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ORIGINAL PAPER

Enhancement of river bank shear strength parameters using Vetiver grass root system

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Abstract

Vegetation has been used as a bioengineering tool for erosion control and slope stabilization for years. It is accepted that the efficiency of different species of vegetation for slope stabilization is not the same. In this paper, the morphological properties of the Vetiver grass root system including root area ratio (*RAR*), root diameter ratio (*RDR*), root diameter and density ratio (*RDDR*), and root length density (*RLD*) in a clayey soil are investigated. Also, the effects of morphological characteristics of Vetiver grass root system on the soil shear strength parameters including soil cohesion (C) and soil internal friction factor (φ) are studied. The results showed that *RAR*, *RDDR*, and *RLD* decrease as the soil depth increases. Also, *RDR* was found to be correlated to the soil depth. The maximum *RAR* value was found to be 7.99% which is much higher than those reported by previous researchers for other plants used for soil protection. The maximum *RDR*, *RDDI*, and *RLD* values were 72.7, 4.4, and 0.1%, respectively. The results show that among the four root morphological traits studied, *RAR* and *RLD* are better correlated to C and φ, respectively. Furthermore, it is found that the plant density is not a significant parameter in the soil reinforcement in the range of densities studied here. Moreover, Vetiver grass roots can increase the soil cohesion and soil internal friction factor up to 119.6% and 81.96%, respectively. Based on regression analysis, some empirical equation are presented for calculation of the soil shear strength parameters as functions of the morphological characteristics of Vetiver grass root. These findings can be used by ecologists for better management of natural waterways by means of a low-cost environmentally friendly technique.

Keywords Vetiver grass · Root morphology · Shear strength · Soil cohesion · Angle of internal friction

Introduction

In many regions of the world, especially in the developing countries, soil losses by erosion have been an environmental and ecological concern over time. It can be related to climate change, deforestation, over-grazing, mismanagement of natural resources, inappropriate cultivation, disturbance of soils and slopes by mining, road construction, etc. River bed and bank erosion are one of the dominant sources of sediment load in rivers and reservoirs (Dang et al. 2014; Neal and Anders 2015; Yu et al. 2015; Balaban et al. 2015). Besides its temporary on-site effects, river bank erosion is important for its long-term and off-site consequences on sustainable development (Al-Mukhtar et al. 2014). The role of vegetation in river bank stabilization and decreasing landslide risk on slopes, referred to as bioengineering, has been studied extensively for decades (Greenway 1987; Coppin and Richards 1990; Gray and Sotir 1996; Norris 2005; Bischetti et al. 2005; Burylo et al. 2011; Ghestem et al. 2014; Khan and Lateh 2015). Soil bioengineering is a practical, cost-effective, low maintenance, environment friendly, and rapid recovery system for river bank stabilization problems (Sotir 1990).

The morphology of the root and the biomechanics of its tissue are the main characteristics of roots that control their efficiency in bank stabilization (Stokes et al. 1996; Watson et al. 1999; Hamza et al. 2007). The role of vegetation roots

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as a soil reinforcement has been studied extensively. When shear force acts on the soil, roots mobilize their tensile strength, whereby shear stresses that develop in the soil matrix are transferred to the root fibers via the tensile resistance of the roots (Ennos 1990). Many studies have shown that vegetation reinforces the soil, increases its shear strength, and binds its particles on an unstable slope (Anderson and Richards 1987; Coppin and Richards 1990; Operstein and Frydman 2000; Barker et al. 2004).

It has been found that there are significant differences in root biomechanical behavior among vegetation types (Ennos et al. 1993; Crook and Ennos 1994). These differences may be due to many parameters such as genetic properties of the species, soil texture and structure, moisture, temperature, and competition with other plants which affect the root morphology. The mentioned parameters follow an erratic pattern, a large spatial variability of root systems, and then a great heterogeneity in soil strengthening that is observed from site to site and plant to plant (Bischetti et al. 2005). Liu et al. (2014) studied development and soil reinforcement characteristics of five native species. They found that some species are not suitable for being used in soil bioengineering techniques. Nonetheless, quick-growing species, adapted to the local soils and climate, which have deep-rooted system, are alternatives to the engineering structures such as revetments and retaining walls used for river bank stabilization.

Vetiver grass (*Chrysopogon zizanioides* L.), originated from South India, is a fast growing grass which have some particular features of both grasses and trees. These special characteristics make Vetiver grass appropriate for river bank erosion control. Due to its fast growing and deep penetrating root system, Vetiver grass can prevent soil from erosion and control shallow movement of surface earth mass (Truong 2006). Also, Vetiver grass is tolerant to extreme climatic variations such as prolonged drought, flood, submergence and extreme temperature from − 14 to 55 °C (Truong et al. 1996). The Vetiver grass stems, leaves, and roots grow 1–2 cm/day (Ke et al. 2003; Likitlersuang et al. 2015). Also, its root is capable of reaching down to 2 to 3 m in the first year, whereas mean tensile strength of Vetiver grass root is about 75 MPa. Hence, Vetiver grass root is even stronger than that of many hardwood species, which have been recognized positive for slope stabilization (Truong 2006; Sanguankaeo et al. 2015).

This very fast growing and deep root system also makes Vetiver very drought tolerant. Also, it is highly resistance to pests, diseases, and fire (Truong et al. 2008).

It is reported that Vetiver grass has a great adaptability to a wide range of soil types (pH 3.0 to 10.5) (Truong and Baker 1998). Also, it is highly tolerant to growing media that are high in acidity, alkalinity, salinity, sodicity, and magnesium (Truong 1994; Truong et al. 2008). While Vetiver comes as a tropical grass, its adaptability permits it to thrive in climatic circumstances outside the tropical and sub-tropical zones. It is recognized that Vetiver grass grows well in China and Southern Europe where it thrives in the Mediterranean countries, particularly in the hot and dry climate of southern Spain, Portugal, and Italy (Pease et al. 2002).

The potential benefits of using Vetiver grass for soil reinforcement has been studied by many researchers (e.g., Hengchaovanich and Nilaweera 1996; Gray and Sotir 1996; Wong 2003 Mickovski and Van Beek 2009; Cazzuffi et al. 2014; Xu et al. 2014; Tardío and Mickovski 2015; Dumlao et al. 2015). It has been proven and accepted as a low-cost technique, effective measure for erosion control and stabilization against shallows seated failure and earthflows (Sanguankaeo et al. 2014). Vetiver grass is now being used as a bioengineering technique for steep slope stabilization, wastewater disposal, phyto-remediation of contaminated land and water, and other environmental protection purposes (Danh et al. 2009).

Totally, Vetiver grass has been used because of its environmental and economic benefits in different regions in the world. However, its general usage encounters some limitations in some cases due to reasons such as low growth rate, low palatability to livestock, and damaging to infrastructure (Hengchaovanich 1998; Owino 2003).

Although many researchers have studied the growth and the use of vetiver grass in its natural environment (Erskine 1992; Hellin and Haigh 2002; Hengchaovanich 1998; Salam et al. 1993; Truong and Loch 2004; Mickovski et al. 2004), the interrelationships between Vetiver grass root system and soil shear strength parameters have not been investigated yet.

The soil shear strength is commonly determined by the Mohr–Coulomb equation:

$$\tau = c + \sigma \tan\varphi \tag{1}$$

where τ is the soil shear strength, c is the soil cohesion, σ is the effective normal, and φ is the soil friction angle.

Some researchers (Davoudi and Fatemi-Aqda 2008; Shariata Jafari et al. 2014) have found relationships between soils shear strength parameters (C and φ) and morphological root characteristics such as root area ratio (*RAR*), root diameter ratio (*RDR*), root length density (*RLD*), and root diameter and density index (*RDDI*). *RDR*, *RAR*, *RDDI*, and *RLD* and are defined as follows:

$$RAR = \frac{A_r}{A_s} \times 100 \tag{2}$$

$$RDR = \frac{d_{\mathrm{m}}}{d_{\max}} \times 100 \tag{3}$$

$$RDDI = \frac{RAR \times RDR}{100} \tag{4}$$

$$RLD = \frac{L_r}{V_s} \times 100 \tag{5}$$

where A_r and A_s are the sum of the roots cross sectional area and soil sample plan area, respectively, and d_m and d_{max} are the mean and maximum diameter of the identified roots in each sample, respectively. Also, L_r and V_s are the total root length and soil sample volume, respectively. The results of in situ direct shear tests on root permeated soils have shown a linear increase in the soil cohesion with increasing root biomass (Endo and Tsuruta 1969; Ziemer 1981; Jotisankasa et al. 2015). Some studies have shown that root tensile strength decreases with diameter according to a power law (Bischetti et al. 2005; Mattia et al. 2005; Jotisankasa et al. 2015). Moreover, their results showed that the maximum *RAR* (the root area ratio, the ratio between the area occupied by roots in a unit area of soil) values are located in the first 30 cm near the ground surface.

Although the importance of Vetiver grass root systems for river bank erosion control and slope stability has received considerable attention in recent years, the relationship between morphological properties of Vetiver root systems and soil strength parameters needs more investigation. In this paper, the results of a field and laboratory study on the vertical distribution and radial extension of Vetiver grass roots are reported. Also, variations of some mechanical and morphological root indices including root area ratio (*RAR*), root diameter ratio (*RDR*), Root diameter and density ratio (*RDDR*) and root length density (*RLD*) are investigated. Finally, the effects of morphological properties of Vetiver grass root system on the soil shear strength parameters are presented.

Materials and methods

The experimental tests, initiated in April 2014, were carried out on the bank of Kor River located in Kamfirooz zone approximately 120 km northwest of Shiraz, Fars province, Iran. The climate at the site is Mediterranean and semi-humid cold with the total annual rainfall amounts to 496 mm/year. The mean annual temperature is 14.7 °C ranging between a mean maximum temperature of 23 °C and a mean minimum temperature of 6.4 °C. The climatic conditions at the study site fall within the tolerances of Vetiver grass according to Truong et al. (2008).

Vetiver grass plants, obtained from full-grown 1-year mother plants, were planted in three different tandem (inline) arrangements with distances equal to 30, 40, and 60 cm in both the longitudinal and lateral directions. The investigation of the distribution of Vetiver grass root system was carried out in September 2014 when the plants were well established and have developed multiple stems.

Roots were collected from soil by excavating trenches, taking care to avoid any root damage. In order to measure the root morphology, the excavated roots and soil samples were soaked in water. The soil with median diameter of 0.83 mm consists of poorly graded material, defined as a silty clayey sand. The roots were detached, and total length measurement was taken on each sample. In each depth increment of 10 cm, several samples were collected and the volume average of the increment was calculated. The total length of root in the sample was estimated by the line intersection method of Tennant (1975).

Conventional direct shear test was used to measure the soil shear strength parameters. Undisturbed block samples (100 mm × 100 mm) of the soil were taken at four depths including 0–10, 10–20, 20–30, and 30–40 cm. Three normal stresses equal to 1.0, 2.0, and 3.0 kg/cm^2 (98.1, 196.2, and 294.3 kPa, respectively) were applied to samples. Then, variations of the shear stress against normal stress for each sample were plotted and soil shear strength parameters (C and φ) were calculated from Eq. 1. In the present study, the tests were performed at the in situ moisture content (undrained). Undisturbed samples (for each conditions, three samples were used) were placed in the shear box. It should be noted that due to the experimental limitation, the applied normal stresses in the shear box tests in the laboratory were somewhat larger than operational confining pressures in the field. However, a preliminary test showed that the difference between the field and laboratory conditions did not affect the results as the failure envelope remains a straight line at low stresses. Nonetheless, the results are valid in the range of the parameters reported in the present study.

Results and discussion

Root distribution

Figure 1 shows the variations of the average values of vetiver grass height against time for the selected plants. It is seen that for 10 days after planting the vetiver grass, the height of the plant has not been changed significantly. From the middle of the second week, when the plant adapts to the new environment, the plant height began to grow and the height of the plant increases with time. Variations of the rate of growth of vetiver grass are shown in Fig. 2. It can be observed in this figure that the rate of growth incresaes from the middle of the second week and continues until the end of the fourth week.

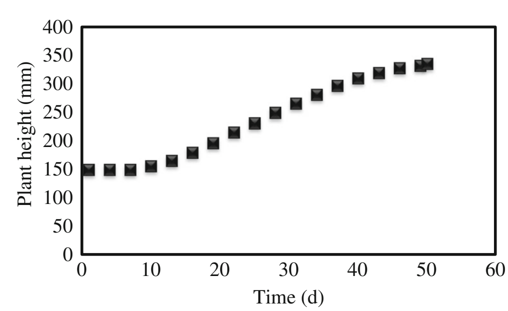

Fig. 1 Variations of the height of the Vetiver grass against time

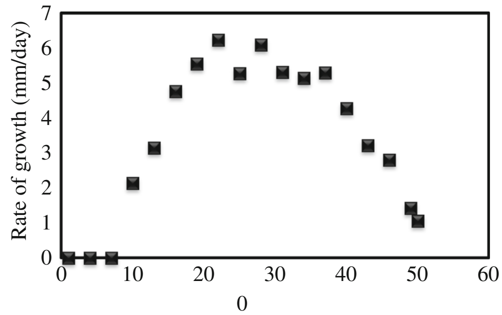

Fig. 2 Variations of the growth rate of the Vetiver grass

Then the growth rate decreases with time while the plant height increases till the seventh week after vetiver grass planting. The maximum growth rate and folliage height observed for the vetiver grass in the study site were 6 mm/day and 340 mm, respectively.

The vertical and lateral extensions of the Vetiver grass root system for different plant densities are shown in Figs. 3, 4, and 5. It is seen that for all three densities investigated, the roots are distributed symmetrically around the plant centerline. It should be noted that as the study site had been used for rice cultivation, a hard pan layer had been formed at 35 cm from the ground surface. Hence, the vertical extension of roots was confined to the surface layer and hardly any roots were found below 400 mm. Therefore, as observed in this study, the hard pan is considered to be a major constraint to Vetiver grass root penetration into the ground at this site. However, in some applications, Vetiver grass rooting depth can reach 3–4 m in the first year (Truong et al. 2008). Hengchaovanich (1998) stated that it can even punch through asphalt concrete pavement. Also, Truong et al. (2008) reported that Vetiver roots can penetrate a compacted soil profile such as hardpan and blocky clay pan common in tropical soils, providing a good anchor for fill and topsoil. This deep root system makes Vetiver grass exceptionally drought tolerant. The maximum lateral extension of the roots for different plant densities was about 150 mm occurring at the depth 300–350 mm below the ground surface, i.e., above the hard pan layer.

Figure 4a–c shows the variations of the percentage of the root distribution across the centerline of the Vetiver grass plant for low, medium, and high densities, respectively. It is seen in these figures that more than half of the roots are located within the 50 mm from the plant centerline. Also, as the vegetation density increases, i.e., the distance between plants decreases, the roots tend to move toward the plant centerline. This may be due to that as the plants come closer to each other, the competition between them increases and the roots tend to move vertically rather than horizontally.

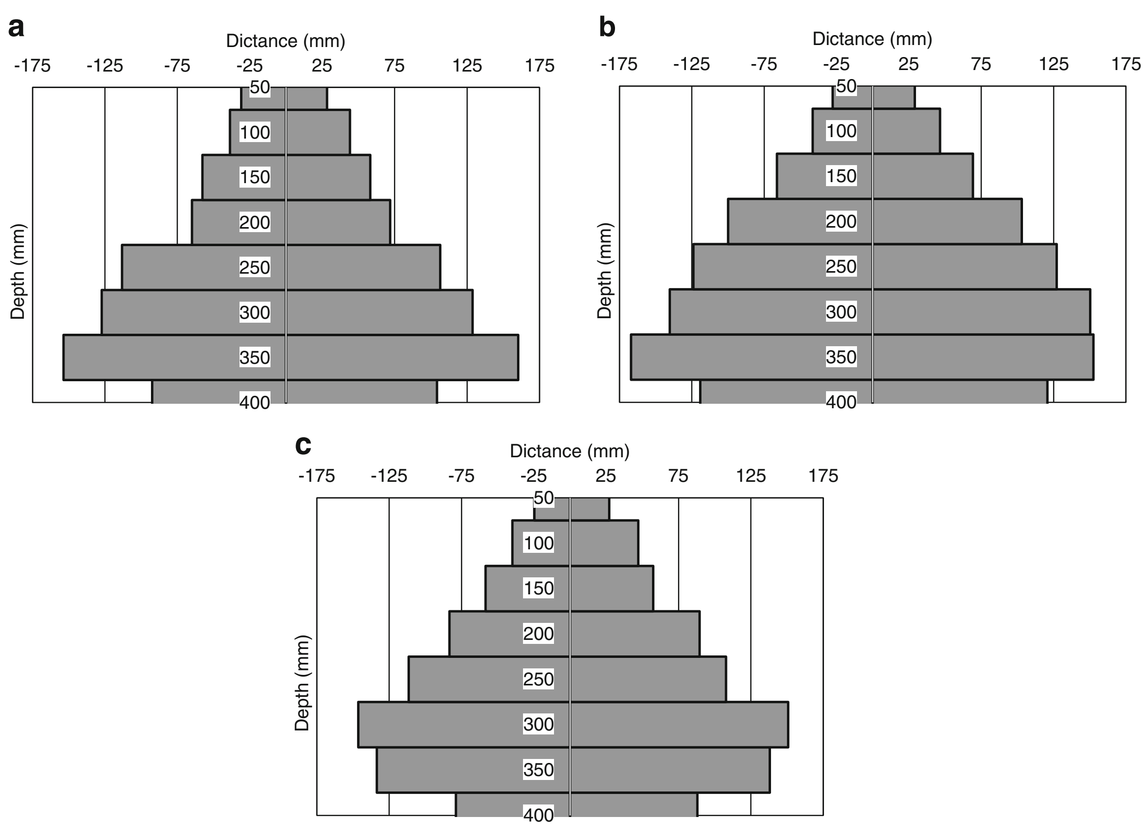

Fig. 3 Vertical and radial distribution of the Vetiver grass root system for **a** low, **b** medium, and **c** high planting density

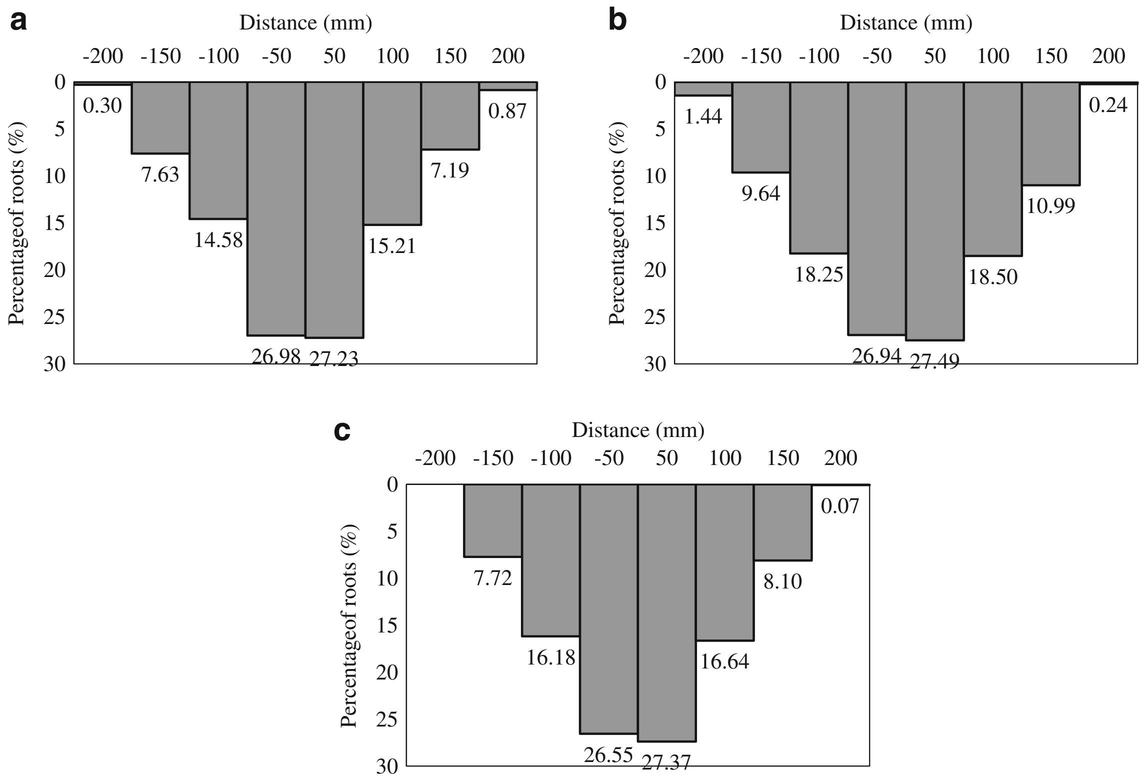

Fig. 4 Percentage of the lateral distribution of the Vetiver grass root system for **a** low, **b** medium, and **c** high planting density

Variations of the root area ratio (*RAR*), which is defined as the ratio of the sum of the root areas to the area of soil profile of root intersecting, for different plant densities are shown in Fig. 5. The calculation of *RAR* implies concept about the 3-D distribution of roots within the sample (Lopez-Zamora et al. 2002; Bischetti et al. 2004). Values of *RAR* were calculated at each depth intervals of 10 cm counting all roots with a diameter between 0.25 and 1.05 mm; roots, less than 0.25 mm, are difficult to be identified, whereas big roots may strongly affect *RAR* values.

It can be observed that the *RAR* values decrease as the soil depth increases. Also, the *RAR* values are more or less the same for different plant densities except for the upper 20 cm soil layer. The minimum and maximum *RAR* values were found to be 0.30 and 7.99%, respectively. These values are higher than those obtained for many other plants and trees. For example, Abdi et al. (2009) found the maximum *RAR* values 6.431% for down slope and 3.995% for up slope of eight hornbeam trees growing on hilly terrain of Northern Iran. Also, Bischetti et al. (2004) reported that the mean *RAR* values for five species (beech, Norway spruce, European larch, mixed hazel, and ash) along the profiles range between 0.1 and 0.35% depending on the species.

Figure 6 shows the variations of the root diameter density (*RDR*) at different soil depths for different plant densities. It is seen that the *RDR* values are higher for lower depths. Also, the *RDR* value increases as the plant density increases. The minimum and maximum *RDR* values were 37.50 and 72.73%, respectively.

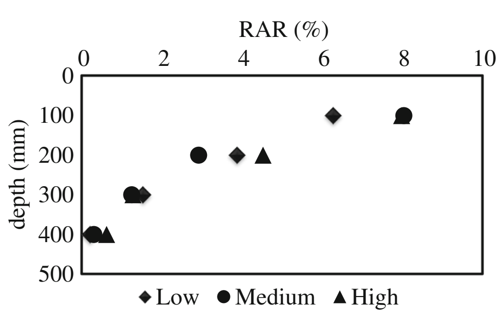

Fig. 5 Variations of *RAR* against soil depth for various Vetiver grass densities

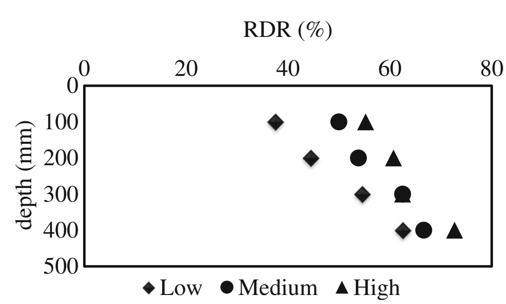

Fig. 6 Variations of *RDR* against soil depth for various Vetiver grass densities

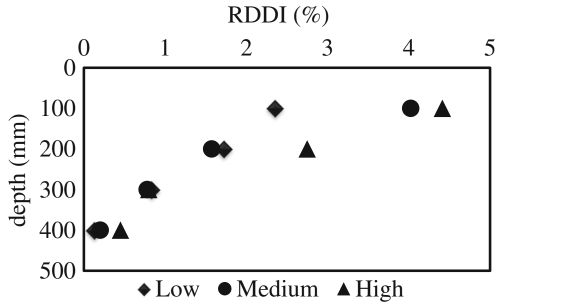

Fig. 7 Variations of *RDDI* against soil depth for various Vetiver grass densities

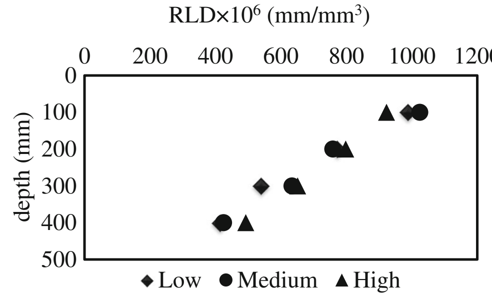

Fig. 8 Variations of *RLD* against soil depth for various Vetiver grass densities

The relationship between the root diameter and density index (*RDDI*) and soil depth is shown in Fig. 7. *RDDI* considers the conjugate effects of the root diameter and its density (Davoudi and Fatemi-Aqda 2008; Shariata Jafari et al. 2014).

As shown in Fig. 7, *RDDI* decreases with soil depth. Also, as the vegetation density increases, *RDDI* increases for the top 10-cm soil layer, whereas the effects of the plant density on the *RDDI* are negligible for lower layers of the soil. However, the results of the medium- and high-density treatments are more or less the same. But the medium density Vetiver grass increased the *RDDI* index value by 71% compared to the low density. It shows that Vetiver grass is more effective for conservation of the top soil layers against erosion.

Figure 8 shows the variations of root length density (*RLD*) against soil depth for various Vetiver grass densities. It can be seen in Fig. 8 that there is an inverse relationship between *RLD* and soil depth. Also, there were no significant differences between *RLD* for different Vetiver grass densities. The *RLD* values vary from a minimum of 0.04 at the lower soil depth to a maximum of 0.1 at the upper soil depths.

Shear stress

Variations of the soil shear stress (τ) against *RAR* for the tests with normal stresses equal to 1.0, 2.0, and 3.0 kg/cm^2 are shown in Fig. 9a–c, respectively. It should be noted that values of zero root area ratio ($RAR = 0\%$), located on the vertical axis, correspond to the tests without Vetiver grass (control tests), in which no roots were present in the soil sample. It can be seen that, for all the three normal

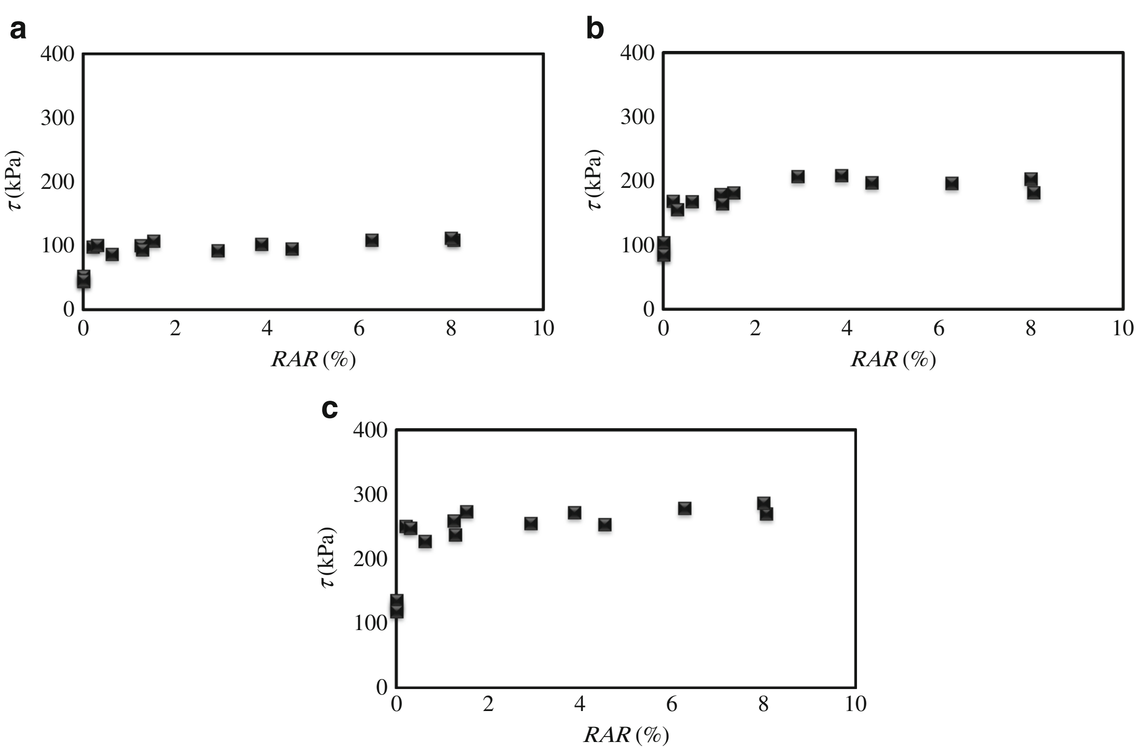

Fig. 9 Variations of the soil shear stress (τ) against *RAR* for normal stresses equal to **a** 98.1, **b** 196.2, and **c** 294.3 kPa

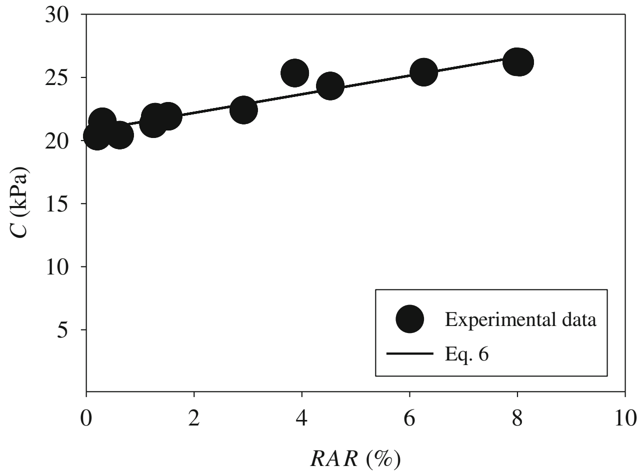

Fig. 10 Variations of soil cohesion (C) against Vetiver grass root area ratio (RAR)

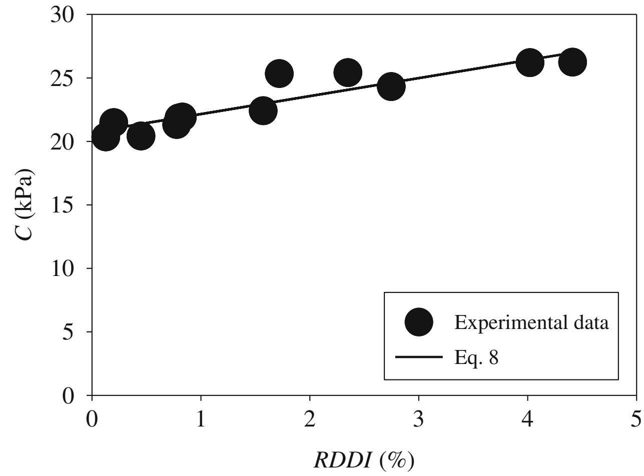

Fig. 12 Variations of soil cohesion (C) against Vetiver grass root diameter and density index ($RDDI$)

stresses studied, the soil shear stress increases with RAR. Nonetheless, comparing Fig. 9a, c, it is obvious that the values of τ for highest normal stress (Fig. 9c with $\sigma = 3$ kg/cm^2) are up to three times higher than those of lowest normal stress (Fig. 9a with $\sigma = 1$ kg/cm^2). A more or less similar trend was observed for the variations of the other morphological traits (including RDR, $RDDI$, and RLD) of Vetiver root systems against soil shear stress for all the normal stresses applied which are omitted for brevity.

Soil cohesion (C)

From the results of the direct shear tests, the soil shear strength parameters (C and φ) are calculated and will be discussed in the following paragraphs. Figure 2 shows the variations of soil cohesion (C) against root area ratio (RAR). It is seen that soil cohesion increases with RAR. Also, the following equation with the correlation coefficient of $R^2 = 0.90$ has been fitted to the experimental data by using regression analysis:

$$C = 0.7371 + RAR + 20.72 \tag{6}$$

According to Eq. 2, as RAR increases, the area in the soil sample occupied by the roots increases. Hence, increased RAR might be expected to improve that the soil reinforcement which in turn increase the soil cohesion, as shown in Fig. 10.

Variations of the soil cohesion (C) against RDR are shown in Fig. 11. A general decreasing trend in cohesion with RDR is observed. For low values of root diameter ratio ($RDR < 50\%$), the values of C are more or less constant to 25 kPa. For RDR values higher than 50%, the soil cohesion decreases to an extreme value of $C = 21$ kPa. These results are in agreement with those reported by previous researchers that the smaller the size of the root is, the higher is its effects on the soil

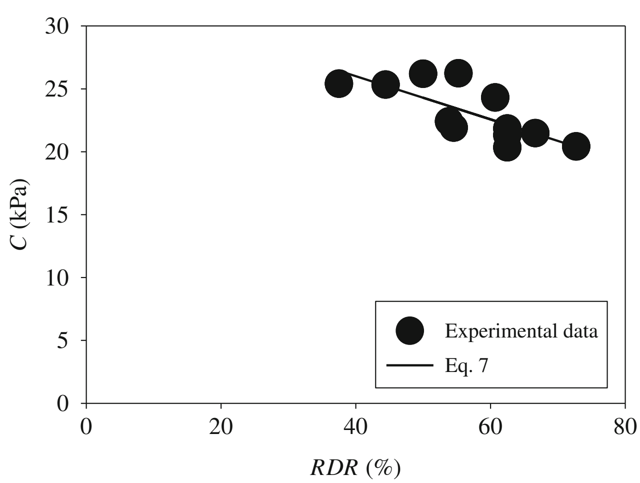

Fig. 11 Variations of soil cohesion (C) against Vetiver grass root diameter ratio (RDR)

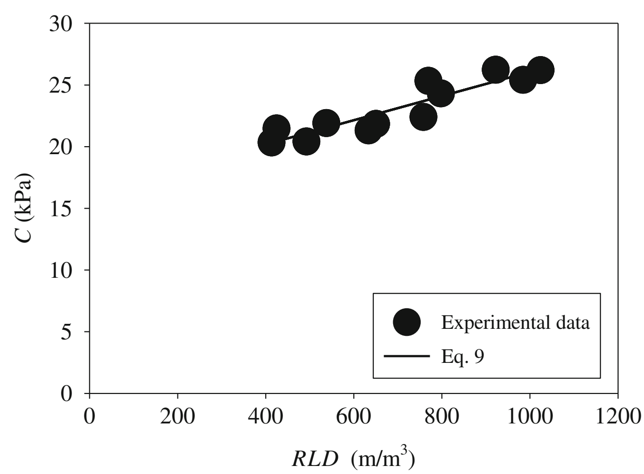

Fig. 13 Variations of soil cohesion (C) against Vetiver grass root length density (RLD)

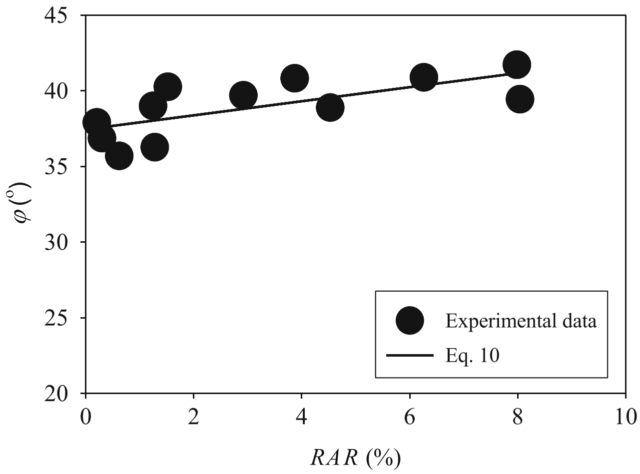

Fig. 14 Variations of angle of internal friction (φ) against Vetiver grass root area ratio (*RAR*)

reinforcement (Bischetti et al. 2005; Mattia et al. 2005; Ghestem et al. 2014). Also, some studies have shown that the plant roots with smaller diameter exhibit larger tensile strength (Hengchaovanich and Nilaweera 1996; Truong et al. 2008). Vetiver grass roots investigated in this study has very small size roots of mean diameter of 0.65 mm, very close to 0.66 mm reported by Truong et al. (2008). Nonetheless, it is higher than that of some other grasses like *Late Juncellus* with mean diameter of 0.38 mm; its tensile strength is up to three times higher than other grasses. The following equation with the correlation coefficient of $R^2 = 0.56$ has been fitted to the experimental data by using regression analysis:

$$C = -0.1715RDR + 32.868 \quad (7)$$

Figures 12 and 13 show the variations of soil cohesion (C) against Vetiver grass root diameter and density index (*RDDI*)

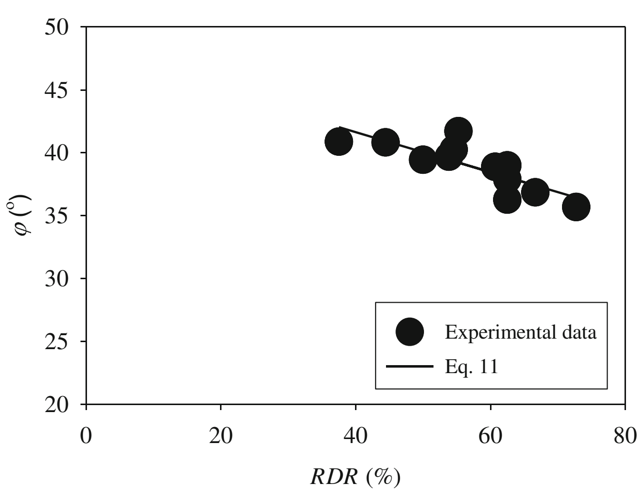

Fig. 15 Variations of angle of internal friction (φ) against Vetiver grass root diameter ratio (*RDR*)

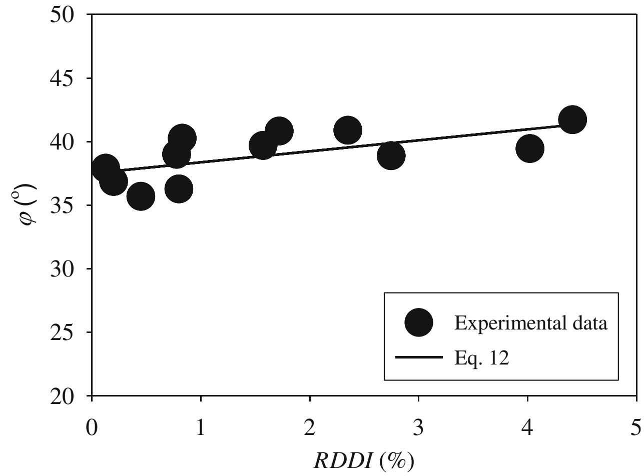

Fig. 16 Variations of angle of internal friction (φ) against Vetiver grass root diameter and density index (*RDDI*)

and root length density (*RLD*), respectively. It is seen that as *RDDI* or *RLD* increases, the soil cohesion increases too. Also, the following equations with the correlation coefficients of $R^2 = 0.83$ and $R^2 = 0.84$, respectively, have been fitted to the experimental data by using regression analysis:

$$C = 1.4144RDDI + 20.743 \quad (8)$$

$$C = 0.0098RLD + 16.268 \quad (9)$$

From Eq. 4, it can be found that *RDDI* is the product of *RAR* and *RDR* parameters divided by 100. Also, from Figs. 10 and 11, it was found that *RAR* and *RDR* have direct and inverse relations, respectively, with soil cohesion (C). Hence, it was expected that soil cohesion to be more or less equal to a constant value for different values of *RDDI*. But the increasing trend in C with *RDDI* observed in Fig. 12 shows that the role of *RAR* on the soil cohesion is more pronounce than that of *RDR*.

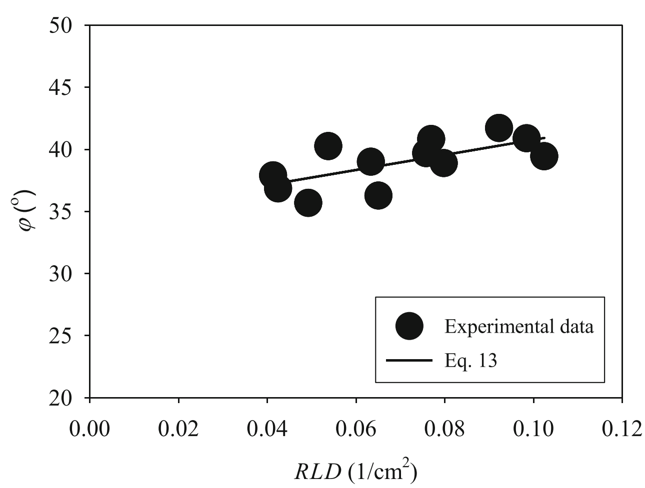

Fig. 17 Variations of angle of internal friction (φ) against Vetiver grass root length density (*RLD*)

Table 1 The average values and changes in soil cohesion (C) and soil internal friction factor (φ)

Vegetation density	$\overline{C}$ (kPa)	$\overline{\varphi}$ (°)	ΔC (%)	$\Delta\varphi$ (%)
Non-vegetated	10.80	21.96	–	–
Low density	23.54	39.97	119.67	81.96
Medium density	22.56	38.75	115.89	76.42
High density	23.54	38.14	119.21	73.64

Angle of internal friction (φ)

Figures 14, 15, 16, and 17 show the variations of the angle of internal friction (φ) against Vetiver grass root area ratio, root diameter ratio, root diameter and density index, and root length density, respectively. Similar to that discussed about soil cohesion (C) in the previous section, it can be seen in these figures that the angle of internal friction increases with *RAR*, *RDDI*, and *RLD*. However, the angle of internal friction has an inverse relation with *RDR*. Hence, φ decreases as *RDR* increase. Using regression analysis, the following equations have been fitted to the experimental data:

$$\varphi = 0.4651\, RAR + 37.4480 \quad (10)$$

$$\varphi = -0.1589\, RDR + 47.9990 \quad (11)$$

$$\varphi = 0.8645\, RDDI + 37.5090 \quad (12)$$

$$\varphi = 60.7360\, RLD + 34.6950 \quad (13)$$

The correlation coefficients (R^2) for the above equations are of 0.49, 0.65, 0.42, and 0.44, respectively.

In order to find the effect of Vetiver grass root system on the soil shear strength parameters, the values of C and φ at different depths are averaged for each plant density and reported in Table 1 which are denoted by $\overline{C}$ and $\overline{\varphi}$, respectively. It is seen that for all the three plant densities studied, average values of both C and φ increase significantly compared to the non-vegetated case. Also, the change in the soil cohesion as well as the angle of soil internal friction, denoted by ΔC and $\Delta\varphi$, respectively, for each vegetation density is determined in Table 1. According to this table, low-density Vetiver grass can increase the average values of C and φ by 119.6 and 81.96%, respectively. Also, it can be found from Table 1 that the Vetiver grass density is not a significant factor for enhancing soil shear strength parameters. ΔC and $\Delta\varphi$ are defined as follows:

$$\Delta C = \frac{\overline{C_v} - \overline{C_n}}{\overline{C_n}} \times 100 \quad (14)$$

$$\Delta\varphi = \frac{\overline{\varphi_v} - \overline{\varphi_n}}{\overline{\varphi_n}} \times 100 \quad (15)$$

where v and n subscripts denote vegetated and non-vegetated cases, respectively.

Finally, some physical and ecological properties of Vetiver grass and some other plants including willow, spruce, sycamore, Tamarix, maple, *Alnus subcordata*, eucalyptus, barberry, and raspberry are summarized in Table 2. It is seen that the minimum median root diameter belongs to Vetiver grass. Also, it has the maximum root tensile strength compared to other plants. While most plants need at least 18 months for establishment, Vetiver grass can grow and consequently protect the soil against erosion after about 2 months. Furthermore, it has high resistance against long drought cycles and also can highly reestablishment compared to after plants after partial damages due to floods or other natural hazards.

Conclusion

Vetiver grass, as a bioengineering technology, is being used widely for steep slope and river bank protection, and it is becoming more and more popular. In this paper, the results

Table 2 Comparison of some physical and ecological properties of Vetivergrass and some other plants

Plant name	Median root diameter (mm)	Root tensile strength (MPa)	Establishment time (months)	Drought resistance	Restoration
Vetiver grass	0.66	85.10	2	High	High
Willow	3	10.33	18	Low	Medium
Spruce	1	28.00	24	Low	Low
Sycamore	3.5	26.00	24	Low	Low
Tamarix	14	4–30.2	36	High	Medium
Maple	3	8.68–30.68	24	Medium	Low
Alnus subcordata	2.5	16–20	24	Low	Low
Eucalyptus	2	29.73	24	High	Medium
Barberry	2	Not available	24	Medium	Medium
Raspberry	1.5	Not available	18	Low	Low

of a field and laboratory study on the vertical distribution and radial extension of Vetiver grass roots are reported. Also, variations of some mechanical and morphological root indices including *RAR*, *RDR*, *RDDR*, and *RLD* were investigated. The maximum growth rate observed for the Vetiver grass was 6 mm/day. The hard pan layer was found to be a major constraint to Vetiver grass root penetration into the ground at this site. Also, about half of the roots were developed within the 5 cm from the plant. While *RAR*, *RDDR*, and *RLD* were found to be inversely correlated to the soil depth, *RDR* increased with soil depth. The maximum *RAR* value was found to be 7.99% which is much higher than those reported by previous researchers for other plants. The maximum *RDR*, *RDDI*, and *RLD* values were 72.7, 4.4, and 0.1%, respectively. Also, the relationship between the soil strength parameters, including soil cohesion (C) and angle of internal friction (φ), and Vetiver grass root morphological characteristics is presented. The results showed that Vetiver grass root morphological attributes such as diameter, length, and occupied area in the soil cross section affect significantly soil strength parameters. While both C and φ increase with *RAR*, *RDDI*, and *RLD*, they are related to *RLD* inversely. Also, some equations are fitted to the data using regression analysis. It is concluded that among the four root morphological characteristics studied, *RAR* and *RLD* have the best correlation with C and φ, respectively, which can be suggested for application not only for erodible slope design but also in soil-root reinforcement models. Furthermore, it is found that Vetiver grass roots can increase the soil cohesion and soil internal friction factor up to 119.6% and 81.96%, respectively. While the results in this paper are restricted to the ranges of variables and climate conditions described in the "Materials and methods" section, they afford a framework for more analysis of field data for river banks and steep slopes.

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