS. Here, variation in factor of safety (FS) due to vetiver under different distribution patterns, variable root zone depth ($h_r$) and altered slope geometry have been investigated. Alongside this, crest deformations at vegetated and bare conditions have been studied.

### 2.6.1 Slope Geometry

The slope angle $\beta$ has been determined at which the slope will be stable and at that angle, the effect of vetiver, with varying $h_r$, has been calculated. Figure 5 shows the schematic diagram of the slope geometry of a natural slope with a slope height H = 15 m. The effect has been further investigated by altering the natural slope into terraced slopes. Here the entire slope height has been divided into steps of different heights ($H_T$). Case I divides the slope into two steps each having $H_T = 7.5$ m. Case II and III respectively have three steps ($H_T = 5$ m) and five steps ($H_T = 3$ m). At varying $H_T$ suitable dimensions have been selected for the model following the basic geometry of Fig. 5.

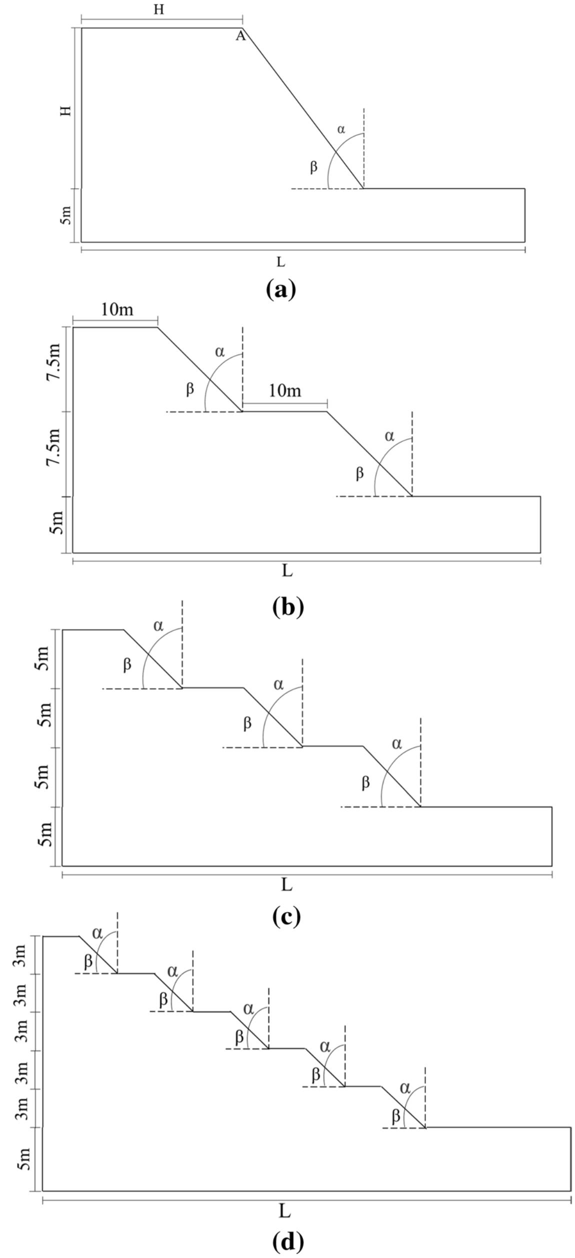


**Fig. 5** Schematic diagram of the model in FEM, **a** H = slope height for natural slope, A = crest of the slope; **b–d**: Case I, II and III where $H_T$ = height of each step of the terraced slope, L is the length of the slope, $\beta$ = slope angle, $\alpha + \beta = 90°$

### 2.6.2 Boundary Conditions

The bottom edge has been restricted against horizontal or vertical displacement. The sides have been fixed allowing only vertical displacement and restricting horizontal displacement. The boundaries are placed far away so that they do not affect the results.

### 2.6.3 *Modeling Soil and Root Reinforcement*

A plane strain model has been used in this study. Soil has been modeled according to the linear elastic perfectly plastic Mohr–Coulomb (MC) model. Parameters obtained from laboratory and field tests, presented in Table 2, have been used to define the soil. The bulk unit weight of the soil in the glass model was 15.47 kN/m$^3$ which was less than the field bulk unit weight of 18.63 kN/m$^3$. When exposed to rainfall, this lower density will generate greater erosion and early slope instability than the field condition owing to the loosely compacted state in the glass model. Thus to simulate field conditions, the in-situ field densities have been employed as input parameters during finite element model generation. The phreatic line has been considered at the bottom edge and the undrained condition has been simulated. The 15 nodded triangular elements have been used to define the soil matrix which has been meshed by selecting an appropriate mesh size. Incorporation of root in the soil can reinforce it in two ways, one is mechanically due to the generation of additional cohesion ($c_r$) and the other is hydrologically that is caused by evapotranspiration and changed hydraulic properties of soil (Ni et al. 2017). Only the mechanical effect of the roots has been studied here while the effect of roots was fused into the soil following the model of Wu et al. (1979).

### 2.6.4 *Roots' Mechanical Properties*

Roots of vetiver are weak in compression and strong in tension (Voottipruex et al. 2008). According to the proposed model of Wu et al. (1979), roots cross the shear plane perpendicularly and its tensile strength is mobilized during shearing. This provides additional shear strength to the root-soil matrix which is termed as added cohesion $c_r$. The added cohesion is defined as

$$c_r = t_r\left(\cos\theta \tan\varphi' + \sin\theta\right) \tag{1}$$

Here $\theta$ is the angle of shear distortion in the shear zone, $\varphi'$ is the soil friction angle and $t_r$ is the total mobilized tensile stress of root fibers per unit area of soil. Sensitivity analysis indicates that the values of ($\cos\theta \tan\varphi' + \sin\theta$) can be approximated as 1.2 for $25° < \varphi' < 40°$ (Wu 1976; Wu et al. 1979). Again, $t_r$ is the product of two parameters, the average tensile strength of the root ($T_R$) and the Root Area Ratio (*RAR*, ratio of the area occupied by roots to the area of soil). Hence, the final equation used for added cohesion becomes

$$c_r = 1.2 \times T_R \times RAR \text{ (MPa)} \tag{2}$$

Past researches provide empirical equations for the determination of average tensile strength of roots, $T_R$ where it is inversely related to root diameter (Voottipruex et al. 2008; Teerawattanasuk et al. 2014; Islam and Badhon 2020). In this study, the equation provided by Teerawattanasuk et al. (2014) ($R^2 = 0.806$) has been used to calculate $T_R$ and the value of $T_R$ for vetiver roots having a mean diameter of 2.90 mm was found to be 5.89 MPa.

Though different methods for determining *RAR* have been investigated in the past (Mattia et al. 2005; De Baets et al. 2008), the values vary largely. Here, the *RAR* of vetiver has been approximated based on the study of Machado et al. (2015) where *RAR* varies with soil depth. According to this procedure, the added cohesion at 0.5 m depth was calculated as 6.36 kPa which is within the range suggested by Chok et al. (2015). This has been assumed to be constant over the depth of soil. Most field studies conclude that predominantly the biomass of roots is found at the top 0.5 m of the soil where roots provide the maximum reinforcement and stabilize shallow slope (De Baets et al. 2007; Leung et al. 2015). The same is observed for vetiver as it has large clumps near the soil. But as depth increases the root diameter becomes smaller and this results in higher tensile strength which may counterbalance the reduction of *RAR* with depth and overall increase their product viz. the added cohesion. Again, a concentrated increase in *RAR* at depths for various species has been observed due to increased nutrient availability (Weaver and Clements 1938) and moisture content (Manschadi et al. 1998). Moreover, at steep slopes, higher root densities at greater depths have been reported (De Baets et al. 2007). These may increase the added cohesion at larger depths which as a result increases the root's reinforcing effect (Kokutse et al. 2016; Tsige et al. 2020). So, by assuming the added cohesion as constant, the mechanical reinforcement of vetiver roots is being taken on a conservative side.

It has been assumed that the effect of mechanical reinforcement by roots will remain till the depth roots penetrate the soil which is termed root zone depth ($h_r$). To incorporate this effect of root up to a certain depth, a different soil layer has been modeled and assigned to that depth. The soil layer has an increased value of cohesion equal to the calculated $c_r = 6.36$ kPa than the bare one. As the root zone depth increased, so did the depth of the soil layer with increased cohesion. Literature suggests that within 1 year of the plantation, vetiver roots can penetrate up to 3–4 m (Truong et al. 1995; Hellin and Haigh 2002) and in tropical conditions, the penetration depth may be up to 5 m (Truong 2008). In this study, while keeping the value of $c_r$ constant, the effect of root zone depth ($h_r$) till 3 m has been observed, dividing it into six classes at 0.5 m interval (0–0.5 m, 0.5–1.0 m, 1.0–1.5 m, 1.5–2.0 m, 2.0–2.5 m and 2.5–3.0 m).

#### 2.6.5 *Calculation of Factor of Safety (FS) and Stable Slope Angles*

In this study, the stability of the slope is calculated based on FS which is the ratio of available strength to strength at failure. When $FS > 1$, the slope is termed as stable or safe and $FS < 1$ results in an unstable slope (Chok et al. 2015; Kokutse et al. 2016; Nguyen et al. 2018). PLAXIS calculates FS based on phi-c reduction technique where the shear strength parameters, $c$ and $\varphi$ are reduced in increments until slope failure occurs. Threshold angles until which vetiver will provide significant safety have been determined by calculating the maximum safe angle at 6 different $h_r$. The geometry of slope has been modified and terraced condition has been modeled by varying the slope height ($H_T = 7.5$ m, 5 m and 3 m). The changes in FS for bare, vegetated conditions and the threshold angles have been determined for mentioned geometries.

### 2.7 Parametric Study

To investigate the behavior of vetiver in stabilizing slopes with different soil types, a parametric study has been conducted with sandy silt containing 14.5% sand and 65.64% silt. The soil was cohesionless having $c' = 0$, $\varphi' = 39°$, $\gamma_{dry} = 14.42$ kN/m$^3$ and $\gamma_{sat} = 18.82$ kN/m$^3$. These parameters have also been obtained from laboratory and in-situ testing of soil collected from another local hill of Chattogram, known as “Tiger Pass Hill”. Its detailed index and chemical properties can be found in Aziz 2020. Maximum bare slope angle, increase in factor of safety due to vetiver incorporation up to $h_r = 3.0$ m and threshold angle for the vegetated condition have been determined. For the terraced slope, FS has been calculated for 6 different slope angles, $\beta = 20°$, 27°, 32°, 37°, 44° and 55° for three different $H_T$ and the relation of FS with slope height and slope angle have been obtained.

## 3 Results and Discussion

### 3.1 Stability of Natural Slope and Safe Slope Angle

Figure 6 shows the obtained FS from the FEM analysis at varying slope angles $\beta$ for the natural slope. An attempt has been made to determine the maximum angle which yields $FS = 1$ for the bare hill slope. The results depict, as the slope angle is decreased, the FS increases. So, slope angle has a prominent effect on the slope stability and low to moderate slopes are more stable (Chok et al. 2015; Kokutse et al. 2016; Tsige et al. 2020). At 30°, the factor of safety is $FS_{bare} = 1.010$. This can be defined as the maximum angle where the natural slope will be stable under existing conditions. As the slope becomes steeper, the tendency of downward movement of materials by gravitational force becomes greater (Biswas et al., 2017). This generates higher shear stresses and results in increased instability. The existing slope angles of

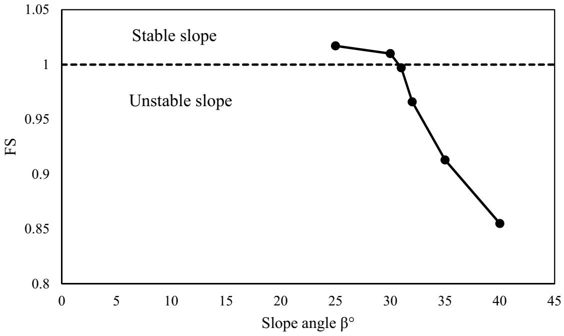


**Fig. 6** Variation of FS with slope angle β at bare condition

Berma Haji hill are higher than 30° in most of the places. Hence, the exiting bare hills are unstable, and measures need to be taken towards stabilizing them.

### 3.2 Effect of Vetiver on the Stability of the Natural Slope

For the natural condition of the slope, the vetiver's effect has been incorporated for increasing the stability at $\beta = 30°$. Vetiver can naturally grow at any part of the hill and so the consequences of its growth on different parts of the slopes have also been investigated. The results are presented in Table 3.

In bare condition, the slope was marginally safe with an FS of 1.010. A slight increase in slope angle reduces the FS below 1 and makes the slope unstable as seen in Fig. 6. The results from FEM analysis show that vetiver has increased the slope stability marginally, by 1.054 times, and reduced crest deformation by 3 mm as it grows all over the slope (including top and bottom surface) having $h_r = 0.5$ m. At the same $h_r$ when vetiver growth is limited to the inclined surface of the slope, the FS increases from 1.01 to 1.045, producing almost no improvement in FS. The reinforcing effect of vetiver roots comes from the mobilized tensile strength of these roots while crossing the failure plane (Wu 1976; Wu et al. 1979). However, at $h_r = 0.5$ m, the slip surface is not intercepted by the roots hence the mechanical reinforcement is not fully achieved. Hence a negligible to no increase of FS is observed.

At bare condition, the failure was shallow slope failure, the slip surface being located at a depth of 2.8 m to 3 m. The highest effective stresses are generated at the inclined slope surface and the crest of the slope. The former location, especially the middle surface, is also accompanied by maximum deformations. As the whole slope is covered with vetiver, despite a low increase in FS, both deformation and effective stresses decrease. On the contrary, when the effect of vegetation is limited to the inclined slope surface only, the effective stresses remain higher than in the previous case and deformations at the crest remain unchecked. As reinforcing the slip surface is vital for stability, the effect of vegetation only at the top or toe of the slope, which does not strengthen the potential failure surface, generates a negligible effect in providing stability. Hence, it can be inferred that to obtain a maximum advantage, the entire slope including the top and bottom of the slope should be covered with vetiver as suggested by previous studies of Chok et al. (2015) and Tsige et al. (2020).

### 3.3 Effect of Root Zone Depth of Vetiver on the Stability of the Natural Slope

The effect of root zone depth on FS of the natural slope is presented in Table 4.

When the effective root zone is up to 0.5 m, the FS increases from 1.01 to 1.064 which is quite insignificant. As the depth of the root zone increases and becomes greater than 2 m, the FS increases and becomes 1.13 to 1.16 times of $FS_{bare}$. Islam et al. (2020) also observed that, for silty sand, vetiver roots can increase the FS by around 15%.

**Table 4** Factor of safety and crest deformation of vegetated slope ($\beta = 30°$) with varying root zone depth ($h_r$)

| Root zone depth $h_r$ (m) | FS | | Deformation of crest A (mm) | |
|---|---|---|---|---|
| | Bare soil | Rooted soil | Bare soil | Rooted soil |
| 0.5 | 1.010 | 1.064 | 37.20 | 34.23 |
| 1.0 | | 1.079 | | 32.37 |
| 1.5 | | 1.081 | | 31.52 |
| 2.0 | | 1.103 | | 30.83 |
| 2.5 | | 1.136 | | 28.58 |
| 3.0 | | 1.171 | | 27.95 |

**Table 3** Factor of safety of rooted soil at $\beta = 30°$

| Condition of soil | Bare slope | Vetiver on entire slope including top and bottom surface of the slope | Vetiver only on the inclined surface of the slope | Vetiver on top of the slope | Vetiver on toe of the slope |
|---|---|---|---|---|---|
| Factor of safety | 1.010 | 1.064 | 1.045 | 1.024 | 1.024 |
| Increase in FS (as multiple of $FS_{bare}$) | – | 1.054 | 1.035 | 1.014 | 1.014 |

The added roots alone cannot provide the desired stability if they cannot reach the slip surface. As depicted in Fig. 7, they need to intercept the shear surface (Kokutse 2003; Kokutse et al. 2006) which may be located up to 2 m below the soil surface (Norris et al. 2008). Here, the roots at greater depth ($h_r = 2.0$ m and beyond) transverse the critical failure surface and increases FS to some extent due to the mechanical effect of the roots. Even though this numerical increase in FS may not be considerable for this slope height of 15 m, the reduction of topsoil erosion due to the cover of vetiver also plays an important part in ensuring stability. In bare slopes, the erosion by wind and rain makes the slope steeper and as a result, the FS reduces. Vetiver coverage reduces the intensity of this process. Thus vetiver imparts stability to the slope both by proving mechanical reinforcement and reducing surface erosion.

Also, the FS at vegetated state may be underestimated as the aspect of hydrological reinforcement via evapotranspiration and changed hydraulic properties of soil induced through roots have not been taken into consideration. Uptake of water by roots generates suction which increases soil shear strength (Ng et al. 2007). The effect of suction goes beyond root zones and has been reported to be as much as 4 times the root depth (Ng et al. 2013, 2014). The previous analytic study by Ni et al. (2017) suggests that not only the mechanical effect of roots but also the effect of hydrological reinforcement is important in addressing shallow slope stability problem as the hydrological effect is pronounced due to higher preserved suction at depths of 1–2 m, where critical slip surfaces typically generate.

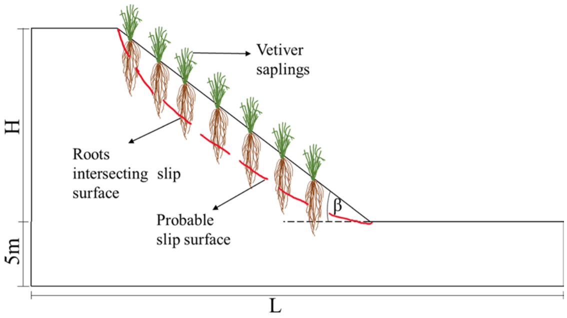


**Fig. 7** Schematic diagram of vetiver roots penetrating potential failure surface

As previous studies of Liang et al. (2015, 2020) reported a significant reduction in crest settlement due to root reinforcement that contributes to slope stability, the total deformation at the crest of the slope (point A), corresponding to the plastic state has also been studied here. For bare condition, the deformation was around 37.20 mm. As vetiver was introduced, deformation of the crest decreased as shown in Table 4. When $h_r$ increased from 0.5 to 3.0 m, the deformation decreased from 34.23 to 27.95 mm. Thus the deformation is reduced by almost 10 mm. The ranges and distribution of total deformation along the slope at $h_r = 0.5$ m and $h_r = 3.0$ m are shown in Fig. 8. The reduction of crest deformation due to increasing root zone depth also advocates the effectiveness of vetiver in slope stability. Similar to this study, due to being fast and providing a first-order approximation of soil behavior the linear constitutive models like Mohr–Coulomb (MC) are commonly used in numerical analysis (Saleh et al. 2021). However, MC model may sometimes overestimate the deformations as it does not take the strain-dependent stiffness behavior of the soil into consideration (Hsiung and Dao 2014) while analyzing it as a linearly elastic and perfectly plastic material. For better approximations of the deformation Hardening Soil (HS) model can be used which follows the same failure criteria as the MC model while adopting a hyperbolic stress–strain relation (Hsiung and Dao 2014).

### 3.4 Threshold Angle of the Vegetated Natural Slope

Table 5 shows the FS at different slope angles greater than the maximum stable slope angle for the natural slope.

Initially, the roots of vetiver provide enough safety to the slope at $\beta = 30°$. As the angle is increased, the safety provided by the vegetation is reduced and so is the FS. At different root zone depths, the maximum stable slope angle with vegetation differs. The maximum safe angle ($FS > 1$), that can be achieved by reinforcing of vetiver is 36° when $h_r$ is 3 m. As the root zone depth decreases, the maximum safe angle also decreases. Hence, from the safety analysis, it can be perceived that the positive effect of vetiver is inhibited by the steepness of the slope after a threshold value for $\beta$ has been reached. This results support the fact that slope angle is the most important geometric parameter in determining stability (Kokutse 2003;

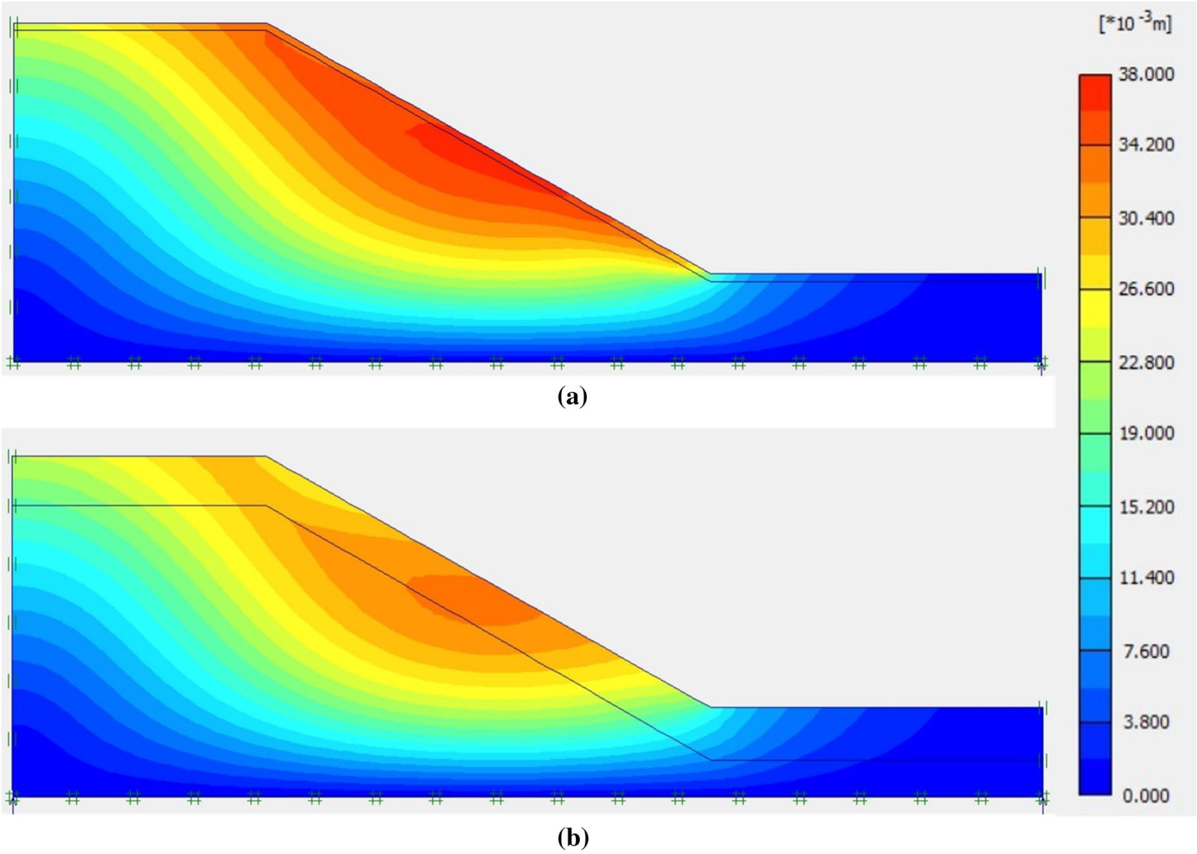


**Fig. 8** Total deformation of the slope at β = 30° with vetiver on entire slope including top and bottom surface **a** $h_r = 0.5$ m; **b** $h_r = 3.0$ m

**Table 5** FS at different slope angles > 30° at varying root zone depth ($h_r$)

| Factor of safety | | | | | | |
|---|---|---|---|---|---|---|
| Root zone depth $h_r$ (m) | 3 | 2.5 | 2 | 1.5 | 1 | 0.5 |
| *Slope angle β (°)* | | | | | | |
| 31 | 1.145 | 1.106 | 1.087 | 1.049 | 1.038 | 1.027 |
| 32 | 1.103 | 1.076 | 1.048 | 1.020 | 1.027 | < 1 |
| 34 | 1.054 | 1.031 | 1.004 | < 1 | < 1 | < 1 |
| 35 | 1.023 | < 1 | < 1 | < 1 | < 1 | < 1 |
| 36 | 1.010 | < 1 | < 1 | < 1 | < 1 | < 1 |
| > 36 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 |

Chok et al. 2015; Kokutse et al. 2016). In this study, the mean threshold angle ($\beta_{lim}$) with a standard deviation has been obtained as 33.33 ± 1.97° for poorly graded sand with silt. Here the FS is 1.06 ± 0.045. Kokutse et al. (2016) obtained $\beta_{lim}$ for silty sand as 31.5 ± 2.43° resulting in a FS of 1.19 ± 0.07.

Due to this, when $\beta > \beta_{lim}$, only the use of vetiver will not be adequate for making slopes stable. In the field condition, most of the slope angles are greater than $\beta_{lim}$. Hence some alternative techniques need to be applied to ensure safety. Previous study by Kokutse et al. (2016) suggests, as the slope height decrease, it has a favorable effect on slope stability. So, reducing the slope height along with the use of vetiver can impart desirable safety to the hillslopes when $\beta > \beta_{lim}$. The concept of cultivation through terraced slope divides the entire slope into smaller steps with smaller slope heights ($H_T$) which is also practiced locally. The reinforcing effect of vegetation can be enhanced through this process at slope angles greater than $\beta_{lim}$.

### 3.5 Stability of Bare Terraced Slope

Terraces have been created by dividing the entire slope into smaller steps by varying the slope height, thus the number of steps. However, the total height has been kept as 15 m for all three cases. FS for different slope heights in terraced condition and at different slope angles have been analyzed for bare condition and presented in Fig. 9.

As compared to the natural slope having H = 15 m, when the slope height is reduced to 7.5 m and then to 5 m by introducing terracing, the increase in stable slope angle is very negligible, 1° and 2° respectively producing FS of 1.010 and 1.026. However, as the number of steps is increased and terraces are created with a further reduction of slope height to 3 m, the stable slope angle increases to 45° corresponding to FS = 1.010. The reduced height of the slope advocates for this advantage gained in the case of stable slope angles at fallow condition. This signifies that terracing with a suitable step size can be adopted as a measure to increase the stability of the barren hills.

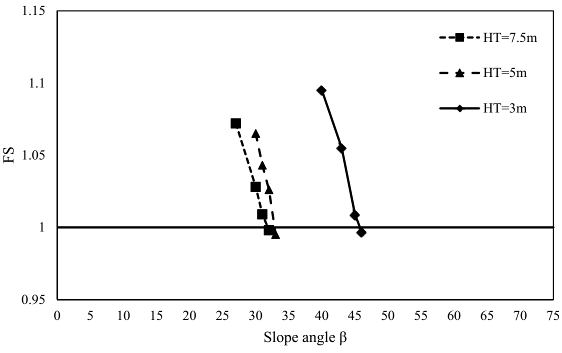


**Fig. 9** FS of terraced slope at different slope angles at the bare condition

### 3.6 Effect of Vetiver on the Terraced Slope

#### 3.6.1 *Increase in Factor of Safety*

Figure 10 presents the effect of vetiver on the terraced slope at 3 different slope heights and their corresponding stable slope angles. From Fig. 10, it is certain that vetiver roots increase the FS with increasing $h_r$ for terraced slope irrespective of slope angle and slope height. However, compared to the natural slope, the positive effect of vetiver in terraced slopes is more pronounced which can be inferred from Table 6.

For the natural slope, the maximum increase of FS due to mechanical reinforcement of vetiver was only 1.16 times of $FS_{bare}$. On the contrary, at $h_r = 3$ m and at slightly higher angles viz, 31° and 32°, the terraced slope's FS increases to 1.432 and 1.678 respectively, which is nearly 1.42 and 1.64 times of the FS at bare condition. For smaller slope height, $H_T = 3$ m and

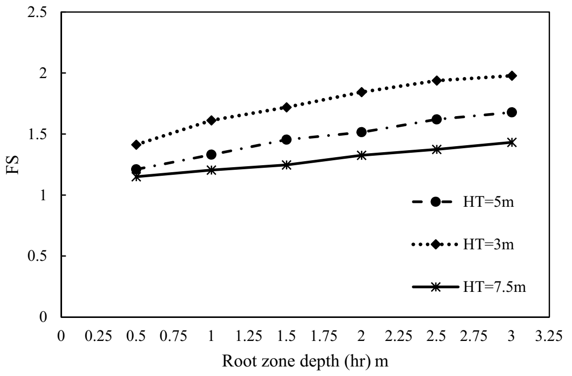


**Fig. 10** FS of terraced slope at 3 different slope heights ($H_T$) with vetiver at varying root zone depth ($h_r$)

**Table 6** Percent increase in FS at different $h_r$ and different $H_T$ for terraced slope

| Root zone depth $h_r$ (m) | % increase in FS for vetiver (multiple of FS at the bare condition of corresponding geometry) | | |
|---|---|---|---|
| | $H_T = 7.5$ m | $H_T = 5$ m | $H_T = 3$ m |
| 0.5 | 13.97 (1.139) | 18.03 (1.180) | 40.04 (1.400) |
| 1 | 19.43 (1.194) | 29.73 (1.297) | 59.76 (1.597) |
| 1.5 | 23.53 (1.235) | 41.72 (1.417) | 70.37 (1.703) |
| 2 | 31.42 (1.314) | 47.66 (1.476) | 82.76 (1.827) |
| 2.5 | 36.17 (1.361) | 57.89 (1.578) | 92.07 (1.920) |
| 3 | 41.92 (1.419) | 63.55 (1.635) | 96.04 (1.960) |

steeper slope angle, $\beta = 45^\circ$, FS increases by 1.4 times at shallow root zone depth of 0.5 m. At $h_r = 3$ m, for this geometry, FS = 1.978 is obtained which is almost 2 times higher than FS at bare condition. The consideration of hydraulic reinforcement may increase the FS even more. Thus, this study implies that vetiver will be much more effective in stabilizing the slopes at the terraced condition with an increased number of steps possessing lower slope heights.

### 3.6.2 *Threshold Angles*

Threshold angles for varying $H_T$ of the terraced slope have been reported in Table 7.

With decreasing $H_T$, $\beta_{lim}$ increases. However, the higher value of $\beta_{lim}$ has greater standard deviations. One probable reason for this is the larger range of safe slope angles ensured at varying root zone depths at different $H_T$. At $H_T = 7.5$ m and $h_r = 0.5$ m, FS > 1 can be obtained until $\beta \leq 38^\circ$ which becomes 57° when $h_r = 3.0$ m. Similarly, for $H_T = 5$ m, $\beta \leq 50^\circ$ yields FS > 1 at $h_r = 0.5$ m which can go up to 85°at $h_r = 3.0$ m. Hence, the safe slope angles at varying $h_r$ have a greater range for $H_T = 5$ m than $H_T = 7.5$ which accounts for the greater deviation from mean values. Again, for $H_T = 3$ m, even at $\beta = 90^\circ$, FS remained 1.35 ± 0.118. Thus, for the terraced slope where each step is 3 m high, vetiver can even stabilize vertical cuts which are quite common in the hills of Chattogram.

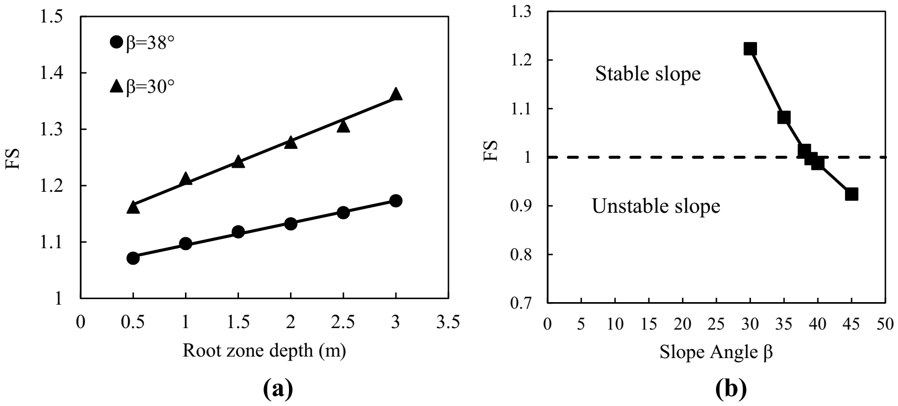
**Table 7** Threshold slope angle of vegetated slope for terraced condition at varying $H_T$

| Slope height $H_T$ (m) | Threshold angles $\beta_{lim}$ (°) | FS |
|---|---|---|
| 7.5 | 47.83 ± 7.57 | 1.02 ± 0.005 |
| 5 | 70.33 ± 12.48 | 1.01 ± 0.008 |

## 3.7 Parametric Study

### 3.7.1 *Effect of Vetiver on Sandy Silt*

In the case of sandy silt, at $\beta = 30^\circ$ and $h_r = 3$ m, as shown in Fig. 11a FS of 1.363 is obtained which is almost 1.30 times higher than $FS_{bare} = 1.064$ and total deformation reduces from 23.73 to 20 mm. Compared to the same geometry of SP-SM, this FS is 1.16 times higher and deformation is 28% lower. Also, for sandy silt the maximum bare stable angle is 38°, having FS of 1.014 as shown in Fig. 11b. Despite being steeper, the total deformation at the crest for this bare condition was 27.36 mm which is again 9.84 mm lower than the deformation obtained at the bare condition of SP-SM at $\beta = 30^\circ$. The higher angle of internal friction of sandy silt is thought to be responsible for this reduced deformation. Yuan et al. 2020 also suggested a reduction of deformation of slope crest due to an increase in the angle of friction for non-cohesive soils. As vetiver was incorporated at $\beta = 38^\circ$ for sandy silt, the FS increased and the values are presented in Fig. 11a. At $h_r = 3.0$ m, the FS is maximum, 1.173, yielding 1.15 times higher FS than the bare condition. The deformation also decreases as vetiver is added and becomes 21.65 mm when $h_r$ is 3.0 m. Though this improvement in deformation reduction for sandy silt, around 6 mm, is lower than the vegetated state of SP-SM, it can also be attributed to the steeper slope angle. Observing the effect of vetiver for both the



**(a)** **(b)**

**Fig. 11** **a** Increase of FS with root zone depth for sandy silt at β = 30° and 38°; **b** Variation of FS with slope angle β at the bare condition for sandy silt

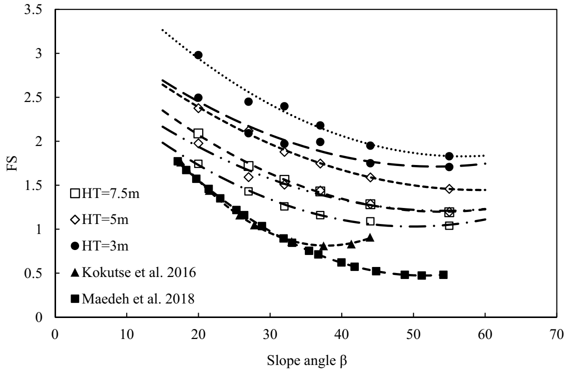


**Fig. 12** Variation of FS with slope angle of terraced slope for 3 different $H_T$

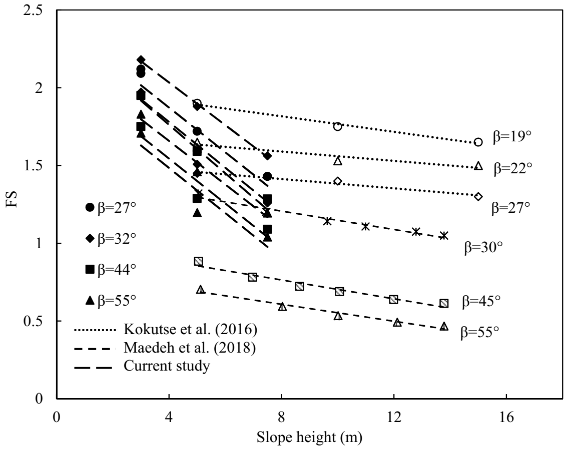


**Fig. 13** Variation of FS with slope height $H_T$ of terraced slope for 4 different slope angles

soils at their respective maximum bare stable angle, the FS and its increase is close. Nonetheless, vetiver can ensure this FS at a much steeper angle for sandy silt. The obtained threshold angle $\beta_{lim}$ for sandy silt is $46.33 \pm 3.50°$ with a FS of $1.01 \pm 0.01$ which is as well higher than that of SP-SM. Thus the effect of vetiver can be inferred to be slightly higher for sandy silt than SP-SM. Previous study by Suhatril et al. (2019) likewise reported better improvement of FS, nearly 43%, with vetiver for silty soil than other cohesive ones. In the case of clayey soil, studies of Suhatril et al. (2019) and Islam et al. (2020) reported almost no to negligible increase in FS after the addition of vetiver root due to the deep seated failure mechanism slopes made of cohesive soil. Therefore vetiver's efficacy in reducing the susceptibility of shallow slope failure in cohesionless soil has been established.

### 3.7.2 *Effect of Slope's Geometry on Stability*

Figure 12 presents the mean values of FS for 6 values of $h_r$ against six slope angles, $\beta = 20°$, 27°, 32°, 37°, 44° and 55°, for three different slope heights, $H_T = 7.5$ m, 5 m and 3 m and two types of soil. In all cases, a parabolic relationship between the FS and slope angle has been established with a strong correlation. The equations are presented in Table 8 where the $R^2$ values varied from 0.94 to 0.99. Kokutse et al. (2016) and Maedeh et al. (2018) proposed similar relation between FS and slope angle as $FS = 0.0023\beta^2 - 0.174\beta + 3.83$ ($R^2 = 0.93$) and $FS = 0.0011\beta^2 - 0.1137\beta + 3.3915$ ($R^2 = 0.96$) respectively for natural slope. These correlations validate the finding of this study. It also signifies that despite changing the geometry of the slope the

**Table 8** Relation between FS and slope angle for different slope height in terraced condition

| Soil type | | Slope height ($H_T$) (m) | | |
|---|---|---|---|---|
| | | 7.5 | 5 | 3 |
| Poorly graded sand with silt | Equation | $FS = 0.0008\beta^2 - 0.0782\beta + 2.9805$ | $FS = 0.0006\beta^2 - 0.0674\beta + 3.038$ | $0.0007\ \beta^2 - 0.0717\ \beta + 3.6162$ |
| | $R^2$ value | 0.9945 | 0.9729 | 0.9462 |
| Sandy silt | Equation | $FS = 0.0008\beta^2 - 0.0819\beta + 3.4084$ | $y = 0.0006\beta^2 - 0.0723\beta + 3.5917$ | $y = 0.0008\beta2 - 0.0931\beta + 4.4768$ |
| | $R^2$ value | 0.9972 | 0.9966 | 0.9785 |

effect of slope angle on FS remains similar and a decrease in slope angle stabilizes the slope. Figure 13 shows the change of FS with slope height in terraced slope for different slope angles. The plot reveals a linearly negative correlation between FS and $H_T$. The $R^2$ value varied between 0.87 and 0.99 for the differing slope angles. The comparison of the correlation with the study of Kokutse et al. (2016) and Maedeh et al. (2018) show similar relations, however, the slope of the regression lines are milder. Due to the small slope heights in the case of the terraced slope, the rate of decrease of FS with an increase in slope height is higher (− 0.14) than compared to the previous study of Kokutse et al. (2016) where the proposed equation was $FS = -0.02H + b$, b being the constant term of the regression equation and H the slope height.

## 4 Conclusion

The study examined vetiver grasses' growth in nutrient deficit hilly soil (SP-SM) of Chattogram through a model study which was found to be satisfactory. Through finite element modeling, incorporating the soil properties derived from laboratory tests, the study further aimed to obtain the safe slope angles of hills and quantify the effect of mechanical properties of vetiver grass root on slope stability at varying distribution and root zone depths for different geometries. Threshold slope angles for vetiver grass to be effective in slope stabilization were determined along with performing parametric studies. Finally, the following have been obtained:

1. At bare condition, the natural slope with a slope height of 15 m, is unstable beyond $\beta = 30°$ for poorly graded sand with silt (SP-SM). As the hill slopes in the field are steeper, this calls for protective measures to increase and ensure slope stability.
2. Comparing all four cases of different spatial distribution, though covering the whole slope yielded a maximum increase of FS at H = 15 m, $\beta = 30°$ and $h_r = 0.5$ m for SP-SM, the increase is negligible due to roots not penetrating the potential slip surface. In the same distribution, with the increase of root zone depth from 0.5 to 3 m the FS increases by 1.16 times than $FS_{bare}$ along with reducing the total crest deformation by nearly 10 mm. According to the parabolic relation between FS and slope angle, the increase in $\beta$ reduces slope stability and thus beyond $\beta = 33.33 \pm 1.97°$, the effect of vetiver is inhibited by the steepness of the slope in case of the natural slope with H = 15 m.
3. In bare terraced slopes, stable slope angles increase to be 31°, 32° and 45° respectively at $H_T = 7.5$ m, 5 m and 3 m. As $h_r$ varies from 0.5 to 3 m, the FS at respective stable slope angles becomes 1.14–1.41 times ($H_T = 7.5$ m); 1.18–1.63 times ($H_T = 5$ m) and 1.40–1.96 times ($H_T = 3$ m) higher than bare slope's FS. Threshold angles of terraced slope show, vetiver can provide safety to slopes up to $47.83° \pm 7.57°$ and $70.33° \pm 12.48°$ respectively for $H_T = 7.5$ m and $H_T = 5$ m. At $H_T = 3$ m, vertical slopes are also found to be stable. Hence, the effect of vetiver in increasing FS is more pronounced in all three cases of the terraced slope than compared to the natural slope of large slope height (H = 15 m) following the negative correlation of FS and slope height. Therefore, while vetiver alone may not be sufficient to provide safety to natural slopes, changing slope geometry accompanied by vetiver can ensure the stability of slopes.
4. Parametric study shows that at the same geometry of natural slope, the increase in FS due to incorporation of vetiver is greater for sandy silt along with lower crest deformations than SP-SM. Bare slopes of sandy silt can be stable up to 38° along with a vegetated threshold angle of $\beta_{lim} = 46.33 \pm 3.50°$, both being higher than poorly graded sand with silt. Thus, vetiver was more effective in tackling shallow slope failure for sandy silt than SP-SM.
5. It can be recommended that for the SP-SM soil, if the existing steeper slopes can be reduced to $33.33 \pm 1.97°$ which is $46.33 \pm 3.50°$ for sandy silt, then stability can be achieved through the application of vetiver only while ensuring a FS above 1.0. However, this may not be viable owing to the requirements of a large amount of earthwork. Hence to address the instability of slopes with angles greater than the mentioned ones, alongside vetiver plantation, terracing the slope by reducing the slope height can be an alternative. The obtained threshold angles for various

slope heights of the terraced slope provide an initial recommendation for selecting an optimal slope geometry for the restoration of slope stability with vetiver.

In this study, the additional cohesion, thus the mechanical reinforcement provided through vetiver has been computed based on root tensile strength and RAR. The latter was calculated based on the equation suggested by previous studies. However, calculating the RAR from the glass model at different depths could have provided a better approximation of the added cohesion. Again, to precisely quantify the practical increase in shear strength of the soil-root matrix, triaxial tests could have been performed. The future study has the scope of incorporating these along with considering the effect of hydraulic reinforcement provided by vetiver. The combined effect of mechanical and hydrological reinforcement would help to better judge the contribution of vetiver on slope stabilization. Despite being time-consuming and costly, field trials can also be initiated to observe the vetiver root morphology and its influence on slope stabilization while comparing the practical results with the numerical findings.

Regardless of these limitations, this study attempted infusing eco-friendly practices in solving the frequent problem of slope instability. As a secondary effect of erosion reduction by vetiver, the sediment load on drainage systems of surrounding urban areas will be reduced that as a result will reduce the water logging problem. Primarily this study will initiate informing the professionals, authorities and policymakers to see the application of vetiver grass as an efficient and sustainable one for reducing landslide risks for built-up hilly areas along with benefiting the socio-economic lives of the local community.

**Acknowledgements** The authors acknowledge Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh for facilitating necessary financial and laboratory support for pursuing this study. The authors also acknowledge the help of Chattogram City Corporation for providing the contour maps of hills of Chattogram.

**Author's Contribution** IMS and AS conceived the idea. AS conducted the laboratory tests and the numerical analysis. IMS supervised the project, provided critical feedback and reviewed all the steps of the research.

**Funding** The research was financially supported by the Academic Research Grant of Bangladesh University of Engineering and Technology (BUET).

**Availability of Data and Material** All the necessary data have been included in the manuscript.

**Code Availability** No new or custom code has been used in this study.

**Declarations**

**Conflict of interest** The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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