An Innovative Biotechnological Method of Protection of River Banks against Scour using Vetiver Plant Cover with a Special Reference to Bangladesh

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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 and compared with the existing methods of riverbank protection and Mathematical Model of Flow in a Meandering Channel. Also, the effects of morphological characteristics 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 grassroots 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 is presented for the 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.

Introduction

In many regions of the world, especially in developing countries, soil losses by erosion have been an environmental and ecological concern over time. It can be related to climate change, deforestation, overgrazing, mismanagement of natural resources, inappropriate cultivation, disturbance of soil sand 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; NealandAnders 2015; Yu et al.2015; Balaban et al. 2015). Besides its temporary on-site effects, riverbank erosion is important for its long-term and off-site consequences on sustainable development (Al-Mukhtar et al. 2014). The role of vegetation in riverbank 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 Sotir1996; Norris2005; 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 riverbank 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 as a soil reinforcement has been studied extensively. When a 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(Ennos1990). 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). fibers via the tensile resistance of the roots (Ennos1990).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 (Ennis et al.1993; Crook and Ennos1994). 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, 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 the 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 systems, are alternatives to the engineering structures such as revetments and retaining walls used for riverbank stabilization. (Chrysopogon zizanioides L.), originated from South India, is a fast-growing grass that has some particular features of both grasses and trees. These special characteristics make Vetiver grass appropriate for riverbank erosion control. Due to its fast-growing and deep penetrating root system, Vetiver grass can prevent soil from erosion and control the shallow movement of surface earth mass (Truong 2006). Also, Vetiver grass is tolerant of 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 3m in the first year, whereas the mean tensile strength of the Vetiver grass root is about 75 MPa. Hence, the 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 make Vetiver very drought tolerant. Also, it is highly resistant to pests, diseases, and fire (Truong et al. 2008). It is reported that Vetiver grass has great adaptability to a wide range of soil types (pH 3.0 to 10.5) (Truong and Baker 1998). Also, it is highly tolerant of 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 subtropical 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 earth flows (Sanguankaeo et al. 2014). Vetiver grass is now being used as a bioengineering technique for steep slope stabilization, wastewater disposal, phytoremediation 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; Owino2003). 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:

$$\tau = C + \sigma \tan\varphi$$

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:

$$\mathbf{RAR} = \frac{A_r}{A_s} \times 100 \quad (1)$$

$$\mathbf{RDR} = \frac{d_m}{d_{max}} \times 100 \quad (2)$$

$$\mathbf{RDDI} = \frac{RAR \times RDR}{100} \quad (3)$$

$$\mathbf{RLD} = \frac{L_r}{Vs} \times 100 \quad (4)$$

where Ar and As are the sum of the roots cross-sectional area and soil sample plan area, respectively, and dm and dmax are the mean and maximum diameter of the identified roots in each sample, respectively. Also, Lr and Vs 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(EndoandTsuruta1969; Ziemer1981; Jotisankasaetal. 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 30cm near the ground surface.

Although the importance of Vetiver grass root systems for riverbank 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 grassroots 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 the Vetiver grass root system on the soil shear strength parameters are presented.

Mathematical Model of Flow in a Meandering Channel

An open channel is a conduit in which a liquid flows with a free surface. The free surface is actually an interface between the moving liquid and an overlying fluid medium and is subject to constant pressure. In engineering practice, activities for utilization of water resources involve open channels of varying magnitude in one way or another. Flows in natural rivers, streams, and rivulets, artificial, that is, man-made canal for transmitting water from a source to a place of need, such as for irrigation water supply and hydropower generation. It is evident that the size, shape, and roughness of open channels vary over a sizable range, covering a few orders of magnitudes. Basically, all open channel channels have a bottom slope and the mechanism of flow is akin to the movement down an inclined plane due to gravity. The component of the weight of the liquid along the slope acts as a driving force. The boundary resistance at the perimeter acts as the resisting force. Water flows in open the channel is largely in the turbulent regime with negligible surface tension effects. In addition, the fact that water behaves as an incompressible fluid leads one to appropriate the importance of the force due to gravity as the major force and the Froude Number as the prime non-dimensional number governing the flow phenomenon in open channels. Natural channels include all watercourses that exist naturally on the earth, varying in size from tiny hillside rivulets, through brooks, streams, small and large rivers, to tidal estuaries. The hydraulic properties of the natural channels are generally very irregular. In some cases empirical assumption reasonably consistent with actual observations and experience may be made such that the conditions of flow in these channels become amenable to the analytical treatment of theoretical hydraulics. The artificial channels are those constructed or developed by human effort; navigation channels, power canals, irrigation canals and flumes, floodways, etc. as well as model channels that are built at the laboratory for testing purposes. The hydraulic properties of such channels can be either controlled to the extent as desired or designed to meet given requirements. The application of hydraulic theories to artificial channels will, therefore, produce results fairly close to the actual condition and hence, are reasonably accurate for practical design purposes.

There have been a number of attempts to mathematically model the flow in meandering channels (Engelund(1977); Ikeda, Parker, and Sawai(1981); Odgaard(1986a,b); Ikeda and Nishimura(1986); Odgaard(1989a,b)). Most of these are essentially models describing flow in shallow, weakly meandering erodible bed streams. A feature of such streams is that the flow may be assumed to be two-

dimensional. Although most meandering river stretches probably fall in the shallow, weakly- meandering category, one can find cases where the river channel is somewhat deeper. In such stretches, one cannot apply the shallow meander models.
The ratio mean depth divided by the width (or d/b), is a convenient parameter to use when talking about shallow and deep meanders. In shallow meanders, i.e. where d/b value is small, the influence of the wall is confined to a small zone near the wall which may be called the "wall zone". The central portion, which may be called the "core zone", is essentially free of wall effects. In deep meanders, i.e. where the d/b value is larger, such a core zone does not exist and the influence of the wall is felt throughout the flow.
Similarly, the ratio of width divided by the least centreline radius of curvature (or b/rcm) is a useful parameter in connection with the sinuosities of the meandering channel. The larger the value of this parameter, the more strongly meandering a channel is.
These two parameters, considered together, can be used to classify meandering channels into different categories. For example, in Ikeda and Nishimura's (1986) channel, d/b equaled 0.18 and b/rcm equaled 0.44. So this channel fell in the shallow and weakly meandering category. In Kar's (1977) experiments, d/b varied from 0.453 to 0.985 while b/rcm equalled 1.06. These experiments, therefore, can be said to have been conducted on a deep, strongly meandering channel flow.
In the present study conducted at IIT Kharagpur (Bhattacharya (1995)), a mathematical study is made of, and experiments have been conducted on, a mild meander which falls into the so-called deep category. A rigid bed is considered as it is felt that in the present state of knowledge of deep, mild meanders, obtaining a picture of the basic nature of flow in such channels is more appropriate.
The meander model formulated in the present work satisfies all boundary conditions – at the bed and at the side walls. In shallow, weak meanders, because of the order of magnitude considerations, considerable simplifications can be made in the governing equations but for deep meanders, such simplifications cannot be made in the governing equations. Therefore for deep meanders, one has to solve the full equations which are quite complex. So, in these circumstances, in place of a direct solution of the governing equations, a different approach is adopted in the present study. Because the model formulated in the present study is not restricted to shallow meanders, it is valid from wall to wall whereas the shallow meander models are for the core zone.
The meandering of the river is one of the natural processes. Leliavsky (1955) in his renowned book says that "The centrifugal effect (which causes the superelevation) may possibly be visualized as the fundamental principle of the meandering theory, for it represents the main cause of the helicoidal cross-currents which remove the soil from the concave banks, transported the eroded material across the channel, and deposit in on the convex banks, thus intensifying the tendency towards meandering. It follows therefore that the slightest accidental irregularity in channel formation turning as it does, the streamlines from their straight course may under certain circumstances constitute their focal point for the erosion process which leads to ultimately to meander". According to Inglis (1947), "Where, however, banks are not tough enough to withstand the excess turbulent energy developed during floods, the banks erode and the river widened and shoals… In channels with widely fluctuating discharges and silt charges, there is a

tendency for silt to deposit at one bank and for the river to move to the other bank. This is the origin of meandering....".

A meander is called shallow if its depth is small compared to its width and it is called mildly-meandering if its width is small compared to its least centerline radius of curvature. These ratios are considered to be very small in the most analysis as in most natural channels. The effect of considering these ratios to be very small is that the governing equation of the flow (three momentum and one continuity) is much simplified from the order of magnitude consideration. However, not all-natural meanders are shallow. Investigators have studied meanders and compound channel flows for a long time. Thomson (1876) was probably the first to point out the existence of spiral motion in a curved open channel. Rozovskii (1957) used the order of magnitude consideration and assumptions of eddy viscosity, vertical distribution of tangential (streamwise) velocity components and zero net lateral discharge and he found an approximate solution for the radial velocity component from the equation of motion. He also tried to solve for the radial distribution of the tangential velocity component and growth and decay of the spiral motion. He concluded that the solution for the vertical distribution of the radial velocity based on the logarithmic distribution of the vertical of the tangential velocity is acceptable. It should be noted that Reynold's number for the experiments were generally low.

Kikkawa, Ikeda, and Kitagawa (1976) reported a study on the flow and bed topography in a constant curvature bend. In their flow model, they assumed that the radius of curvature is large and that the width is sufficiently large compared with the depth. They considered the equation of motion governing the secondary flow and obtain an equation for the radial velocity distribution.

Zimmermann and Kennedy (1978) made a formulation for the transverse bed slope in a constant curvature bend. In the process of doing so, they assumed that a power-law could express the vertical distribution of the tangential velocity.

Meandering channel flow is considerably more complex than constant curvature bend flow. Unlike a constant curvature bend, where one finds that in the initial portion of the bends, the flow is in the developing stage and thereafter it is in the developed stage, in meanders due to the continuous streamwise variation of the radius of curvature, no the developed region is reached and the flow parameters vary continuously in the streamwise direction.

De Vriend and Geldof (1983) compared the results of a mathematical model for the depth-averaged main flow velocity in shallow river bends with measurements in two consecutive sharply curved short bends in the river Dommel.

They found that,

a) The velocity distribution in the Dommel showed essentially the same features as observed in other channels of similar geometry.

b) A mathematical model derived from the “Kalkwijk/De Vriend model” worked rather well in the greater part of the two bends if secondary flow convection is ignored.

c) The inward skewing tendency of the velocity distribution near the entrance of the bend was due to the main flow inertia combined with the longitudinal pressure gradients arising from the growth of the transverse surface slope.

d) In the river section under consideration, the gradual outward shift of the main velocity maximum further downstream in the bend was a matter of retard adaptation of the flow to the bed configuration, rather than of secondary flow convection.

e) Secondary flow convection was only important in the last part of each of the surveyed beds; there it seemed to hamper the outward skewing of the flow instead of enhancing it.
f) As the flow stage became higher, the main velocity maximum tended to shift towards the inner bank; this was attained to the reduced symmetry of the channel, rather than to the slower development of the secondary flow.
Ikeda and Nishimura (1986) presented an analytical model for describing three-dimensional flow. This was presented as an extension of the depth-averaged two-dimensional flow model of Engelund (1974) which had not treated the secondary flow in sinuous channels. To describe the flow they split the flow into the depth-averaged two-dimensional flow component and secondary flow component. The depth-averaged flow was expressed as the sum of unperturbed reach-averaged hydraulic variables and the perturbed quantities denoting perturbations induced by curvature. The reach-averaged tangential velocity, the perturbed component of tangential velocity and the perturbed component of radial velocity were evaluated (the reach-averaged radial velocity is zero). Next, an expression was formulated for the zero depth-average pure helical components of the radial velocity. These results were incorporated in a bed topography model and the bed topography model was validated thus indirectly validating the flow model also.
Johannesson and Parker (1989a) studied the secondary flow in a mildly sinuous channel. They obtained a derivation of the phase lag (the lag between the secondary flow and the channel curvature). They found that the predicted lag was small in natural channels. However, the predicted lag was much higher in many experimental channels, in agreement with data.
Johannesson and Parker (1989b) presented an analytical model for calculating the lateral distribution of the depth-averaged primary flow velocity in meandering rivers. The method they used took into account the convective transport of primary flow momentum by the secondary flow.
Zhou, Chang, and Stow (1993) reported a study on the phase lag of secondary flow in Meanders. Bhattacharya (1995) conducted a mathematical study and experiments on a deep mild meander without and with adjacent floodplains.

Geometric Elements of Channel Section

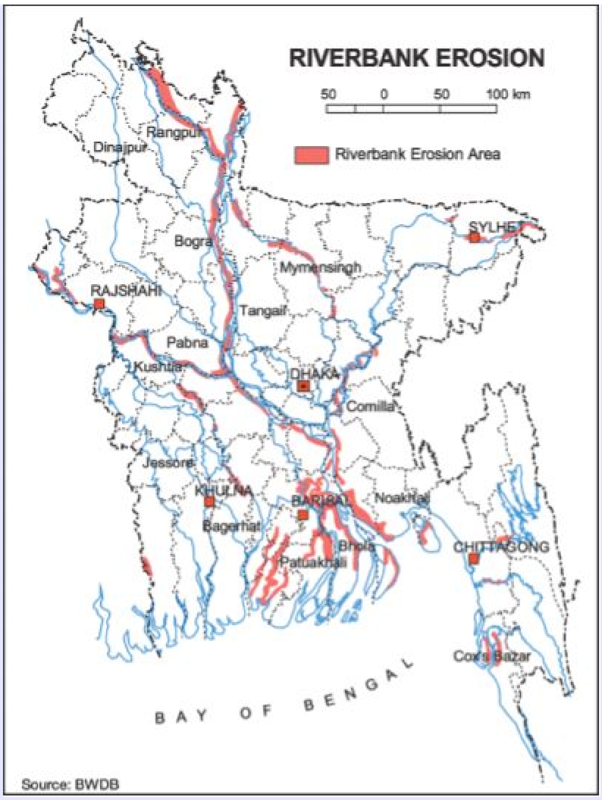
Geometric elements are properties of a channel section that can be defined entirely by the geometry of the section and the depth of flow. These elements are very important and the area used extensively in flow computations.
For simple rectangular channel sections, the geometric element can be expressed mathematically in terms of the depth of flow and other dimensions of the section.
The definition of several geometric elements of channel cross-section are given below
1. Depth of flow: The depth of flow is the vertical distance of the lowest point of a channel section from the free surface. Strictly speaking, the depth of the flow section is the depth of flow normal to the direction of flow or the height of the channel section containing the water.
2. Stage: It is the elevation or vertical distance of the free surface above a datum. If a lowest point of the channel section is chosen as the datum, the stage is identical with the depth of flow.
3. Top width (T): It is the width of the channel section at the free surface.

4. Water area (A): It is the cross-sectional area of the flow normal to the direction of flow.
5. Wetted perimeter (P): It is the length of the line of intersection of the channel-wetted surface with a cross-sectional plane normal to the direction of flow.
6.Hydraulic Radius (R): It is the ratio of the water area to its wetted perimeter i.e R=A/P
7. Hydraulic Depth (D): It is the ratio of water area to the width of the top D=A/T
8. Sinuosity (Sr): It is defined as the ratio of one wavelength of the main channel in the down-valley direction (ls) to the one wavelength of the main channel along its center line (lc) i.e. Sr=ls/lc

CASE STUDY: Application of Vetiver as a Biotechnical Slope Protection Measure in Bangladesh:

Bangladesh is a country in South Asia with an approximate population of 166 million (2018) and total area of 147570 km^2 of which 50% of the land is within 6-7m of Mean Sea Level. Disaster this country needs to encounter are heavy rainfall and floods, cyclones, earthquakes. arsenic contamination, salinity intrusion, river bank erosion, seismicity, contamination of water. In the past this country has been affected severely by the disasters and resulted in a setback both environmentally and economically. Being a small country, densely populated and low-lying with coastal line of about 710 km adds to major losses in the impacts due to disaster events. In order to overcome this various methods have been proposed and utilized a comparative analysis has been detailed.

River Bank Erosion in Bangladesh and Usual practices of Riverbank Protection



Riverbank Erosion in Bangladesh

River Bank Erosion in Bangladesh

The usual practices of Riverbank protection include 'Slope protection work with CC slab on slope and palisading work at toe' and Slope protection by brick block and geo-textile. The common practices are expensive and in many cases these are not effective during their design life.

Riverbank protection by CC Blocks (Daily Prothom Alo, dt: 04.04.2011)

Riverbank protected by Geo-Textile

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

Materials and methods

The experimental tests, initiated in April 2014, were carried out on the bank of Kor River located in Kamfiroozie 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 the 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 the 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 a median diameter of 0.83mm consists of poorly graded material, defined as 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). The 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/cm2 (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 (Candφ) were calculated from Eq. 1. In the present study, the tests were performed at the in situ moisture content (undrained). Undisturbed samples (for each condition, three samples were used) were placed in the shear box. It should be noted that due to the experimental limitations, 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.

Vetiver: The root system goes up to 14 ft deep in 6 to 8 months time

Results and Discussions

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 increases from the middle of the second week and continues until the end of the fourth week.

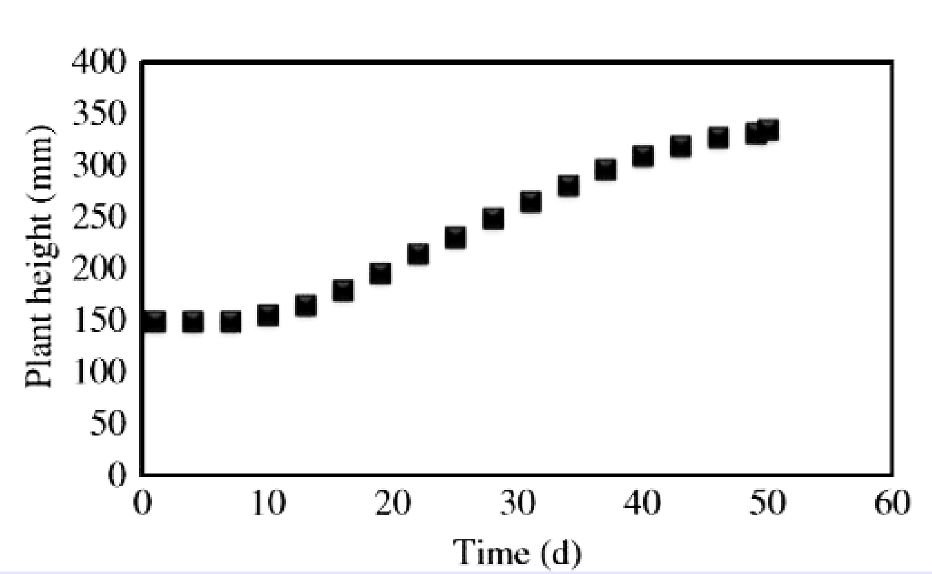


Fig. 1 Variations of the height of the Vetiver grass against time

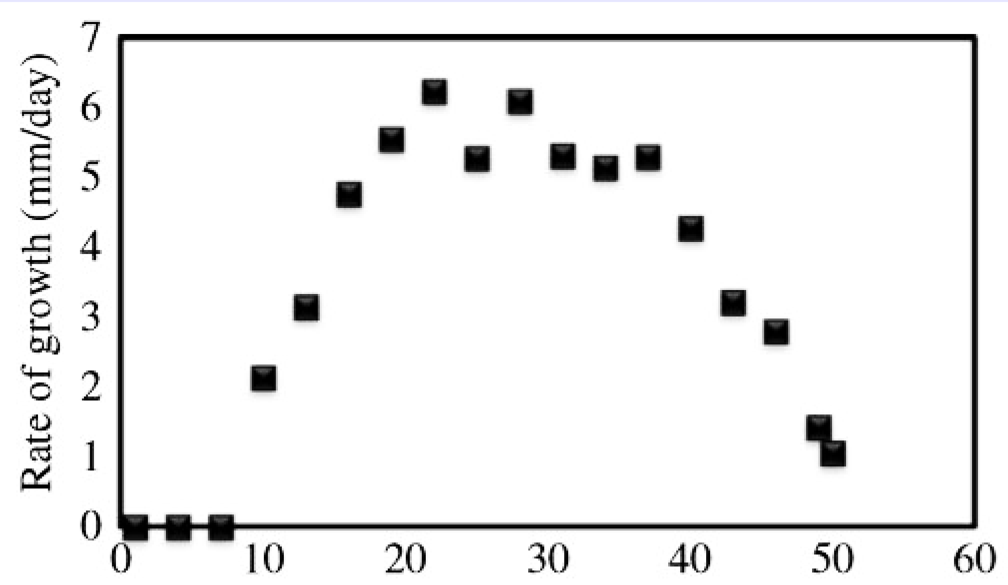


Fig. 2 Variations of the growth rate of the Vetiver grass

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 foliage height observed for the vetiver grass in the study site was 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, and5. 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 hardpan 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 hardpan is considered to be a major constraint to Vetiver grass root penetration into the ground at this site. However, in some applications, the 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 hardpan 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.

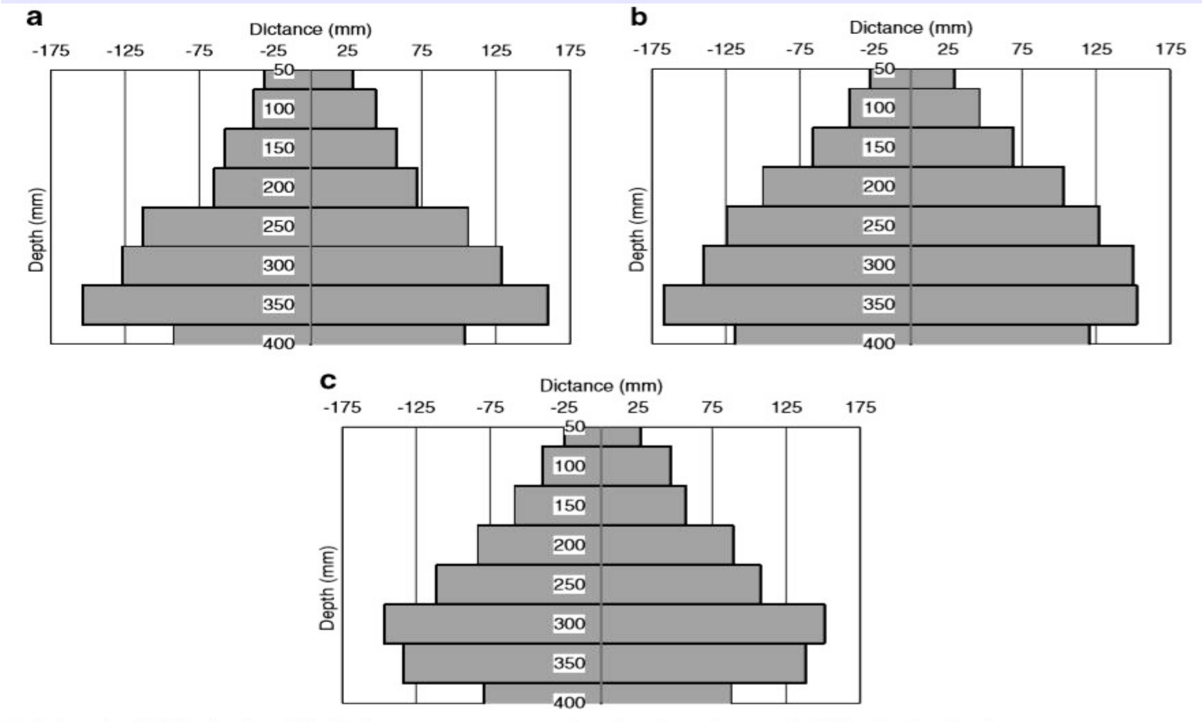


Fig. 3 Vertical and radial distribution of the Vetiver grass root system for a low, b medium, and c high planting density

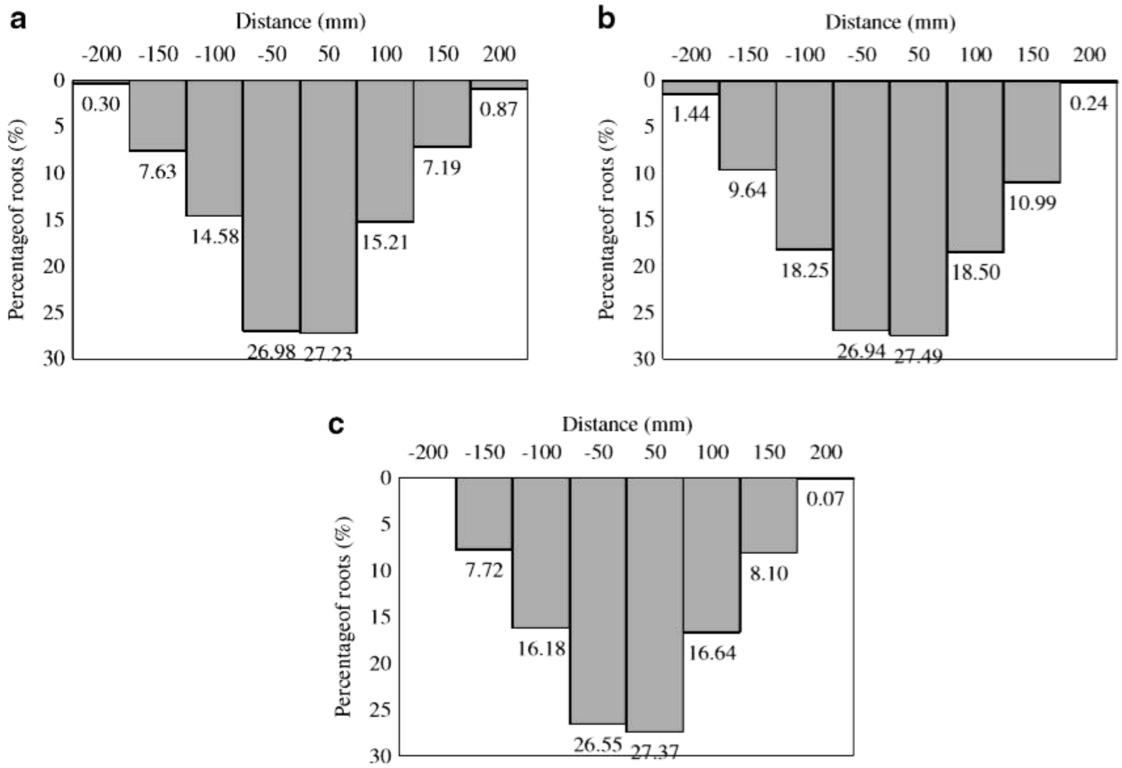


Fig. 4 Percentage of the lateral distribution of the Vetiver grass root system for a low, b medium, and c high planting density

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 a 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 interval 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 downslope and 3.995% for the upslope of eight hornbeam trees growing on the hilly terrain of Northern Iran. Also, Bischettietal. (2004)reportedthatthemeanRARvalues 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.

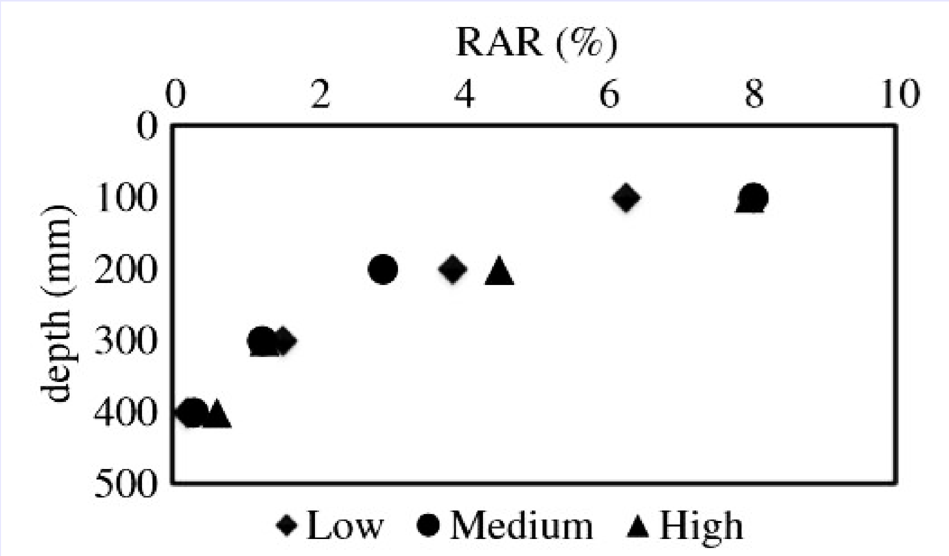


Fig. 5 Variations of RAR against soil depth for various Vetiver grass densities

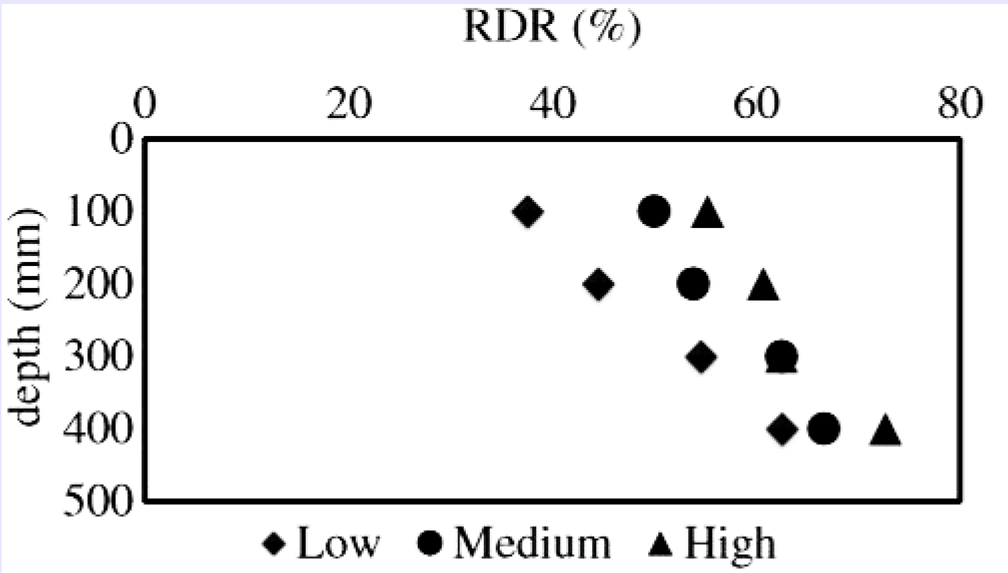


Fig. 6 Variations of RDR against soil depth for various Vetiver grass densities

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 the conservation of the topsoil 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.

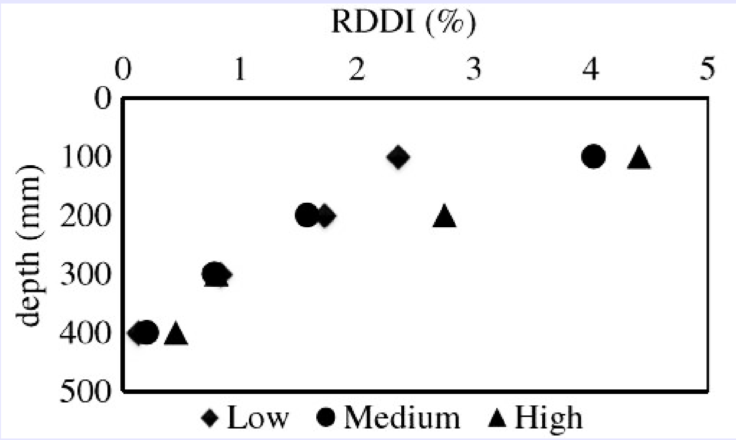


Fig. 7 Variations of RDDI against soil depth for various Vetiver grass densities

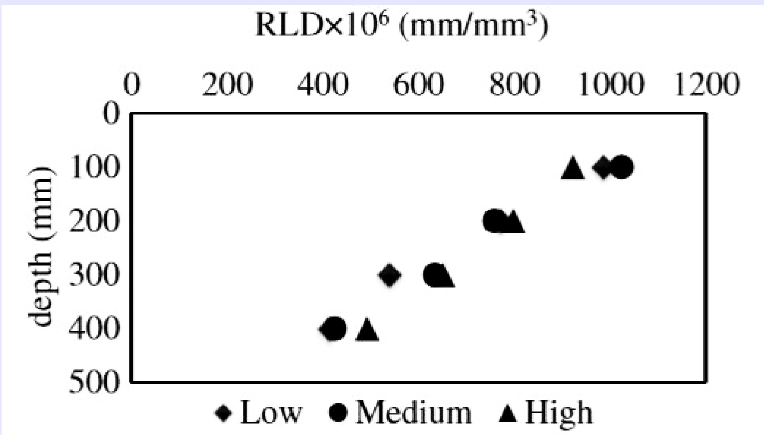


Fig. 8 Variations of RLD against soil depth for various Vetiver grass densities

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, corresponding 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 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 withσ= 3 kg/cm 2) are up to three times higher than those of lowest normal stress (Fig. 9a withσ=1kg/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.

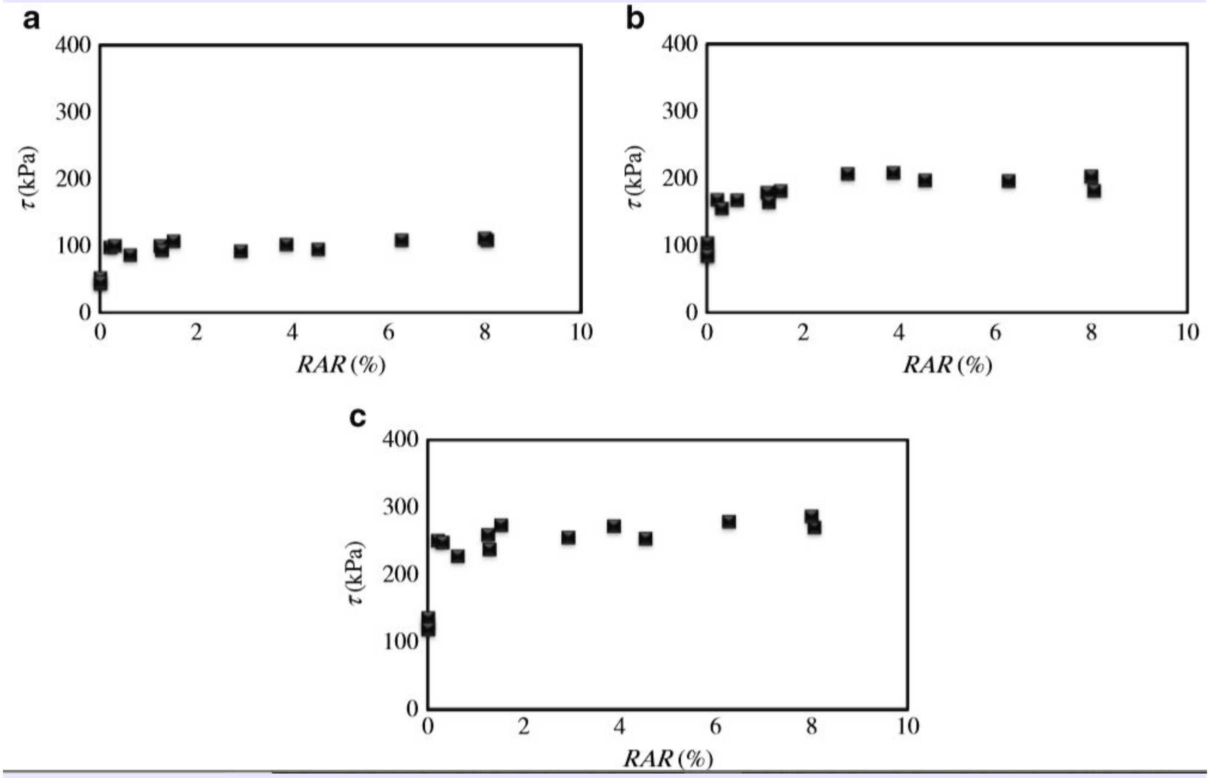


Fig. 9 Variations of the soil shear stress (τ) againstRAR for normal stresses equal to a 98.1, b 196.2, and c 294.3 kPa

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. Figure2 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:

$C = 0.7371 + RAR + 20.72$..(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 increases the soil cohesion, as shown in Fig. 10.

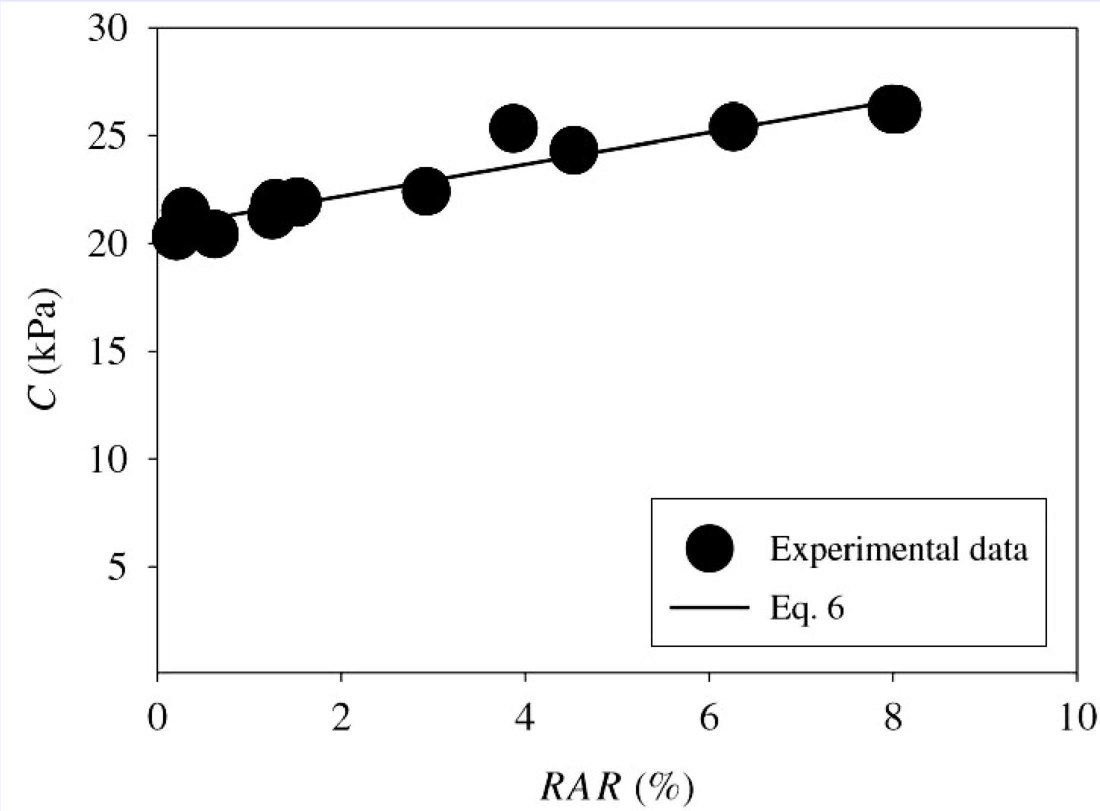


Fig. 10 Variations of soil cohesion (C) against Vetiver grass root area ratio (RAR)

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 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 grassroots investigated in this study have very small size roots of mean diameter of 0.65mm, very close to 0.66 mm reported by Truongetal.(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:

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

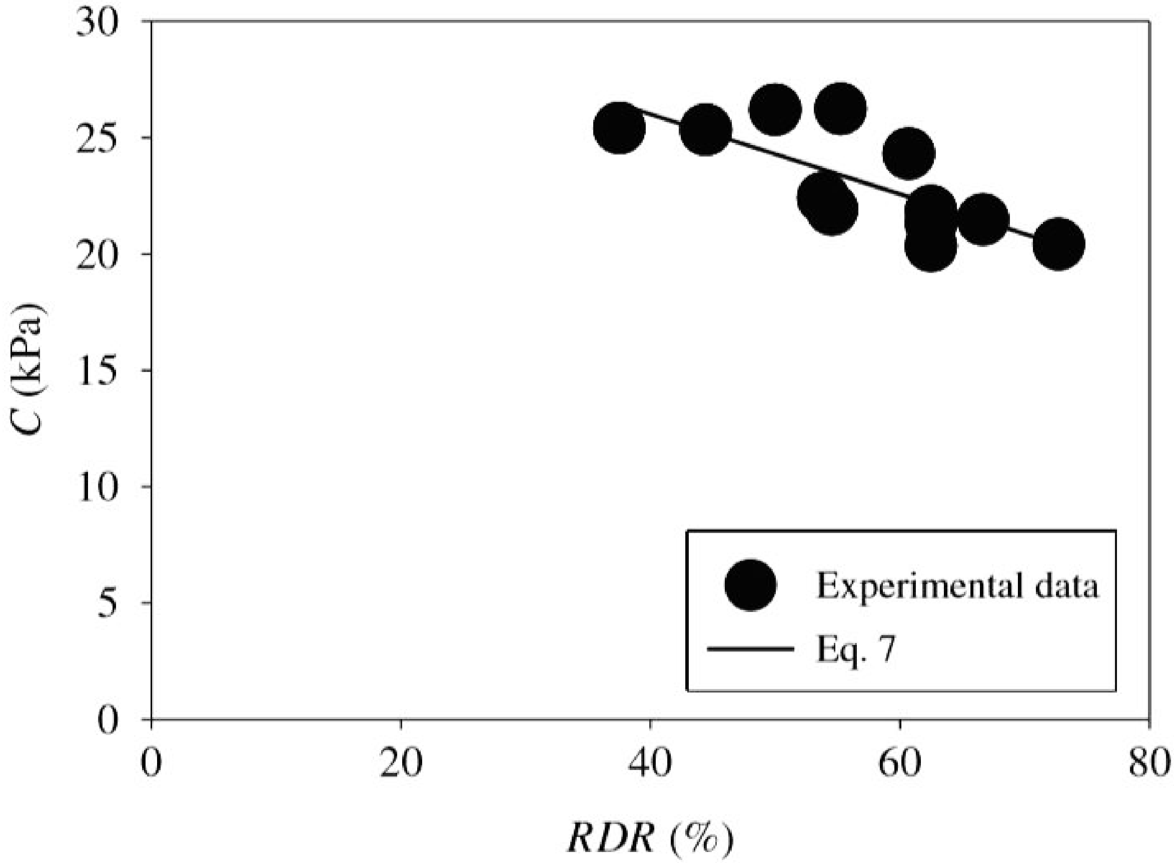


Fig.11 Variations of soil cohesion (C) against Vetiver grass root diameter ratio (RDR)

Figures 12 and 13 show the variations of soil cohesion (C) 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 =0.83and R^2=0.84, respectively, have been fitted to the experimental data by using regression analysis:

$C = 1.4144\,RDDI + 20.743$...(8)

$C = 0.0098\,RLD + 16.268$..(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 pronounced than that of RDR.

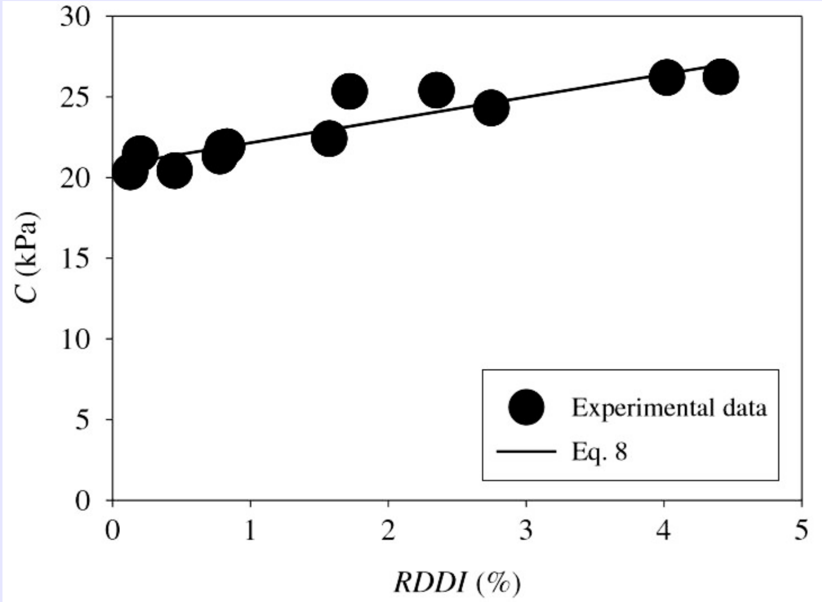


Fig.12 Variations of soil cohesion (C) against Vetiver grass root diameter and density index (RDDI).

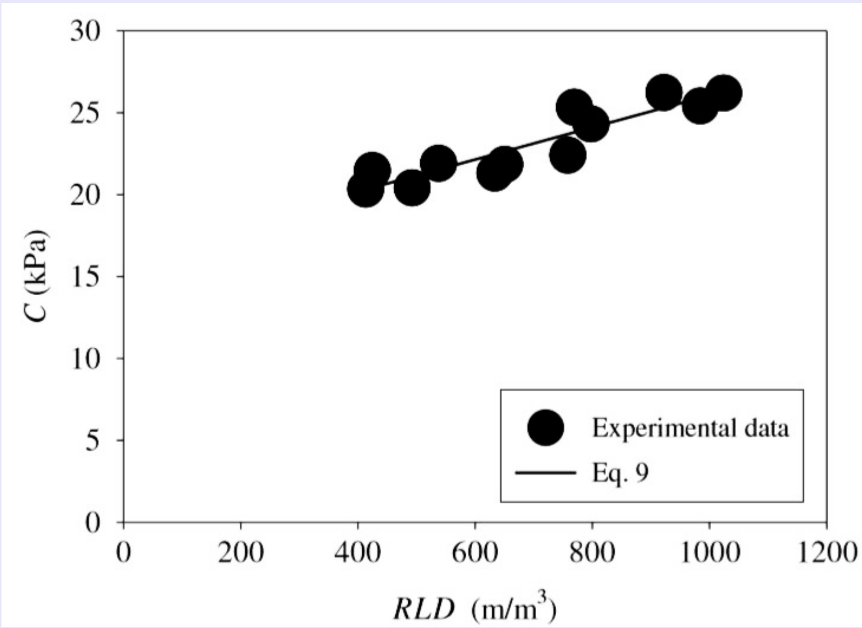


Fig. 13 Variations of soil cohesion (C) against Vetiver grass root length density (RLD)

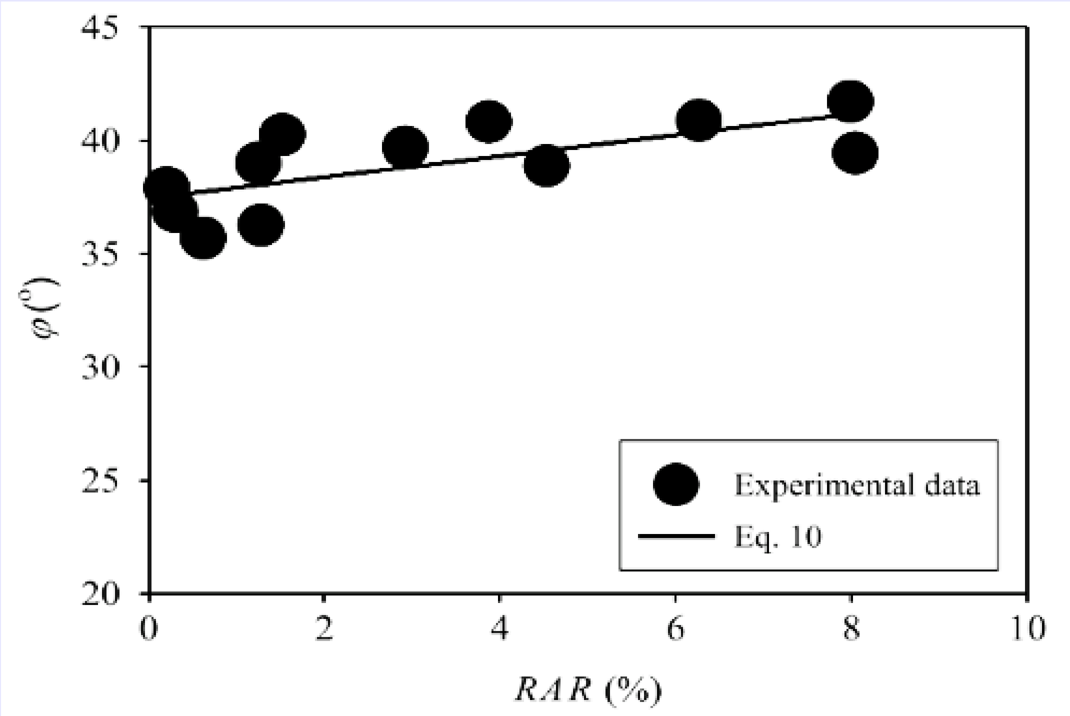


Fig. 14 Variations of angle of internal friction (φ) against Vetiver grass root area ratio (RAR)

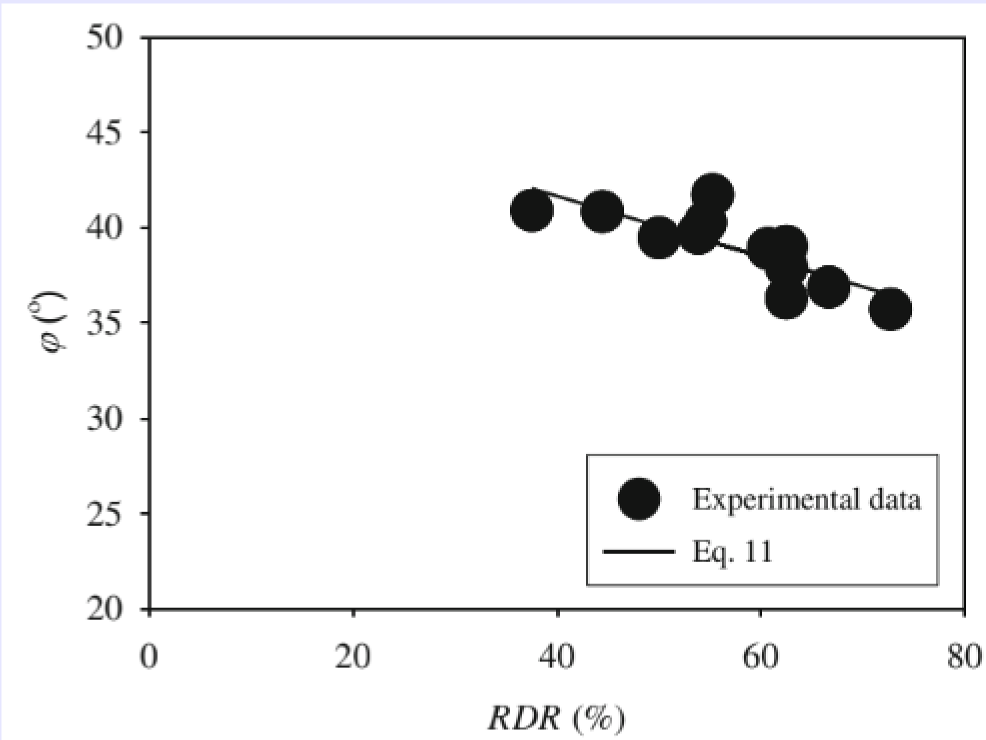


Fig. 15 Variations of angle of internal friction (φ) against Vetiver grass root diameter ratio (RDR)

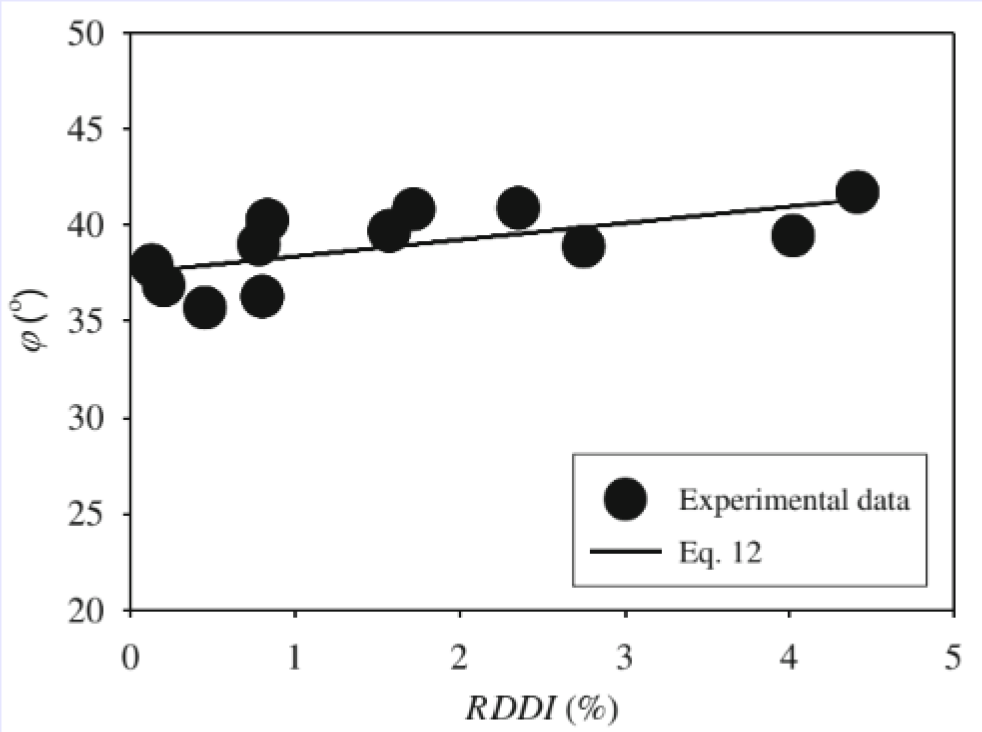


Fig. 16 Variations of angle of internal friction (φ) against Vetiver grass root diameter and density index (RDDI)

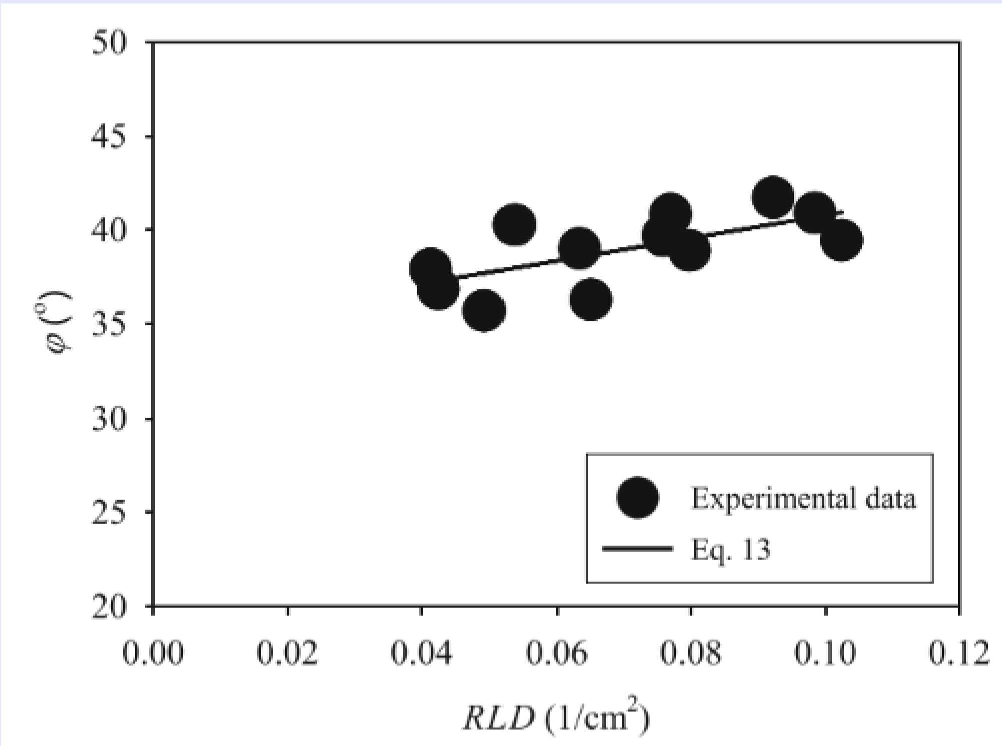


Fig. 17 Variations of angle of internal friction (φ) against Vetiver grass root length density (RLD)

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

Vegetation density	C (kPa)	φ (°)	ΔC (%)	Δφ (%)
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:

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

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

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

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

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 $\underline{C}$ and $\underline{\varphi}$, 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 Δφ, 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 Δφ are defined as follows:

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

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

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, syca-more, 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.

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

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 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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