



A simple approach for estimating contribution of vetiver roots in shear strength of a soil–root system

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Abstract

Bio-engineering technology, using vegetation, is an innovative and low-cost measure to address slope failure-related problems. To quantify the contribution of vegetation roots for increasing the strength of soil, several laboratory and field investigations have been conducted in this study. At first, the morphological characteristics of vetiver (*Chrysopogon zizanioides*) were studied. It was found that vetiver root can grow up to 1 m in three months in sandy soil. The average tensile strength of full-grown vetiver root was 27 MPa, and with the increase in root diameter, root tensile strength decreases. A correlation was developed between the tensile strength and diameter of the root, which was compared with previous studies. Laboratory tests were conducted on root mixed soil and found that the shear strength of rooted soil increases with the increase in root length and decrease in soil water content. Also, an attempt has been made to estimate the improved shear strength of rooted soil by developing a correlation between the additional shear strength of rooted soil and the tensile strength of roots per unit area of soils. To evaluate the shear strength of vetiver-rooted soil, in situ tests were conducted in naturally grown vetiver land for both rooted soil and bare soil. An approximately linear relationship was observed between the additional shear strength of rooted soil and the mobilized tensile strength of roots. Finally, a mathematical model was developed based on the experimental outcomes. This simple model can be used to estimate the shear strength parameters of rooted soil.

Keywords Additional shear strength · Mathematical model · Rooted soil · Slope stabilization

List of symbols

A	Cross-sectional area of the soil shear plane
A_R	Total cross-sectional area of the roots crossing the shear plane
ASTM	American Society for Testing and Materials
D	Mean root diameter
F_{\max}	Maximum force at the failure of the root
T_R	Tensile strength developed in roots
T_{ult}	Ultimate tensile strength of root
γ	Shear strain
τ	Shear stress

θ	Angle of shear distortion in the shear zone
σ_{tR}	Mobilized tensile stress of root fibers per unit area of soil
φ	Friction angle
$\Delta\tau$	Increase in shear strength

Introduction

Earthen slopes constructed of soft soils, including natural slopes like those of riverbanks; hillsides; and man-made slopes and road embankments, are vulnerable to rain-cut erosion and stability problems [1]. Slope failures and related damages occur every year in many countries [2]. A variety of approaches to dealing with slope instability is available, and the choice of one depends on needs, risks, and available funds. The conventional slope stabilization technique includes removal and replacement of existing soil with competent soil materials, introduction of retaining walls, installation of soil nails, use of geosynthetics, and so on [3]. However, the major drawback of conventional techniques is that they are all extremely expensive solutions and also provide

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unnecessary environmental impacts. A low-cost sustainable solution for stabilization of shallow slope failure includes the plantation of vegetation. Planting vegetation along the slopes is one of the most effective and economical solutions that is used worldwide [4–7]. Compared to the conventional methods, use of vegetation is beneficial in terms of economic, environmental and aesthetic aspects [8].

Vegetation has gained recognition now a days because of its effectiveness in slope stabilization [9]. However, to evaluate its actual performance in stabilizing earthen slopes, it is important to evaluate the characteristics of the soil–root matrix [10, 11]. Field and laboratory tests were carried out by many researchers [12–15] to determine the strength behavior of soil–root matrix, and it was found that the greatest benefits of planting vegetation are derived from root reinforcement. It should be noted, however, that the relative importance of roots on soil aggregation varies among biomes, soil, and climate conditions [16]. The effects of root as reinforcement can be assessed directly in terms of the additional shear strength contributed by roots in soil–root matrix [17, 18]. Relatively simple and straight forward force equilibrium models have been developed and offer convenient insights into the characteristics of root-reinforced soil [19].

Root morphology is a very important characteristic of roots that controls their efficiency in slope stabilization. Some most common vegetations found in Bangladesh are wild cane (*Saccharum spontaneum*), tiger grass (*Thysanolaena maxima*), and vetiver grass (*Chrysopogon zizanioides* or formerly, *Vetiveria zizanioides*). Among these, vetiver has a longer, stronger, and bushy root network system, which makes it suitable for shallow slope stabilization and erosion control [20, 21]. The root of vetiver grass can grow very fast and can reach up to 3 m in depth [22]. The massive, deep penetrating, and strong root system largely affects the shear strength of the rooted soil matrix [23].

The shear strength parameters for rooted soil is essential for the analysis of slope stability and other geotechnical analysis. In most cases, small scale laboratory test arrangements do not simulate the actual field conditions of the soil–root matrix; and thus, the additional shear strength due to the roots cannot be obtained [24]. So large scale shear tests or in situ tests are recommended for determining the shear strength of rooted soil. But arranging large scale tests or in situ tests is often difficult, time-consuming, and expensive. So, the development of a simple approach for estimating the additional shear strength created by roots in soil is essential to analyze in situ test results. But very few efforts [12–15, 18] have been made to develop a mathematical model for vetiver-rooted soil, which will be able to predict the increased shear strength of rooted soil from basic soil and root parameters. The prime objective of this study is to develop a mathematical model that can be used to assess the

increase in shear strength of soil due to soil–root matrix and provide a convenient means for analyzing soil stability by finite element or classic stability analysis methods.

Materials used

For the vetiver growth study, sandy soil was used because most of the embankments in Bangladesh and similar deltas are constructed of sandy soil due to its local availability. Sandy soil was collected from Buriganga riverbed located in Dhaka, Bangladesh, in this study, and so this soil is named ‘Buriganga Soil’. In situ tests were conducted in a naturally grown vetiver nursery located at Pubail, Gazipur, Bangladesh. This soil is named ‘Pubail soil’. Soil samples were collected for detailed laboratory investigations to determine the index and shear strength properties of the used soils. The laboratory test results have been summarized below:

Buriganga soil

The specific gravity of the Buriganga soil was 2.74. Grain size distribution was conducted by sieve analysis (Fig. 1). Test results indicated that the coefficient of uniformity and coefficient of curvature of the soil sample are 1.86 and 1.1, respectively. As per Unified Soil Classification System ASTM D2487 [25], the Buriganga soil was classified as poorly graded sand (SP).

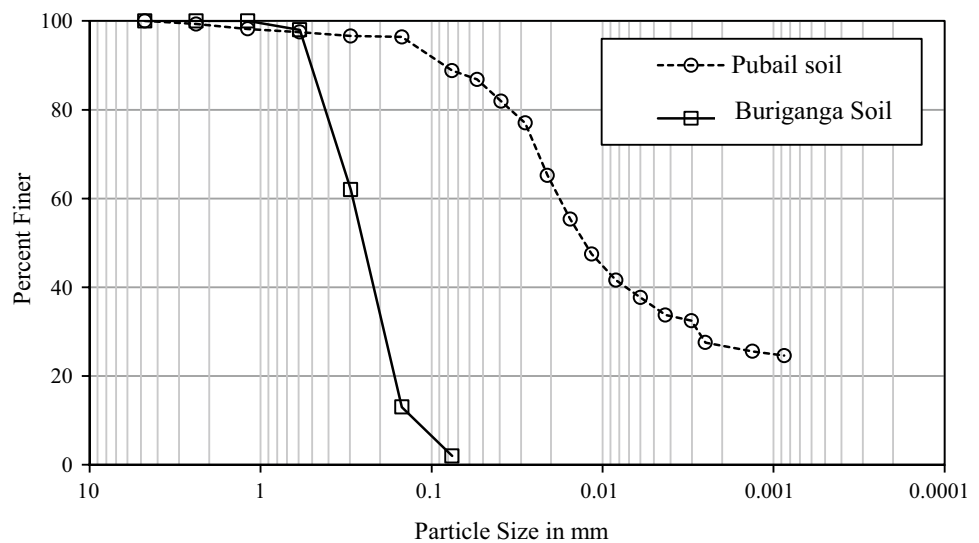
Pubail soil

The specific gravity of the Pubail soil was 2.68, and its natural moisture content was 16%. The grain size distribution was conducted by both sieve analysis and hydrometer analysis. The grain size distribution curves for Pubail and Buriganga soil are shown in Fig. 1. The particle size distribution of the clay was determined according to ASTM D422 [26], and it was found that the sand, silt, and clay content of the soil are 16%, 60%, and 24%, respectively. Atterberg limits were determined according to ASTM D4318 [27], and it was found that the Liquid Limit and the Plastic Limit of the Pubail soil are 44% and 21%, respectively. Therefore, the Pubail soil was classified as clay of low plasticity (lean clay; CL), according to ASTM D2487 [25].

Methodology

As a part of the total experimental setup, at first, root morphology was investigated. Then root tensile strength was measured of naturally grown matured vetiver grass. Direct shear tests were conducted in the laboratory to evaluate the effect of moisture content and root length on shear strength

Fig. 1 Grain size distribution curves of selected soils



of rooted soil. In situ direct shear tests were performed to determine the shear strength of both bare and rooted soil to measure the additional contribution of the root in soil–root system. Finally, based on the test results, a mathematical model was established to predict the shear strength of rooted soil from the known root tensile strength.

Investigation of root morphology

Vetiver grass was planted at Bangladesh University of Engineering and Technology (BUET) premises (23° 43' 32.9" N 90° 23' 16.4" E) to study its growth. The temperature of this area ranges between 14 °C and 34 °C, and humidity generally varies from 45 to 79%. The average annual rainfall is 1875 mm. The soil used for preparing the bed for the growth study was dredged sand of the Buriganga riverbed (Buriganga Soil). No additional fertilizer or nutrient was added to the sand. Vetiver grasses were collected from BUET nursery.

A 2.75 m × 1.75 m × 0.60 m frame was prepared, using 25.4 mm thick wood. The wooden frame was filled with dredged sand. The compacted density of the sand bed varied between 14.7 and 15.9 kN/m³. The density was kept similar to the road embankment construction practices in Bangladesh. A total of 97 recycled plastic bottles (254 mm height and 100 mm diameter) were filled with dredged sand and placed on top of the sand bed of the wooden frame. Thus the total depth of the bed was 0.85 m. The bottles were placed at 125 mm center-to-center distance in both directions (Fig. 2). The plastic bottles were used in order to get the additional height of the plant and to investigate the root growth in a simple way. 2–3 tillers of vetiver were planted at each point on August 14, 2016. Regular irrigation was done using potable water to ensure enough moisture for the proper growth of vetiver grass. In this study, irrigation volume and frequency were selected based on the local rainfall data. To nurse the

plants properly, they were irrigated uniformly by a sprinkler once a day for the first 2 weeks after plantation. For the next 2 weeks, the plants were irrigated once on alternate days. After that, water was given once/twice a week up to the end of the study.

After 5 weeks of the plantation, a single vetiver tiller was carefully pulled up every week to measure the dimensions of shoot and root. Following the uprooting, the soil between the root systems was carefully washed to observe the root matrix clearly. The tiller was replanted in the same location as soon as the monitoring process was completed. The growth study was conducted for a period of four months. After four months, the in situ root matrix was identified. To do that, a 3D frame was built using bamboo surrounding the wooden frame, and steel wire was tied with the top of the frame. Vetiver plants were tied with nylon rope and hanged with the steel wire added to the top of the frame so that tillers could withstand vertical after removal of sands from the sand bed. The wooden frame was removed from all sides, and the sand was washed out. After the complete removal of the sand from the bed, the root matrix was visible, and photographs were taken to capture the in situ 3D root system.

Tensile strength test of grass root

In this study, the tensile strength of vetiver grass roots was measured by Regger, as shown in Fig. 3. The capacity of this machine is 100 kN that is generally used for determining the tensile strength of steel fibers or thin sheets. Loading was applied at a constant rate of 10 mm/min. For the tensile strength test, 2 (two) years old matured vetiver grasses were collected from the Pubail region, a naturally grown vetiver nursery. Vetiver roots were collected from the uprooted clump, and the roots were chopped to 100 mm (Fig. 3a). The root diameter of both ends of the sample to be tested was

Fig. 2 Schematic view: **a** vetiver plantation on sand bed; **b** top view of vetiver planted on sand bed

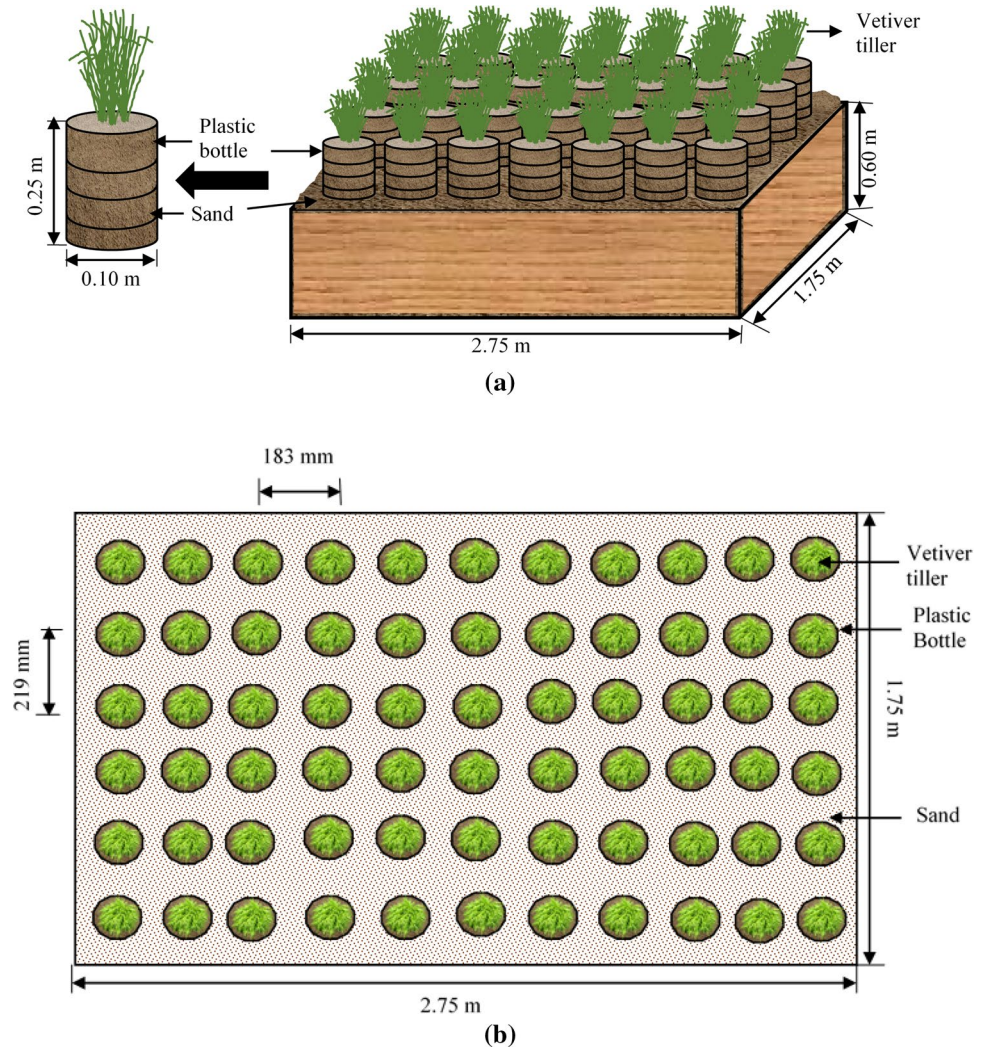
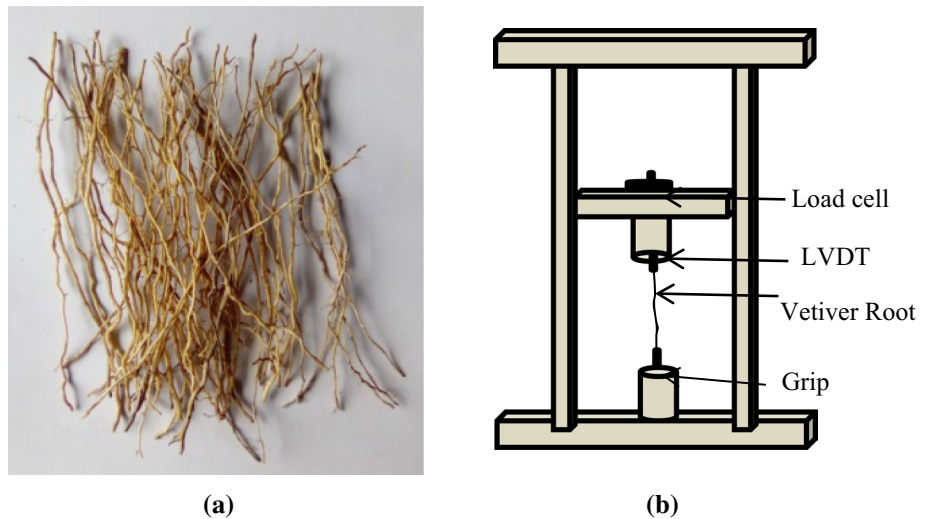


Fig. 3 **a** Chopped fresh vetiver root; **b** vetiver root clamped between two grips of Regger: schematic diagram



measured using a micrometer. Then the roots were clamped between two wedge grips of the Regger machine (Fig. 3b). The reading was set at zero, the motor of the Regger was

turned on, and the clamps holding the sample moved at a constant rate of 10 mm/min. Load was recorded at the time

of failure. Then the following formula was used to calculate tensile strength, T :

$$T = \frac{F_{\max}}{\pi \left(\frac{D}{4}\right)^2} \tag{1}$$

where F_{\max} = maximum force at the failure of the root, and D = mean root diameter before stretching.

Determination of shear strength of soil–root matrix by laboratory test

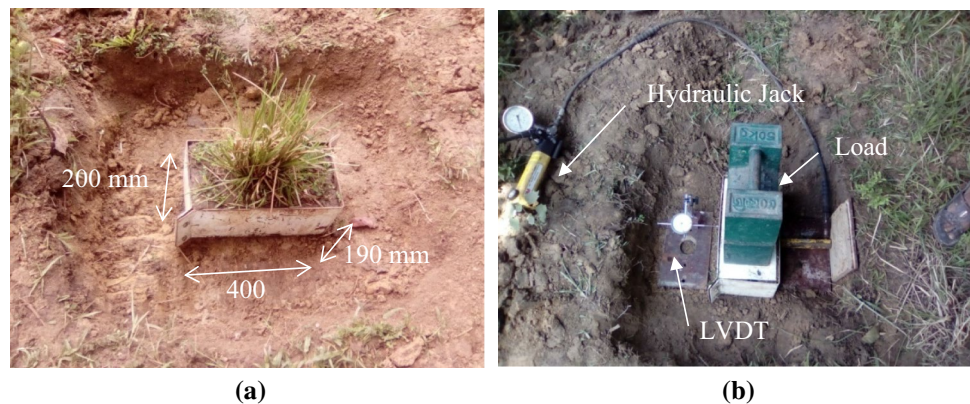
Growth of the plant depends on the irrigation frequency, water quality, etc. [28–30]. Irrigation water has effects on the growth of root length, root diameter, and root matrix diameter, which affect the shear strength of the rooted soil. To quantify this effect, reconstituted soil samples were prepared by mixing vetiver grass root with soil having different root length and at different moisture contents. Direct shear tests were conducted on both bare and rooted soil samples to evaluate the shear strength parameters of the soil–root matrix. Pubail soil (collected from the Pubail region of Bangladesh) was used for the tests. Roots were collected from uprooted matured vetiver grass and chopped to the desired length. Then the roots were mixed arbitrarily with dry soil samples, and water was added to prepare the soil specimen at different moisture contents. Root content was 3% of the dry weight of the soil sample. To observe the effect of moisture content on soil–root matrix, soil samples were prepared at 15% moisture content, 30% moisture content, and at saturated condition. For all these three samples, 25.4 mm long roots were used. Again, soil samples were prepared having roots of different lengths (12.5 mm, 25.4 mm, and 50.0 mm) at 15% moisture content to observe the effect of root length on the shear strength of rooted soil. Then the remolded soil samples were placed in the shear box, and 10 to 20 kPa normal loads were applied. When the sample is fully consolidated, 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 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.

Determination of shear strength of soil–root matrix by in situ test

The shear strength of vetiver-rooted and bare soil was evaluated by conducting in situ tests in Pubail, Gazipur (23° 56' 18.2976" N, 90° 28' 2.8194" E) where naturally grown vetiver was found. The temperature of this area ranges between 14 °C and 34 °C, and the humidity generally varies from 45 to 79%. Special equipment was used to evaluate the in situ shear strength of both soil–root matrix and bare soil [14]. The device developed by Islam et al. [14] was slightly modified and used to evaluate the in situ shear strength. The equipment consisted of a hydraulic jack with a 5-ton capacity, a pressure gauge with a 690 kPa capacity, a wooden plate, metal plates, a 400 × 200 × 190 mm³ metal box with a normal load of 100 kg, and a linear variable displacement transducer (LVDT) with a range up to 50 mm. Prior to the use of the equipment, the pressure gauge and LVDT were calibrated according to standard specifications. A clump of grass was trimmed at the ground surface with a sickle, and a trench of approximately 1 m × 1 m and 0.19 m deep was dug around. Care was taken not to disturb the roots. A sharp knife was used to carve the rooted area into the desired block sample shape (400 × 200 × 190 mm³). Then a metal plate (12 mm thick) was placed on top of the in situ block sample, and a vertical load of 100 kg (12.26 kPa) was applied. Horizontal force was applied through a hydraulic jack on one side of the block sample, and LVDT was placed on the opposite side to measure the horizontal deformation. The total experimental setup is illustrated in Fig. 4. At the end of the testing, the number of roots crossing the failure shear surface was counted, and the diameter of the roots was measured by a micrometer.

Fig. 4 In situ test: **a** earth block in metal box; **b** test arrangement for in situ shear test



Development of mathematical relationship

When the rooted soil is subjected to horizontal force, that force is resisted by both root and soil. The tensile strength of the root contributes to the additional strength provided by rooted soil. To tear the roots in the shearing plane, the root tensile strength must overcome its maximum capacity. For simplicity, it was assumed that the roots in the shearing plane were placed vertically, and the horizontal force made it inclined at an angle θ . Based on the perpendicular force equilibrium model, as shown in Fig. 5, the increase in shear strength of a soil–root matrix is given by the following equation:

$$\Delta\tau = \sigma_{iR}[\sin \theta + \cos \theta \tan \varphi] \tag{2}$$

where: $\Delta\tau$ =the additional shear strength of rooted soil, φ =friction angle, θ =the angle of shear distortion in the shear zone, and σ_{iR} =the mobilized tensile stress of root fibers per unit area of soil.

In Eq. (2), the unit of $\Delta\tau$ will be similar to σ_{iR} .

The mobilized tensile force in roots per unit area of soil, σ_{iR} can be calculated by

$$\sigma_{iR} = T_R * (A_R/A) \tag{3}$$

where T_R =the tensile stress developed in roots, A =the cross-sectional area of the soil shear plane, A_R =the total cross-sectional area of all roots crossing the shear plane, and A_R/A is defined as the root area ratio.

In Eq. (3), the unit of σ_{iR} will be similar to T_R .

The value of the term $(\sin \theta + \cos \theta \tan \varphi)$ in Eq. (2) is relatively insensitive to normal variations in the angle of shear distortion ($\theta = 40^\circ$ to 90°) and friction angle ($\varphi = 25^\circ$ to 40°). Thus, Wu et al. [13] proposed a constant value for this term. So the proposed model in this study was developed on the

basis of Eq. (2). The additional shear strength of soil–root matrix for the presence of roots was measured from in situ shear strength tests. The tensile strength of vetiver root was measured and mobilized tensile stress of vetiver roots per unit area of soil was calculated using Eq. 3.

Results and discussion

Growth of vetiver grass

Figure 6 depicts the vetiver root growth, and Table 1 presents a summary of the growth study results, all of which were based upon observations related to the increase in the length of the root and shoot with time. The root network of the vetiver grown in sandy soil was massive. Vetiver grasses were planted with a 40 mm long root, and the vetiver root and shoot length was measured at time intervals of 39 days, 46 days, 51 days, 90 days, and 110 days (Fig. 7).



Fig. 6 In situ 3D vetiver root matrix grown in sandy soil in 110 days

Fig. 5 Perpendicular root-reinforcement model (redrawn from Gray and Lieser [19])

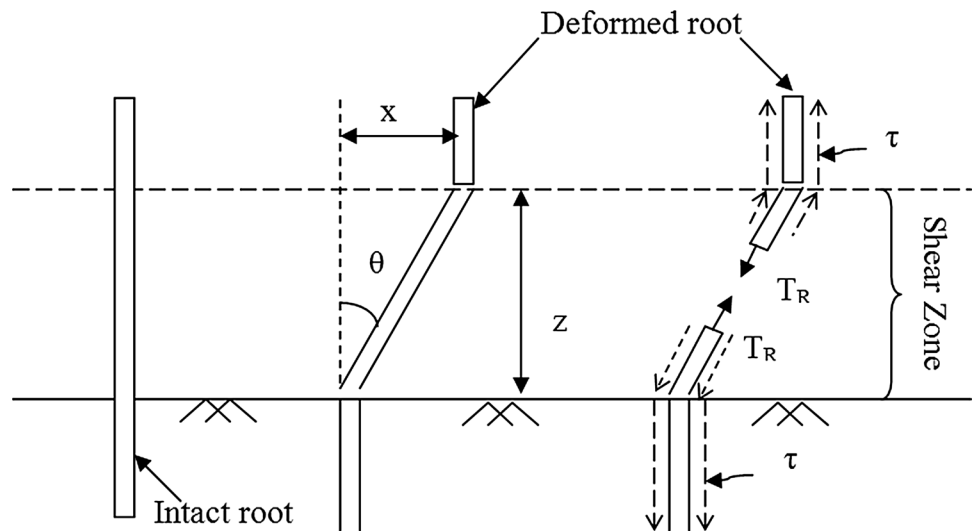
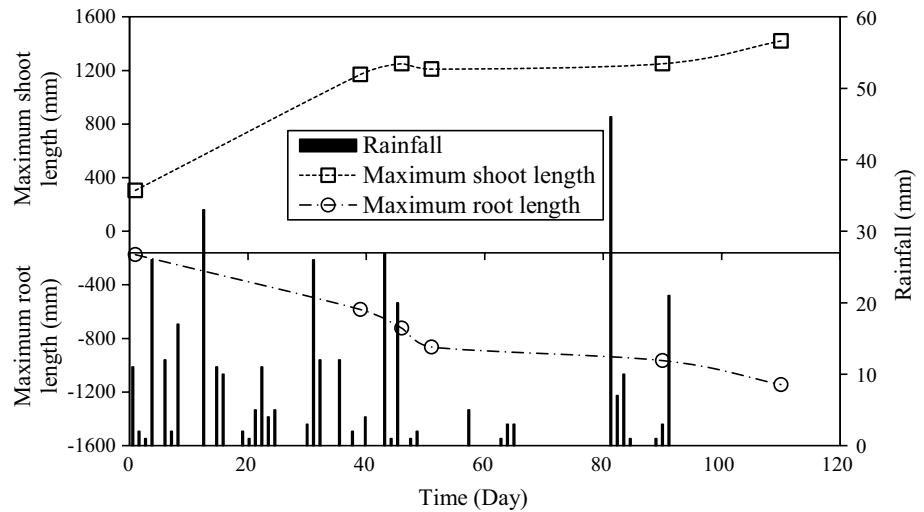


Table 1 Growth of vetiver root and shoot with time

Parameters	Unit	Plantation day	39 days	46 days	51 days	90 days	110 days
Overall range of shoots	cm	30.5	23–117	23–125	05–121	11–125	48–142
Average root diameter	cm	0.12	0.11	0.12	0.12	0.13	0.13
Sample maximum root length	cm	17.48	58.42	72.39	86.36	96.52	114.4
Sample minimum root length	cm	10.16	8.89	6.35	5.08	10.16	12.34
Root matrix diameter	cm	8	12.7	15.24	10.16	17.78	18.72

Fig. 7 Growth variation of vetiver shoot and root with time; rainfall data during the study period August 2016 to November 2016



The maximum root and shoot lengths were 1144 mm and 1420 mm, respectively, after 110 days of the plantation. The variation of rainfall throughout the plantation and growth period is shown in Fig. 7. It is observed that both the shoot and root grew rapidly until 46 days; subsequently, the growth was not significant. During these 46 days, the rainfall was consistent and uniform, which helped the vetiver grass to grow faster. Afterward, the incidents of rainfall were insignificant; hence, the growth was close to constant. At 81 and 92 days, there was two considerable rainfall for which a sudden rise in the growth was observed. The root matrix diameter, which is dependent upon sunlight exposure and the availability of water, increased with time, as expected. The average diameter of the root was from 1.1 to 1.2 mm. It was concluded that a vetiver mass creates a matrix that contributes significantly to protect slopes by providing resistance to the movement of the soil particles.

Tensile strength of grass root

A total of 33 roots were tested. The average tensile strength of the roots was obtained as 26.6 MPa at 0.7 to 0.8 mm root diameter. This range of diameter is the most common diameter class of the matured vetiver roots. A decreasing trend of root tensile strength was observed with the increase in root diameter. The ultimate tensile strength of roots was plotted

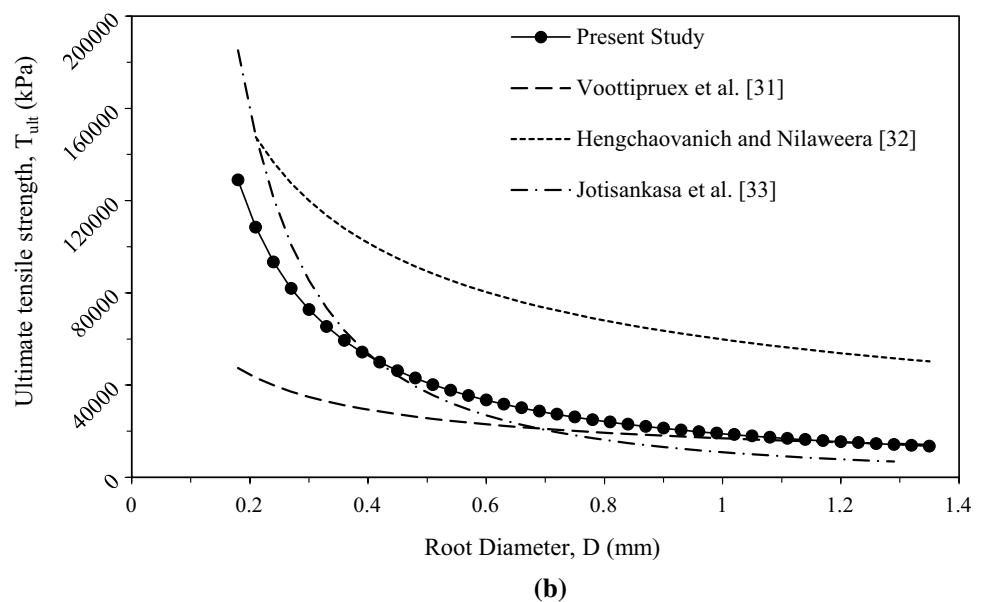
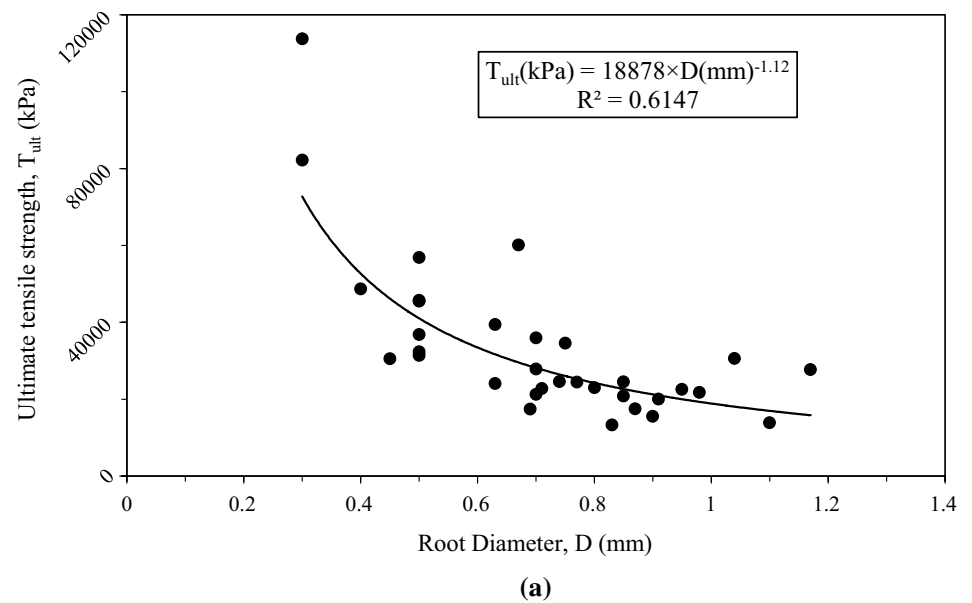
against its corresponding diameter, and an exponential relationship was found, as shown in Fig. 8a. The relationship can be expressed by the following equation:

$$T_{ult}(\text{kPa}) = 18878D(\text{mm})^{-1.12} \tag{4}$$

where T_{ult} = the ultimate tensile strength of the root in kPa, and D = the mean root diameter before stretching in mm.

The power regression indicates that finer roots provide higher resistance resulting in higher tensile strength. The obtained relationship was compared with other previous studies (Fig. 8b). Voottiruex et al. [31] suggested a similar power relationship for vetiver roots where they determined the tensile strength from pullout tests. The relationship between the tensile strength of root and root diameter has been expressed by a power relationship with $R^2 = 0.755$. Hengchaovanich and Nilaweera [32] showed that the average tensile strength of vetiver grass is higher compared to the hardwood root. Jotisankasa et al. [33] made an improvement on the root tension test equipment and also found a power relationship between root tensile strength and root diameter with $R^2 = 0.6122$. A similar trend has also been observed in the present study with $R^2 = 0.6147$. The relationship from the present study is in close agreement with Jotisankasa et al. [33], and underestimates than Hengchaovanich and Nilaweera [32] and overestimates than Voottiruex

Fig. 8 a Variation of ultimate tensile strength with root diameter; **b** comparison of the developed model with other studies



et al. [31]. Since the present study was carried out on vetiver grown under proper nursing conditions, it appeared reasonable that the tensile strength obtained was closer to those of Jotisankasa et al. [32] than that of Hengchaovanich and Nilaweera [32]. The variation of obtained results from the previous study may occur due to the different soil and meteorological conditions.

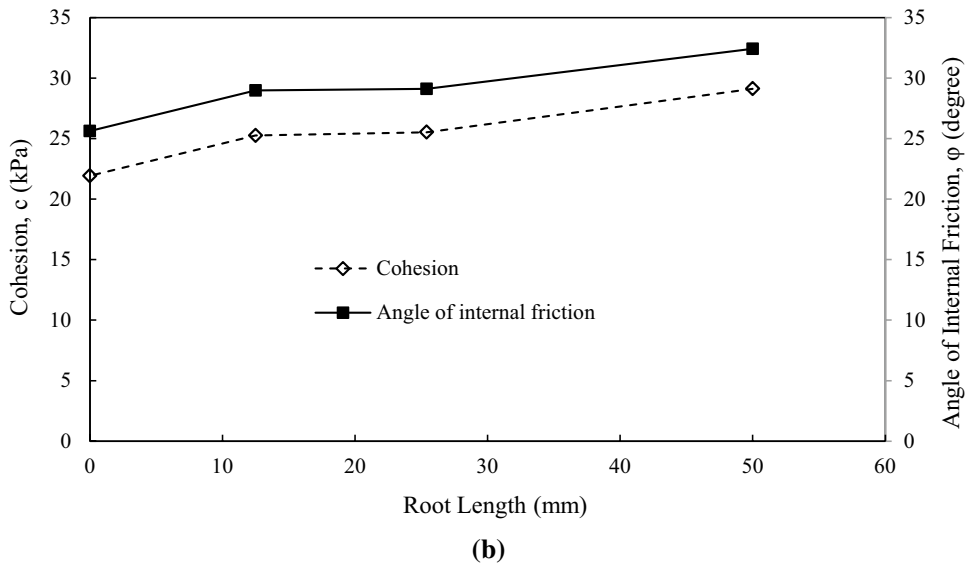
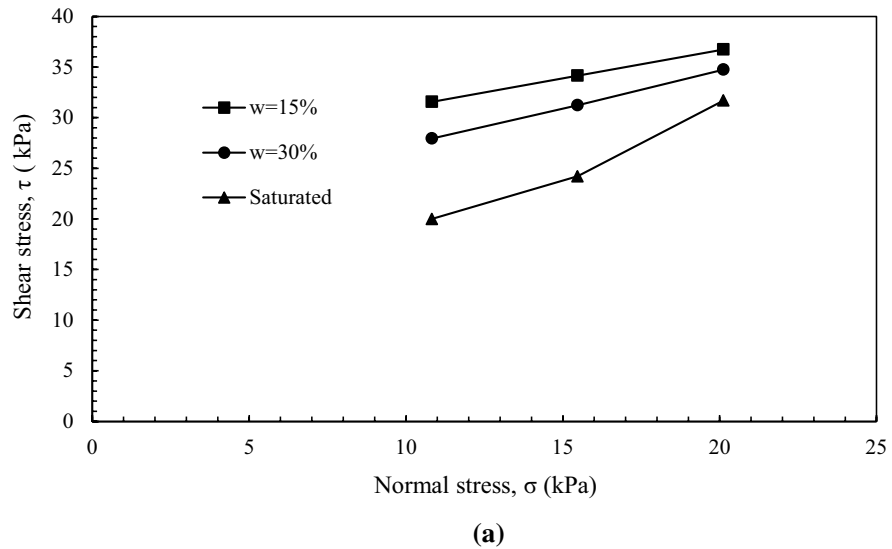
Effect of moisture content and root length on shear strength of rooted soil by laboratory tests

Effect of moisture content and root length on the shear strength of the soil–root matrix is presented in Fig. 9. From the graphs, it has been observed that under the same normal

stress conditions, peak shear stresses of vetiver-rooted soil are 36.74 kPa, 34.74 kPa, and 31.69 kPa for 15% moisture content, 30% moisture content, and saturated condition, respectively. Figure 9a shows an increase in shear strength values of the rooted soil with the decrease in moisture content.

Figure 9b shows the variation of shear strength of rooted soil with the change of root length. With the increase in root length, the shear strength of the rooted soil increases significantly. Maximum shear strength was observed for the rooted sample, which was prepared with 50.0 mm long roots. This sample experienced 32.8% higher cohesion and 26.5% higher angle of internal friction value compared to that of bare soil. For 25.4 mm long rooted sample, the increase in

Fig. 9 a Comparison of shear strength of rooted soil samples at different moisture content; **b** change of shear strength of rooted soil with the increase in root length



cohesion and angle of internal friction compared to bare soil is 16.4% and 13.6%, respectively. For 12.5 mm long rooted sample, the increase in cohesion and angle of internal friction compared to bare soil is 15.2% and 13.1%, respectively.

Additional shear strength of rooted soil by in situ tests

In situ shear strength test was conducted on a total of eleven block samples. Among them, one sample was bare soil (without any root), and the other ten samples were vetiver-rooted samples. All the samples were tested under the same normal stress (12.26 kPa) and at the same depth. Figure 9 shows the failed block samples, in which the torn roots are clearly visible. Graphs of the shear stress versus shear strain of a total of 11 block samples are presented in Fig. 10. From the diameter of the grass root, tensile strength was calculated

using Eq. (4). Then the mobilized tensile strength of the vetiver root was calculated from Eq. (3).

Development of mathematical model

All eleven in situ tests data were used to develop a relationship between the additional shear strength provided by roots and σ_{iR} . Variation of the additional peak shear strength, $\Delta\tau$ with root area ratio and σ_{iR} are presented in Fig. 11. The approximately linear relationship between the $\Delta\tau$ and σ_{iR} was obtained and is represented by

$$\Delta\tau = 5.10\sigma_{iR}$$

Fig. 10 Failed block samples: **a** lower root concentration ($\sigma_{IR} = 1.04$ kPa); **b** higher root concentration ($\sigma_{IR} = 2.54$ kPa)

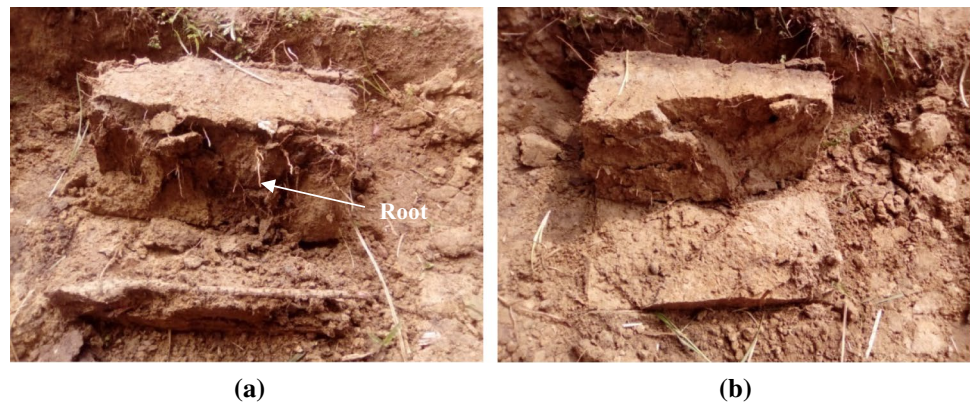
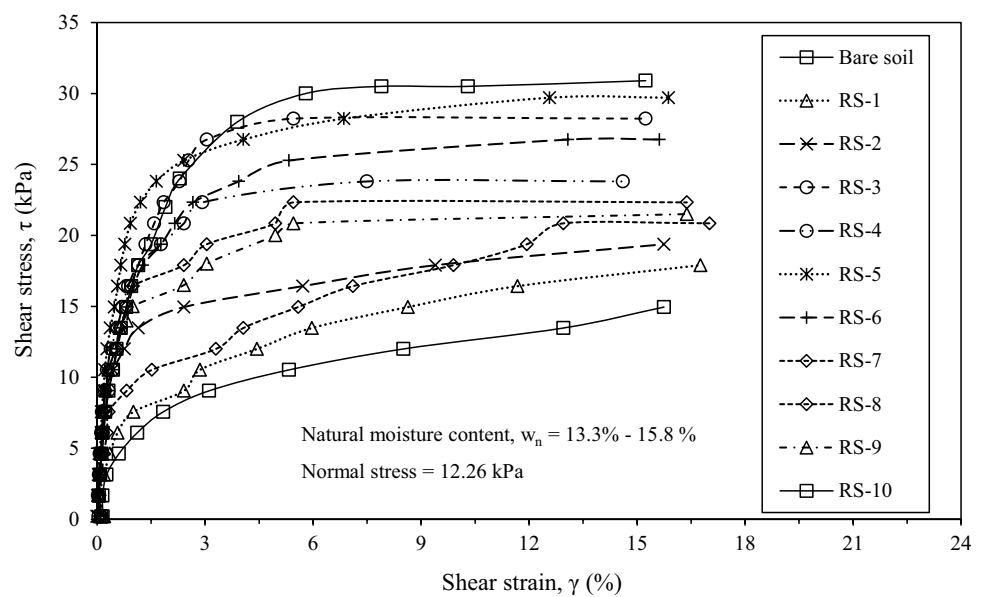


Fig. 11 Shear stress vs shear strain curves obtained from in situ shear tests



The present model was compared with previous models, and the comparison is shown in Fig. 12. Previous models showed that the additional strength offered by roots is 0.25 to 1.2 times higher than the average measured root tensile strength. In the current study, it is observed that the additional shear strength, $\Delta\tau$, provided by vetiver roots is equal to $5.10 \sigma_{IR}$ for low-plastic clay. Because of the high tensile strength and fibrous nature of vetiver roots, the additional shear strength was found much higher than the other kind of roots. The tensile strength of vetiver roots is found higher in the present study compared to the results obtained from Voottipruex et al. [31]. Furthermore, the root length and density were observed higher than the other studies. This indicates that the present soil condition and meteorological conditions were suitable for the ideal growth of vetiver roots. Therefore, the derived model overestimates the added shear strength compared

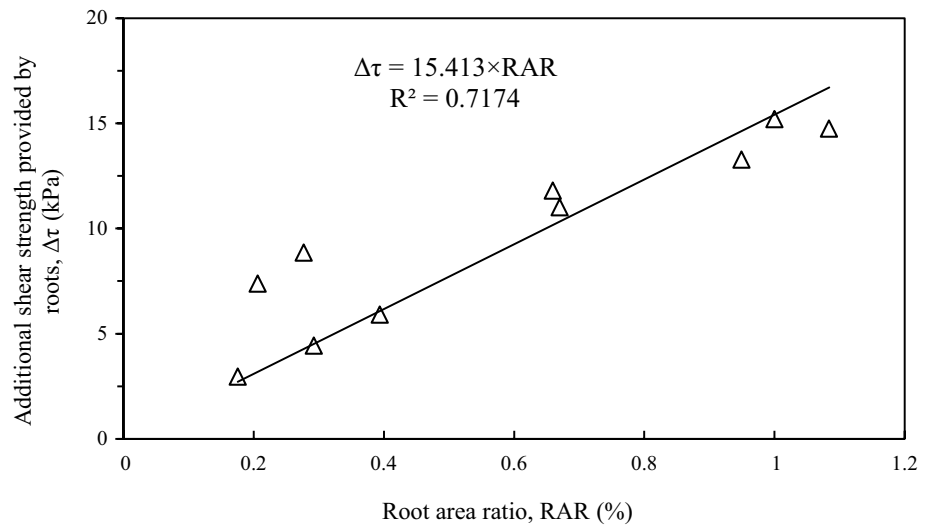
to the other studies. This may be due to the higher tensile strength of vetiver roots (Fig. 13).

Summary and conclusion

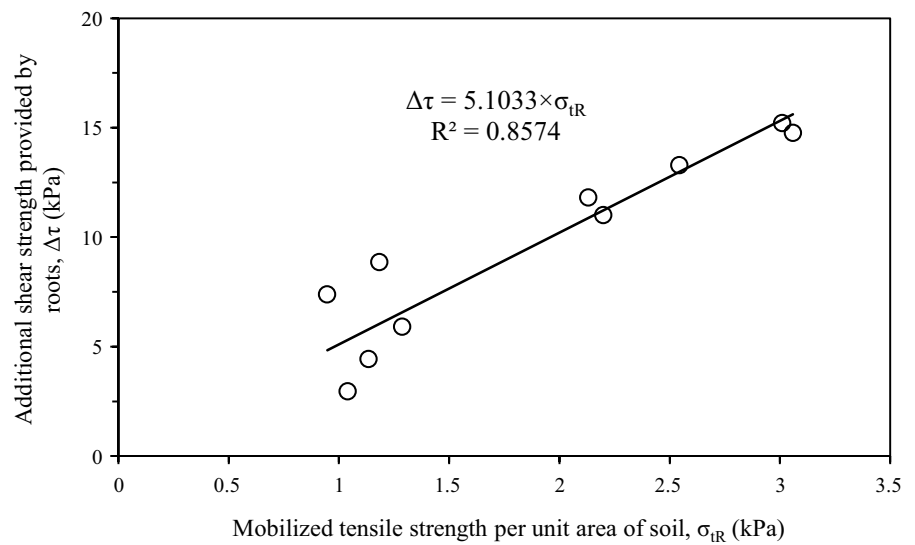
In this study, a simple mathematical model has been developed to predict the additional shear strength of vetiver root-reinforced soil. With this objective, the growth of vetiver grass was studied in sandy soil. The tensile strength of the vetiver root was also determined. Finally, in situ direct shear tests were conducted on both bare and vetiver-rooted block soil samples to measure the root contribution. The primary findings of the study are summarized below:

1. Vetiver has a very long and dense root matrix, and its root can grow up to 1.0 m in only 3 months in sandy soil without the addition of fertilizers and nutrients. With

Fig. 12 The experimental relationship of the additional shear strength provided by roots, $\Delta\tau$ with **a** root area ration and **b** the mobilized tensile strength per unit area of soil, σ_{tR}



(a)



(b)

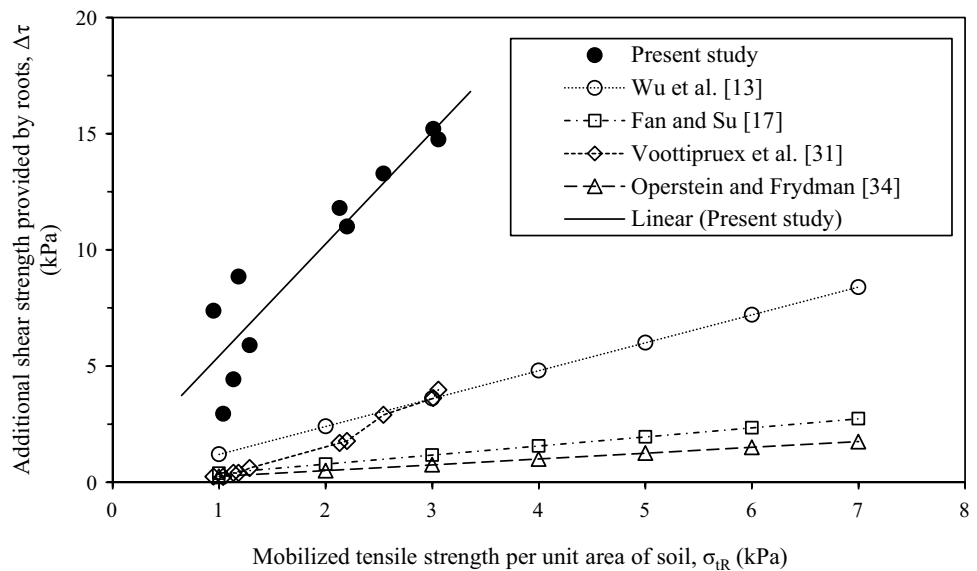
time both the roots and shoots increased gradually, and the maximum root and shoot lengths were found to be 1144 mm and 1420 mm, respectively, after 110 days of the plantation. The average diameter of root varied from 1.1 to 1.2 mm, whereas the average root matrix diameter was found to be 187.2 mm.

2. Tensile strengths of 33 fresh vetiver root having a diameter in the range of 0.3 to 1.2 mm were determined. The average tensile strength of a fresh matured vetiver root was 27 MPa, indicating that vetiver grass is effective for improving the shear strength of root-reinforced soil. It is found that the ultimate tensile strength (T_{ult}) of root decreases with the increase in root diameter (D) following the relationship, $T_{ult}(\text{kPa}) = 18878D(\text{mm})^{-1.12}$. The

present model was compared with previous studies and found in close agreement with other models.

3. From the laboratory shear strength tests on reconstituted soil samples, it is found that the shear strength of rooted soil decreased with the increase in moisture content. But the higher length of roots caused higher shear strength of the rooted soil.
4. From in situ shear tests, it is observed that the shear strength of soil–root matrix increases linearly with an increase in the mobilized tensile strength of the roots per unit area of soil. A mathematical model has been developed based on in situ test results to estimate the additional shear strength of the soil–root system. The model developed in this study is $\Delta\tau$ (additional shear

Fig. 13 Comparison of the model developed in the present study with other studies



strength provided by roots) = $5.10 \sigma_{iR}$ (mobilized tensile strength per unit area of soil), which is comparable to other models.

This simple, straightforward model can be a useful tool for analyzing the stability of vegetated slopes and the bearing capacity of the rooted ground.

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Author contributions Badhon FF and Islam MS conceived and presented the idea. Badhon FF contributed to sample preparation and carried out the experiments with the cooperation of Arif MZU. Islam MS supervised the project and critically reviewed all the steps. Badhon FF and Islam MA aided in analysis and interpreting the results. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Data availability The authors confirm that all relevant data supporting the findings of this study are included in the article.

Code availability Since the study is based on mainly laboratory experiment, no custom or new code was used in this paper.

Compliance with ethical standards

Conflicts 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.

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