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Study on Shear Strength of Soil In Relation to Plant Roots as A Combind Matrix

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Abstract

Shear data for the unvegetated soil control samples, *Thysanolaena maxima*, and S*accharum spontaneum* after 4,8 and 12 weeks of growth were studied. The soil stabilization effect of plant roots is based on two components ,first by friction between the soil particles that transfer shear stresses from the soil to the root reinforcement system, and second by soil arches that build up between cylindrical soil units that are reinforced by roots (root stock-soil elements) and stabilize areas that are not rooted. Shear increase in rooted soil is based on the model of a combined matrix of a material that consists of fibres of relatively high strength and adhesion to a matrix of lower tensile strength. The reduction factor is defined as the ratio of particle size of the output material. The proportion of particle close to 0.425 mm was quite large and the amount of clay sized particle was too small to make the whole sample plastic. The 0.075mm sieve were limited to a maximum of 2% although this percentage was permitted to rise to10% if the fines of this size were non plastic. Although exhibiting lower shear strengths than their unvegetated counterparts in the 4-week growth scenario, both species were seen to approach higher soil stability by the 12-week growth scenario. *Thysanolaena maxima* handled higher shear stresses than the soil control sample after 8 and 12 weeks. The existing root area occupied by roots on a potential shear surface at a certain depth or by using the relationships of shear-strength increase in the soil versus the root- area ratio or the bulk weight of root per volume unit of soil. Together all these three plants (*Thysanolaena maxima,* S*accharum spontaneum* and *Vetiveria zizanioides*) are very effective as reinforcer for the prevention of soil erosion. Reinforcement is provided by both thin and coarse roots, the former acting more as tensile elements within the soil matrix, whereas large diameter roots can also act as tendons or anchors connecting planted surface layers to underlying or adjacent stable soil zones.

Keywords: Soil, Shear strength, Root reinforcement, Mohr and Coulomb shear curve, Root area

Introduction

The goals of environmental engineering are the restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance, and the development of new sustainable ecosystems that have both human and ecological value[1]. Loss in agricultural production can be related to poor soil quality. High rates of erosion are due to floods occurs every year, generally weak soil shear strength [2,3,4,5].It can occur due to a variety of factors, both natural and human-induced, such as: sediment compaction, organic matter oxidation, faulting[6,7].The reduction rates in ground surface elevation on average of 1.5 mm/yr, as high as 10 mm/yr , and as high as 25 mm/yr in certain locations[8,9,10,11]. Land erosion can be classified into two categories: *sheet/rill erosion* and *gully erosion*. These are two terms that essentially describe the same process—rill erosion being gully erosion on a small scale. Gully erosion is due to local scour and is caused by flowing water in a defined channel[12,13]. Shear strength is of sincere importance to gully formation and *epehemeral gully erosion*, which is term explaining erosion that occurs on areas of such topography that runoff collects and concentrates in few well-defined channels that form in local low points and at the confluences of surface water currents before exiting[13]. The work of Hergault[14] cites the shearing processes of a moving fluid as an important parameter involving granular flow of sediment bed load transport in a supercritical flow. Erosion is believed to occur once a critical shear stress exerted by the moving fluids over a bed of sediment is exceeded[15,4,16]. When this critical value is obtained, erosion will occur over a range of fluid shear stresses and sediment properties if given sufficient time[17] and under critical conditions, a stream is said to be competent to move its sediment[18]. Critical shear stress is an important parameter governing detachment by runoff which appears in numerous erosion models[3] .

There is a immediate need to develop the design for sustainable ecosystems that integrate human society with its natural environment for the benefit of both[1]. It is the creating or restoring of ecosystems to serve as engineering solutions that have value to both nature and humans. Soil shear strength is a valuable parameter to examine for civil engineering applications. The safety of any geotechnical engineering structure is dependent on the shear strength of the soil beneath it [19]. The shear strength of soils is an important aspect in many foundation engineering problems such as the bearing capacity of shallow foundations and piles, the stability of the slopes of dams and embankments, and lateral earth pressure on retaining walls[20]. Understanding shear strength can lead to the classification of the condition of a soil entity[21] and can assist engineers in drawing critical conclusions about the overall soil mechanics of a specific environment.

From a engineering point, shear strength of common engineering materials, such as steel, is governed by the molecular bonds that hold the material together. The higher the shear strength of a material, the stronger the molecular structure[20]. However, soil shear strength operates under a different set of principles. Soil is a particulate material, so shear failure occurs when the stresses between the particles are such that they slide or roll past each other. Due to the particulate nature of soil, unlike that of a continuum, the shear strength depends on the inter-particle interactions rather than the internal strength of the soil particles themselves[21].

Erosion is the removal of a region of the Earth’s surface due to weathering and transport of sediments, specifically by currents or flows [2,13,17,22] . Sediment transport is the movement of solid particles due this. To remedy this, we need to conserve materials, reduce their unnecessary erosion, produce, make them last longer. We also need to develop community consumer initiatives and regulatory processes to support these reforms and deal with evaluation, production, consumption, recycling and regulation materials with the intention of clarifying the relationship between these realms, and therefore contributing to possible economic conversion strategies linking these areas. Our relationship with materials is thus a major influence on our economy, the natural world, and our personal and spiritual well-being. Some terms that describe the complex processes associated with the movement of sediments are erosion, deposition, initiation, motion, suspension, and many others[17]. Sediment transport is of major importance to flood alleviation, water resource management, and environmental sustainability[14]. *Erosivity* refers to the intensity of the eroding agent (i.e., water, wind, etc.) to cause detachment and transport of a sediment, while *erodibility* defines the resistance of the sediment to those erosional processes. Erodibility can depend on a variety of factors, but it is claimed that the actual properties of the soil are the most important characteristics, such as: soil texture, aggregate stability, infiltration capacity, organic and chemical content (clay content), plasticity index, and soil shear strength[22].

The role of plant roots on soil shear strength is very important to stabilize the soil. However, literature in this field is lacking. Sundborg[23]suggested that the cohesive force resisting entrainment of a grain is proportional to the shear strength of the sediment as determined in standard soil tests, and it acts in a direction opposite to the fluid force. Cohesive sediments can be described as those for which the resistance to initial movement or erosion depends also on the strength of the cohesive bond between the particles[17]. In marshy soils , root network protect the cover, and root presence can act to increase cohesiveness [13,17].

It has been widely recognized that plant root systems can improve soil shear strength. Studies have been conducted that indicate a distinct increase in shear strength from soil containing no roots to those containing embedded root systems[24,25,26,27,28,29] . In an experiment to evaluate the effect of roots on soil shear strength, Zhang[26] used consolidated-drained triaxial compression tests on samples of composites comprised of representative loess from the Loess Plateau in Northwest China and roots of *Robinia pseucdoacacia*. The samples were manually prepared and the roots were placed in the soil in three different configurations: vertical, horizontal, and a cross vertical-horizontal alignment. Two sets of samples were prepared at different soil water contents. Testing was conducted with a strain-controlled triaxial compression test apparatus, and each sample was subjected to four different confining pressures at a constant shear velocity. Grain-size distribution curves, stress-strain curves, and Mohr-Coulomb calculations were performed on the test data. Test results confirmed the hypothesis that plant roots can indeed improve soil shear strength in a rather effective manner. This was confirmed by observing a significant increase in cohesion, with the horizontal-vertical root configuration showing the most dramatic increases. Soil water content also proved to have a significant effect on the shear strength properties of the composites tested. Findings indicate that with an increase in water content, a decrease in cohesion is found along with a possible effect on the internal angle of friction, having an overall reducing effect on soil shear strength. It has been widely recognized that plant roots can improve soil shear strength and can act to reinforce a mass of soil against shear failure[26]. Roots, being relatively strong in tension and weak in compression, can increase the shear strength of soil media, which is relatively weak in tension and strong in compression, in a manner that is akin to the reinforcement of concrete structures by steel or fiberglass[25]. During the past twenty years, rapid growth in the field of ecological engineering has coincided with an increased interest in the use of vegetation as an effective, economical and environmentally friendly solution for slope and streambank stabilization and similar applications [24,26,29].

Establishing vegetation by planting is one solution method used in practice for such applications. The plant roots can improve soil shear strength and that over time the beneficial impacts can become significant, little is known for how long after planting do the benefits on soil shear strength begin to be realized. Coefficients in equations for erosion of cohesive sediments are determined based on laboratory testing of samples carefully extracted in-situ from the field site of interest [30]. Analyzing soil shear strength can help explain the mechanics of erosional processes in generally weak wetland clays and cohesive sands. Erosion is said to occur once a critical shear stress exerted by moving fluids over a bed of sediment is exceeded [15,4,16]. When this critical value is obtained, erosion will occur over a range of fluid shear stresses and sediment properties if given sufficient time, and under these critical conditions, a stream is said to be competent to move its sediment[17,18]. Plant roots can increase soil stability and ultimately increase surface erosion resistance by promoting an increase in soil stiffness and shear strength [2,32,31].

During the past twenty years, rapid growth in the fields of biological and ecological engineering has coincided with increased interest in the use of vegetation as an effective, economical and environmentally friendly solution for slope and stream bank stabilization and other similar applications[26]. Observing soil and plant roots as a combined matrix, plant root systems act to reinforce the soil media against shear failure, much like that of steel rebar in reinforced concrete design[25]. There are many factors affecting the degree to which root systems can strengthen a soil media that would otherwise not benefit from such a shear strength increase. Some models incorporate root reinforcement as an additional shear strength term in the Mohr-Coulomb shear equation. Thomas and Pollen-Bankhead[25] assumed that all roots extended vertically across a horizontal shear zone, and that the root matter behaved in a manner much like laterally-loaded piles when horizontal shearing was applied. This study gave way to other research investigating the angle of alignment of each root relative to the shear plane and its effect on the incorporated term in the Mohr-Coulomb equation.

Vetiver grass (*Vetiveria zizanioides*) has been utilized to reduce soil erosion in many countries throughout the world for a long time. It is well understood that the root properties of vetiver grass can help reduce soil erosion and strengthen slope stability when planted properly. Vetiver hedgerows cultivated across slope soil can block the passage of soil particles and develop terraces between the hedges enhancing stability of the slope. Some previous studies on vetiver have elucidated the morphological properties of the root and their qualitative significance for erosion control and slope stabilization [32,33]. They emphasize the early developing deeply penetrating (sometimes up to 3.5 m) fibrous root system of vetiver and its capability of anchoring, themselves firmly into slope soil profiles. However, the strength properties of vetiver root, which also play an important role in terms of erosion control and slope stabilization by means of their influences on the shear strength of slope soil has not yet been adequately understood. When a plant root penetrates across a potential shear surface in a soil profile, the distortion of the shear zone develops tension in the root; the component of this tension tangential to the shear zone directly resists shear, while the normal component increases the confining pressure on the shear plane. Therefore it is essential to determine tensile root strength properties in the process of evaluating a plant species as a component in slope stabilization. Recently, in Malaysia the vetiver hedgerow technique starts to gain popularity in erosion control and slope stabilization.

Aims and Objectives

The aim of this research is, therefore, to develop and verify the technical viability of using the soil shear strength with plant roots. The objective of this study to measure changes in soil shear strength due to the existence of plant root systems. It is intended to understand how long after planting do root-enhanced shear strength increases begin to manifest themselves. It is generally accepted that soil shear strength correlates positively with erosion resistance. Furthermore, it was investigated how shear strength can be improved by the presence of plant roots to increase stabilization in soils. In addition it also provides a thorough understanding of the stress dependent mechanical behavior The general aim of this research is to establish an innovative and relatively simple material characterization technique to enable a more easy application of the mechanical behavior of soil in relation to plant root for day to day practice .

Material and Method

The plant materials is shown in figure 1and 3. A direct shear test is conducted by applying shear to a soil specimen under constant vertical loading and was done according to ASTM D3080[34]. The actual physical input of interest (i.e., load, pressure, temperature, etc.) and is done so as follows

$P = CF X (V_S - V_0 / V_E)$

Where: P = value of measured physical property

CF = calibration factor

VS = signal voltage value for reading

V0 = signal voltage zero value

VE = excitation voltage value

A test specimen, being roughly 1.25-in deep by 2.5-in diameter, is loaded into the shearbox (Figure 2) with the alignment pins and the bottom porous stone in place. It is then placed into the movable bath chamber to house the test specimen assembly. Another porous stone is placed atop the specimen, the load distributor is placed atop the upper porous stone, and the setup is verified for proper alignment in the horizontal and vertical directions. During the shear phase of testing, the top plate of the shearbox remains fixed while the bottom plate moves along with the bath chamber. The top plate contains two pistons that fit onto a metal L-shaped piece that connects to the central longitudinal axis of the horizontal load cell. Testing begins by initiating the consolidation phase. The vertical load cell is positioned near the vertical load distributor, and then upon pressing the “start” button, seating takes place as the specified vertical load is applied to the specimen. The vertical load cell continues to lower itself onto the load distributor until the desired normal loading is reached.

At this point the software prompts to fill the bath chamber with deionized water (if required) and then to start the test, thereby beginning the first step. Vertical displacement is measured while the specimen is undergoing consolidation, and this step can be terminated at any time. After the first step, the user can terminate the consolidation phase by pressing the “done” button. The next step is the shearing phase. At this time, the software prompts to remove the alignment pins that lock the two shearing plates in place. Next, the horizontal load frame imparts a constant horizontal displacement on the consolidated specimen while the shear force response is measured by the horizontal load cell. This entire procedure is conducted on an array of specimens over a range of constant vertical loadings to perform a direct shear analysis.

Basic soil shear strength equations were developed using an approach not too unlike that of classic sliding friction equations from basic physics theory. instead of using μ a parameter is defined called the friction angle, ϕ (or the effective angle of internal friction ϕ), and is related to ??as follows Coduto [21]:

$\varphi = \tan^{-1}\mu$

Where: φ (φ') = (effective) angle of internal friction

μ = coefficient of friction

Similar to basic physics theory for friction equations, in geotechnical engineering the surrogate parameter for the normal force relating to the coefficient of friction is called the effective stress, σ. The effective stress concept was developed by Carl Terzaghi and plays an important role in most any geotechnical design or analysis. The effective stress concept is as follows [19]:

$\sigma' = \sigma - u$

Where: σ' = effective stress

σ = total stress due to vertical geostatic pressure

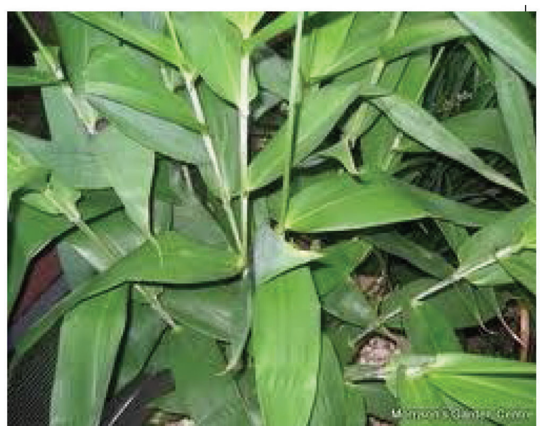
1. S*accharum spontaneum*

1. *Thysanolaena maxima*

2. S*accharum spontaneum*

2. *Thysanolaena maxima*

3. S*accharum spontaneum*



3. Thysanolaena maxima

Fig.1: Plants of ***Thysanolaena maxima and* S*accharum spontaneum***

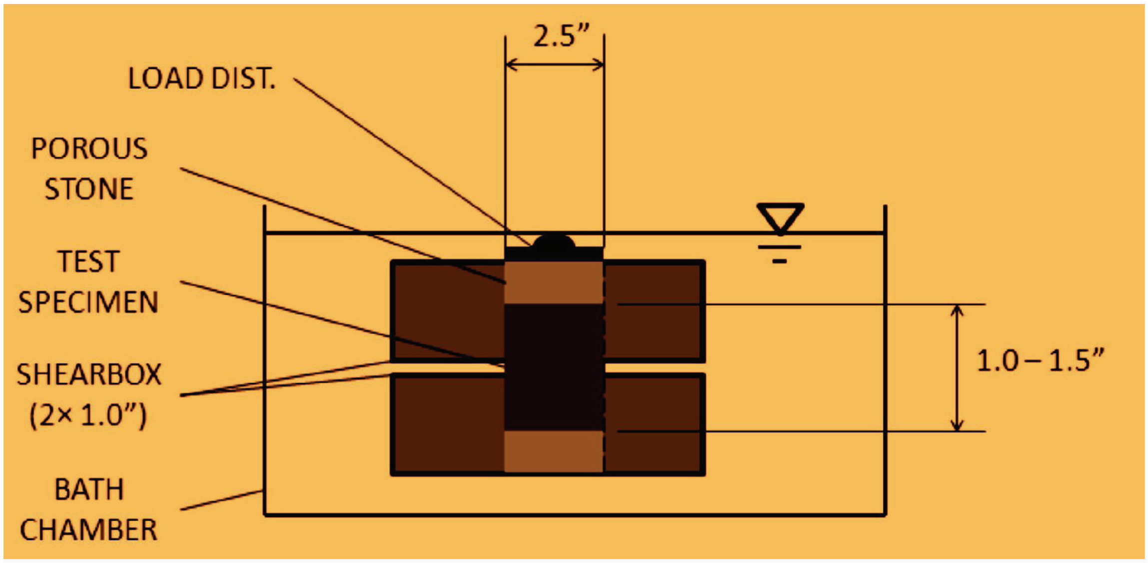


Fig. 2: Shear Box

= γH; where ã is soil unit weight and H is soil stratum thickness

u = hydrostatic porewater pressure

= γwzw; where ãw is unit weight of water, zw is vertical distance to groundwater table

The Mohr-Coulomb failure criterion states that failure along a plane in a material occurs by a critical combination of normal (effective) and shear stresses. Effective stress and friction angle appear frequently in commonly used equations. Shear strength is related to these parameters by another parameter called cohesion, c. Cohesive strength is a term given to soils that have shear strength but exhibit zero effective stress [21]. These soils are called cohesive soils. The following equation relates shear strength, effective stress, and cohesion. This is called the Mohr-Coulomb failure criterion and is defined as follows [20]:

$\tau = c + \sigma \tan\phi$

Where: τ = shear strength

c = cohesion

To understand the effect that subsurface plant matter can have on soil shear strength and to observe changes in shear strength with increased time after planting. Direct shear testing was done on vegetated samples of a known soil media that had been cultivated in a controlled environment. Direct shear test specimens were composites of soil and subsurface plant root matter of two grass species that were sampled after four, eight, and twelve weeks of growth.

Plant Species and Establishment (Tray Setup)

Two species of coastal grasses were selected for this analysis.*Thysanolaena maxima*, Roxb(Gramineae) and S*accharum spontaneum,* Linn, (Gramineae) are two perennial grasses. In order to understand the soil shear strength improvement characteristics of these grasses, a series of direct shear tests was performed on soil-root composites (SRCs) of these species in a controlled soil media. A correlation was established between the above-ground biomass (AGB) and the shear strength properties for each grass species over time. A total of eight mother plant clusters were manually removed with a serrated-edge knife. Four 25-qt rectangular plastic bins were used as growth containers. First, each bin was filled to a depth of approximately four to five inches of soil media. Two small impressions were made, and two clusters were then transplanted into each bin. Next, water was added to completely submerge all soil media. The water level was maintained approximately one to two inches above the soil-water interface within (ground surface) and was watered at least twice per week.

Multiple cultivation scenarios were performed to obtain data in a progressing time series from four to twelve weeks as well as an extreme case of a nearly completely root-bound sample of S*accharum spontaneum*. This sample was compaired with the 12-week growth scenario for *Thysanolaena maxima* and was called a "time equals infinity" sample. This was done to examine the effects that a fully matured below-ground root system could have on soil shear strength after a sufficiently large time after planting. The plants were fertilized and stem counts were recorded and observe rhizomal propagation throughout the growth period. At least once every three days, the plants received water from a garden hose connected to a municipal water line. A fertilizer solution was prepared and was sprayed on the exterior of the plant stems at the same frequency that stem counts were performed.

Sampling

At the end of each growth period, all specimens were extracted. This began by emptying the standing water from each growth chamber. Water was poured from the bin into an external container and was removed from the chamber. Using a serrated-edge knife all specimens were removed by cutting out a core of soil-root media beneath each stem cluster. The next step was to remove all AGB with a knife. All plant stems were removed at the ground surface and their weights were recorded. The SRC sample was then wrapped in aluminum foil for preservation. All samples were then packed into labeled plastic bags for storage. A soil control sample was also taken by filling a plastic bag with soil from each bin. No root or plant matter was included in this sample. The set of samples was stored at 0°C to halt growth and to preserve natural root orientations.

Laboratory Details

Testing was performed in the Soil Mechanics Laboratory. Each sample produced one test specimen. In order to perform a thorough direct shear evaluation, a minimum of three tests must be carried out [19]. ASTM standard D3080[34] was consulted, where the inclusion of root matter in the test specimens deviated from the procedure. A total of three vertical loadings were selected based on the increase in effective stress due to the addition of fill media. The tests were run at vertical loadings of 40, 100, and 300 psf (2, 5, and 14 kPa). Table 4 shows normal stress values corresponding to fill depths of soils with properties. For the shearing phase of testing the horizontal displacement rate was set to 0.01 in/min and sheared until the external limit of the shearbox, which is the dual shearing plate assembly used for direct shear tests. Saturated soil conditions were replicated in the laboratory by submerging the shear box with de ionized water.

For the determination of tensile root strength, mature root specimens were sampled from two-year-old vetiver plants grown on an embankment slope. The specimens were tested in fresh condition limiting the time elapsed between the sampling\ and the testing to two hours maximum. The unbranched and straight root samples, about 15-20 cm long, were vertically connected to hanging spring balance via a wooden clamp at one end while the other end was fixed to a holder that was pulled down manually until the root failed. At failure, the maximum load was monitored. Subsequently, the mode of failure was examined for each sample and the results of end sheared samples and those with unusually altered rupture points were discarded. To calculate the tensile root strength, the root diameter without bark was used since the bark failed before the root due to its weaker strength properties, and eventually the total tensile stress transferred to the root core. About 80 vetiver root specimens of different diameter classes varying from 0.2 to 2.2 mm were tested and the results were interpreted as the ultimate tensile force and tensile strength in relation to root diameter without bark.

Direct Shear Tests on Root-Permeated Soil

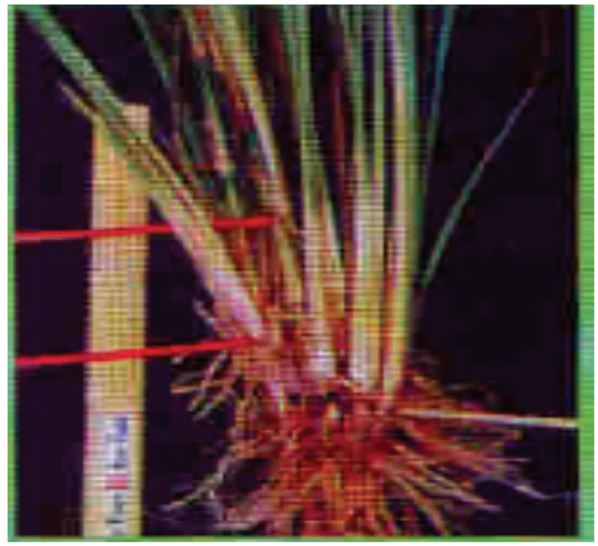
Roots of trees and other vegetation provide a reinforcing effect to soil through tensile resistance and frictional or adhesional properties. The reinforcing effect or the increase of shear strength in soil due to roots can be quantified by conduction in-situ direct shear tests on root –permeated and root-free soils at the same location. The difference between shear strength values of root permeated soil and root-free soil sheared under the same conditions gives the shear strength increase due to the roots. In order to determine the root reinforcement effect of vetiver grass, large-scale direct shear tests were performed on a sloped soil profile of an embankment vegetated with vetiver. The test apparatus comprised a shearbox, a hydraulic jacking system, a proving ring and dial gages.

The shear box was made of 8 mm thick steel plates capable of m holding firmly a soil block of 50 cm x 50 cm x 50 cm in dimensions. A hydraulic jacking system with capacity of 10 tons produced the shear load through the proving ring of 3 tons of measuring capacity which controlled the shear force while four dial gages measuring the shear displacement (Figure 2).

The test plants were selected from a 50-cm-long vetiver hedgerow that usually includes 3 plants planted at a spacing of 15 cm. The soil surrounding the plants was removed leaving a 50 cm x 50 cm x 25 cm root-permeated soil block centering the hedgerow. Subsequently, the shear box was set so as to cover the soil block and the loading and displacement measuring systems were assembled. The soil block with 25 cm height then sheared horizontally towards the slope direction under stress controlled- condition. After shearing, the shear surface and the orientation of failed roots were examined carefully in order to estimate the shear distortion during failure. It was observed that the average shear distortion during failure was about 30º. The total cross sectional root area on the shear plane and the bulk weight of roots in the sheared soil block were measured in order to determine the root area ratio and the biomass, respectively. This procedure was followed for each 25 cm of depth under the entire vetiver hedgerow length of 50 cm up to 1.5m depth. For each depth level of shearing, a root-free soil profile adjacent to the root-permeated soil profile was also sheared under the same shearing conditions. Each soil block was sheared under its self-weight as the normal load. The bulk density of test soil was determined before each test for a comparison of the normal load on the root-permeated soil block with that on the counterpart root-free soil block. Each pair of tests was made under equal, normal stress conditions.

Theoretically, the average tensile strength of roots can be used to compute the shear strength increase in soil due to penetration of roots across a shear plane. The computation adapts the simple model of root-reinforced soil subjected to direct shear[35]. According to this model, the tensile force that develops in the roots when the soil is sheared can be resolved into a tangential component which directly resists shear and a normal component which increases the confining stress on the shear plane. The model simply assumes that the roots are fully mobilized during shearing. The mobilized tensile resistance in the roots translates

Vetiver (*Vetiveria zizanioides*)Growth



Vetiver (*Vetiveria zizanioides*)Enlarge view

Vetiver(*Vetiveria zizanioides)* Roots

Vetiver(*Vetiveria zizanioides)* as SoilBinder

Fig. 3: Plants and Roots of Vetiver

into an increase in shear strength in the soil as expressed by the following equation :

$\Delta = tR\ [\cos\theta ß\tan\phi + \sin\theta]$

Where are: θ – angle of shear distortion

ϕ – angle of internal friction

tR – average tensile strength of roots per area unit of soil

The average tensile strength of roots per area unit of soil can be determined by multiplying the average tensile strength of the roots (TR) by the fraction of the soil cross-section occupied by roots, or the root area ratio (AR/A).

Table 1: Direct Shear Tests

Test	Description of Direct Shear Test
Afer 4 Weeks	*Thysanolaena maxima* and S*accharum spontaneum* samples at 4 weeks, 40,100and 300 psf normal load
After8 Weeks	*Thysanolaena maxima* amples at 8 weeks, 40,100and 300 psf normal load
After12 Weeks	*Thysanolaena maxima* and S*accharum spontaneum* samples at 12 weeks, 40,100and 300 psf normal load
Afer 4 Weeks	Soil samples at 4 weeks, 40,100and 300 psf normal load
Afer 8 Weeks	Soil samples at 8 weeks, 40,100and 300 psf normal load
Afer 12 Weeks	Soil samples at 12 weeks, 40,100and 300 psf normal load

Result and Discussion

The soil stabilization effect of plant roots is based on two components: (1) by friction between the soil particles that transfer shear stresses from the soil to the root reinforcement system, and (2) by soil arches that build up between cylindrical soil units that are reinforced by roots (root stock-soil elements) and stabilize areas that are not rooted. Shear increase in rooted soil is based on the model of a “combined matrix” of a material that consists of fibres of relatively high strength and adhesion to a matrix of lower tensile strength. Most geotechnical models express the increase in shear strength of rooted soil as an increase in cohesion exclusively based on the anchoring effect of plant roots. Rarely do such combined matrix take into account an increase of the angle of inner friction due to biologically changed soil properties.

Roots of trees and other vegetation provide a reinforcing effect to soil through tensile resistance and frictional or adhesional properties. The reinforcing effect or the increase of shear strength in soil due to roots can be quantified by conduction in-situ direct shear tests on root permeated and root-free soils at the same location. The difference between shear strength values of root permeated soil and root-free soil sheared under the same conditions gives the shear strength increase due to the roots. In wind erosion, fine cohesion less soil particles are blown away. Wind force disturbs the exposed soil surface leading to gradual depletion of soil particles that cement the larger ones and hold the soil surface together, causing erosion. Wind velocity over 12 to 15 km/h at 150 mm above ground level is the threshold value for the grain size of 0.10 to 0.15 mm(Table 2).

Table 2: Relationship between particle diameter and susceptibility to wind erosion

Particle Diameter,mm	Wind Susceptibility
<0.42	High Erodibility
00.42-0.84	Difficult to Erode
0.84-6.4	Usually non Erodible
>6.4	Non Erodible

In the table 3, grading requirement of material is in terms of percent by weight passing the sieve. Class-I grading material is fine silt/clay or their mixture, class–II grading material is coarse silt/medium sand/ sandy soil and class –III grading material is gravelly sand. In general there was adequate porosity for normal plant growth functions in all soil-aggregate systems, tested, above a proposed benchmark minimum of 22% in urban soils [36]. The systems drained quickly with a high internal gravitational, porosity, providing aeration [37] which also, provided rapid infiltration ability. The rate of rapid drainage can be influenced by the stone-soil mixing ratio, choice of soil, choice of aggregate and compaction level. Soil type affects the balance between water stress and high soil strength and it is possible that whether a soil shrinks or not as it dries determines this balance. The ability of shrinking soils to stay mechanically weak when they dry may contribute significantly to the greater yields found on clay soils, although this is conventionally attributed to better nutrient status.

Table 3: Gradation Data

Type of Grading Material	Class-I	Class-II	Class-III
Sieve Size	Fine Silt/Clay	coarse Silt to Medium sand	Gravely Sand
53mm	-	-	100
45mm	-	-	97-100
26.5m	-	100	-
22.4mm	-	95-100	50-100
11.2mm	100	48-100	20-60
5.6mm	92-100	28-54	4-32
2.8mm	83-100	20-35	0-10
1.4mm	59-96	-	0-5
710mm	35-40	6-18	-
355mm	14-40	2-9	-
180mm	13-5	-	-
90mm	0-5	0-4	0-3

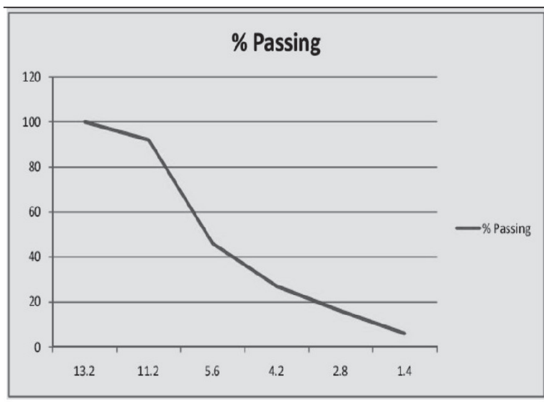
Table 4: Grading of Aggregates

Sieve Size(mm)	% by weight Passing
13.2	100
11.2	92-100
5.6	27-46
2.8	3-16
1.4	0-6

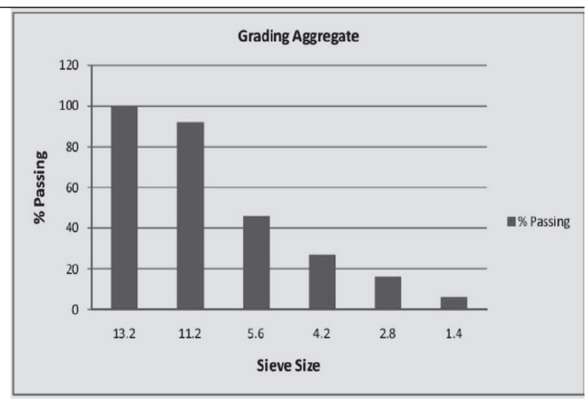
The particle grading of an aggregate confirms the particle grading standard(Table 4 and Figure 4). We did not get the equal grading for both the plant soil . The variation comes due to climatic conditions. The particle size distribution of soil is also affected by various kind of human activities and environmental stress. In general, these impacts have larger reduction factor. The reduction factor is defined as the ratio of particle size of the output material. The particle size less than 37.5 mm. may have contributed to the high densities . The inclusion of upto 15% of particle larger than 37.5 mm should not alter density significantly. Water absorption of coarse and fine particle of soil passing 19 mm 4.75 mm respectively is higher. The proportion of particle close to 0.425 mm was quite large and the amount of clay sized particle was too small to make the whole sample plastic. The 0.075mm sieve were limited to a maximum of 2% although this percentage was permitted to rise to10% if the fines of this size were non plastic. Soil must resist fracture (shear strength) and remain dryer than its plastic limit. In real soils with grains of many different sizes and shapes, the shear loss rate may be lower as the more irregular and different size particles may help to protect the biomass from shear detachment[38].

Table 5 shows normal stress values corresponding to fill depths of soils with properties typical of those used for reinforcement. For the shearing phase of testing the horizontal displacement rate was set to 0.01 in/min[39] and sheared until the external limit of the shearbox, which is the dual shearing plate assembly used for direct shear tests [20]. At the depth of 40 inch the stress was observed maximum and minimum was at 3 inch. Simultaneously maximum shear stress was obtained at 0.0705kN force. There is a direct relationship between force and stress.(Figure 5).

The pull out resistance of a root is the measured resistance of root structure to be pulled out of the ground and is likely to be only a little less than the measured tensile strength of the root which is the roots resistance to breaking as measured in the laboratory. In the cases where there is no pull out data available the tensile strength data maybe used as a rough guide to the maximum pull out resistance available[40]. The tensile root strength of a range of diameters over a range of species has been tested in the laboratory and has been found to be approximately 5 – 60MN/m². In order for the root to actually enhance slope stability the root must have sufficient embedment and adhesion with the soil. The way that roots interact with the soil is intricate but for engineering purposes the available force contributions may be measured with in situ pull out tests[40].



% passing and Sieve size



Grading Aggregates

Fig. 4: Relationship between Sieve size and passing percentage

Roots that do not have branches generally fail in tension and pull straight out of the ground with only minimal resistance. The root reaches its maximum pullout resistance then rapidly fails at a weak point. The root easily resistance. The root easily slips out of the soil due to the gradual tapering (progressive decrease in root diameter along its length) which means that as the root is pulled out it is moving through a space that is larger than its diameter which consequently has no further bonds or interaction with the surrounding soil[41].Forked roots require a greater force to be pulled out as the cavity above the fork is thinner than the root which is trying to move through the cavity, this can then result in deformation of the soil as the root moves through the soil[41].Roots that have multiple branches or forked branches also can undergo tensile failure but predominantly fail in stages as each branch breaks within the soil. These roots break with increasingly applied force in stages in the form of stepped peaks corresponding to the progressive breaking of roots of greater diameters. The root progressively releases its bonds with the soil until final tensile failure[41]. Norris[41] observed that the pull out resistance of roots are affected by intra species differences, inter-species variations and root size (diameter) in a similar as way as root tensile strength varies (as measured in the laboratory). In the pull out test the applied force acting on the root acts across a larger root area, which involves multiple branches, longer lengths than the short (approximately 150mm) length of root used in tensile strength tests. In pull out test the root is likely to fail at weak points such as branching points, nodes or damaged areas. Norris(2005)[41]showed that there is a positive correlation between maximum root pull out resistance and root diameter for root. Smaller diameter roots had a lower pull out resistance or breaking force than the larger diameter roots. Vegetation can also be used to control water erosion by limiting surface processes such as sheet wash and overland flow.[42,43]. Vegetation can provide a considerable contribution to the stability of slope through enhancing soil cohesion. This cohesion is dependent upon the morphological characteristics of root systems and the tensile strength of single roots[44].

Table 5: Normal Stress Calculations

Fill Depth	Diameter	Area		Volume		Bulk Density	Force	Stress
in	in	in^2	m^2	in^3	m^3	kN/m^3	kN	kPa
3	2.0	4.50	0.00250	25	0.00030	15	0.005261374	2
6	2.0	4.50	0.00250	27	0.00040	15	0.0083571	3
9	2.0	4.50	0.00250	35	0.00060	15	0.01338213	4
12	2.0	4.50	0.00250	50	0.00090	15	0.019255	5
20	2.0	4.50	0.00250	110	0.00185	15	0.03415	10
40	2.0	4.50	0.00250	230	0.00375	15	0.0705	20

Table 6: Four Week Direct Shear Test Results

Parameter	*Thysanolaena maxima* Normal Loading [kPa]			*Saccharum spontaneum* Normal Loading [kPa]			Unvegetated Soil Normal Loading [kPa]		
	2	5	14	2	5	14	2	5	14
Shear Stress Range[kPa]	8	12	17	6	16	19	12	18	21
Shear Stress at 0.5 in[kPa]	9	14	20	5	16	18	12.2	20.4	26.2
Stem count[a][stems]	-	70	-	-	52	-	-	-	-
Growth rate[b][stems]	-	7	-	-	5	-	-	-	-
Dry AGB[g]	3.14	3.85	3.02	6.05	3.43	5.10	-	-	-

Notes: No shear failure was observed for any sample
a = stem count on extraction date for both trays
b = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)

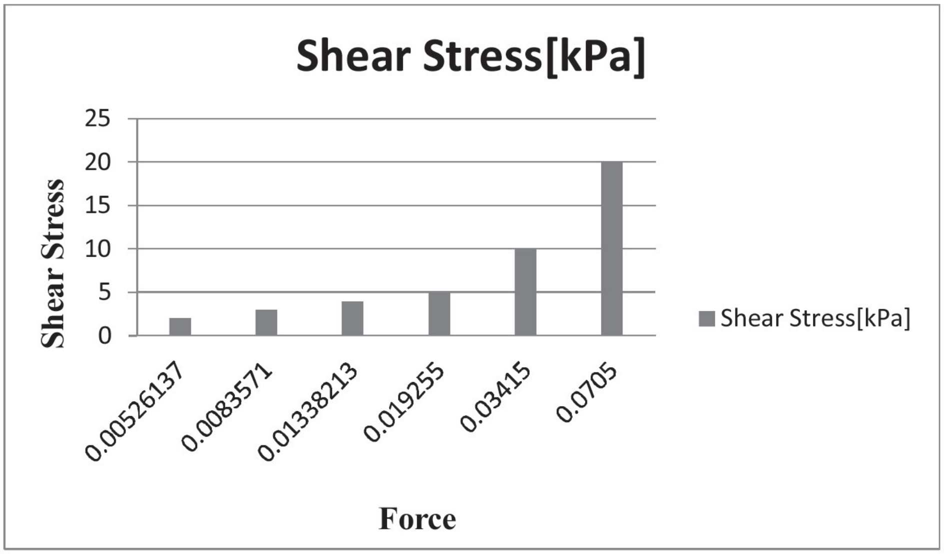


Fig. 5: Relationship between Force and Shear Stress

Table 6 summarizes direct shear data for the unvegetated soil control samples, *Thysanolaena maxima*, and S*accharum spontaneum* SRCs after four weeks of growth. There was no shear failure exhibited for any sample. The shear response increase was measured and was termed the shear stress range. This was obtained by taking the maximum value at the terminus of the shear response curve and the minimum value near the beginning of the shear response curve after the initial strengthening period of high slope. The highest terminal value obtained was 26 kPa for the 300 psf (14 kPa) normally loaded direct shear test on the unvegetated sample, and the range covered 20 kPa of increasing shear response. The lowest terminal value obtained was 6 kPa for the 40 psf (2 kPa) normally loaded direct shear test on S*accharum spontaneum*, and the range covered 4 kPa of increasing shear response. Shear stresses were recorded after 0.5 in of horizontal displacement. The highest value obtained for this parameter was 26.2 kPa, which occurred for the 300 psf (14 kPa) normally loaded direct shear test on unvegetated soil. The lowest value obtained for this parameter was 5 kPa, which occurred for the 40 psf (2 kPa) normally loaded direct shear test on S*accharum spontaneum*. Stem counts after four weeks of growth were 70 and52 for *Thysanolaena maxima* and, S*accharum spontaneum* respectively. The growth rate, which is a measure of the rate of change of stem accumulation between stem counts, was calculated by averaging the difference in stem counts between readings throughout the growth period. *Thysanolaena maxima* had an average growth rate of 7 stems per approximately 4 days, while S*accharum spontaneum* had an average growth rate of 5 stems per approximately 4 days. The average dry AGB masses were 3.14 and 5.10g for *Thysanolaena maxima* and, respectively.Figure 7 showed that maximum shear stress was obtained at 14kPa in all cases of after four week of plantation.The S*accharum spontaneum* has been found more effective than *Thysanolaena maxima* but at 0.5kPa the *Thysanolaena maxima* was more positive. When roots grow across the plane of potential failure there is an increase in shear strength by binding particles. The roots anchor the unstable superficial soil into the deeper stable layers or bedrock[44]. This most readily occurs when there is rapid deep growth (1.5m deep) of roots which last for more than two years. However it is important to note that the strength exerted by roots generally only extends down to 1m while most failures occur between 1.2 – 1.5m soil depth. The root reinforced earth root model is the result

Thysanolaena maxima Two week after Planting

S*accharum spontaneum* Four week after Planting

S*accharum spontaneum* Eight week after Planting

S*accharum spontaneum* 12 week after Planting

Fig.6: *Thysanolaena maxima* and S*accharum spontaneum* after weeks of planting

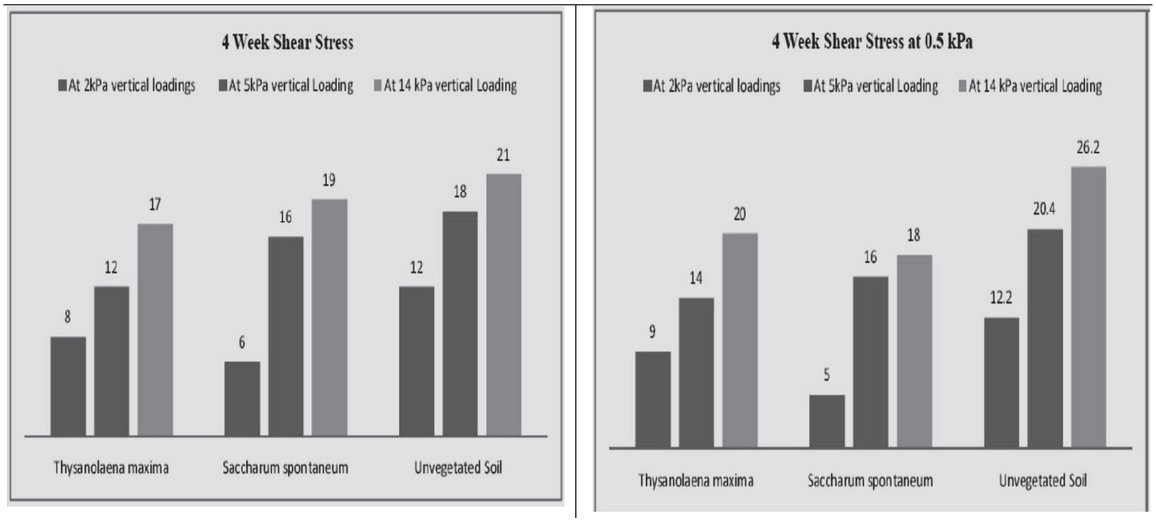


Fig. 7: Shear stress after 4 week

of the root elongation across a potential slip plane which produces a tensile root force which is transferred to the soil by cohesive and frictional contacts between the root and the soil[45].

Table 7: Eight Week Direct Shear Test Results

Parameter	*Thysanolaena maxima* Normal Loading [kPa]			S*accharum spontaneum* Normal Loading [kPa]			Unvegetated Soil Normal Loading [kPa]		
	2	5	14	2	5	14	2	5	14
Shear Stress Range[kPa]	12	10	20	20	11	17	10	14	15
Shear Stress at 0.5 in[kPa]	11	10	22	13.5	10.7	15	10.3	20	19.6
Stem count[a][stems]	-	137	-	-	158	-	-	-	-
Growth rate[b][stems]	-	7	-	-	10	-	-	-	-
Dry AGB[g]	5.64	7.35	4.82	15.13	13.05	8.42	-	-	-

Notes: No shear failure was observed for any sample
a = stem count on extraction date for both trays
b = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)
c = shear failure at 0.41 in horizontal displacement

Table 7 summarizes direct shear data after eight weeks of growth. There was no shear failure exhibited for any sample except for the unvegetated soil sample under 300 psf (14 kPa) of normal load. The shear response increase was measured. The highest terminal value obtained was 20 kPa for the 300 psf (14 kPa) normally loaded direct shear test on, *Thysanolaena maxima* and the range covered 20 kPa of increasing shear response. The lowest terminal value obtained was 10 kPa for the 40 psf (2 kPa) normally loaded direct shear test on the soil control sample, and the range covered 8 kPa of increasing shear response.

Shear stresses were recorded at 0.5 in of horizontal displacement for comparison, except where noted. The highest value obtained for this parameter was 22 kPa, which occurred for the 300 psf (14 kPa) normally

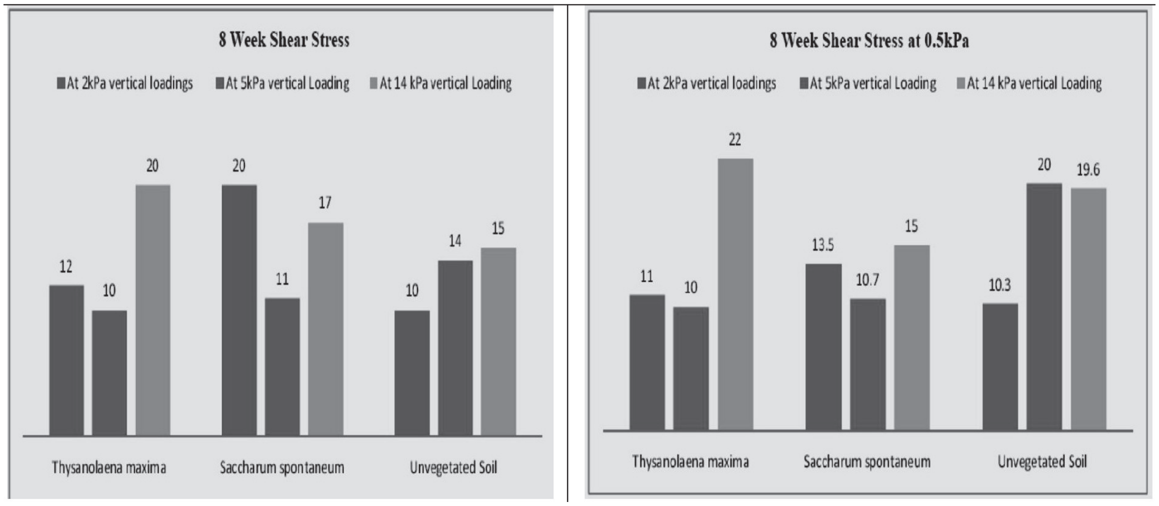


Fig.8: Shear stress after 8 week

loaded direct shear test on *Thysanolaena maxima*. The lowest value obtained for this parameter was 10 kPa, which occurred for the 40 psf (2 kPa) normally loaded direct shear test on the soil control sample. Stem counts after eight weeks of growth were 137 and 158 total for *Thysanolaena maxima* and, S*accharum spontaneum* respectively. *Thysanolaena maxima* had an average growth rate of 7 stems per approximately 4 days, while the same was calculated for. S*accharum spontaneum* The average dry AGB masses were 7.35 and 15.13 g for *Thysanolaena maxima* and, S*accharum spontaneum* respectively. Figure 8 showed the maximum shear stress in *Thysanolaena maxima* and minimum for unvegetated soil. At 0.5kPa maximum shear was obtained for *Thysanolaena maxima* and minimum for S*accharum spontaneum*. The time for ground water flow to the next node is small in areas of high shear, so this approximation is not believed to affect the results significantly. In high shear stress areas high concentration of biomass was present. This suggest that shear stress can play an important role for high biomass concentration. Shear effects may not only be important for preventing excessive biomass concentration but they also could have important impact on contaminant bioremediation

Table 8: Twelve Week Direct Shear Test Results

Parameter	*Thysanolaena maxima* Normal Loading [kPa]			S*accharum spontaneum* Normal Loading [kPa]			Unvegetated Soil Normal Loading [kPa]		
	2	5	14	2	5	14	2	5	14
Shear Stress Range[kPa]	17	12	18	15	8	25	8	12	19
Shear Stress at 0.5 in[kPa]	10	13	29	10.5	8	20	14.3	12	22
Stem count[a][stems]	-	140	-	-	-	-	-	-	-
Growth rate[b][stems]	-	7	-	-	-	-	-	-	-
Dry AGB[g]	14.10	14.60	12.10	21.50	14.70	28.15	-	-	-

Note-At 2kPa, 5kPa and 14kPa vertical loadings of 40, 100, and 300 psf (2, 5, and 14 kPa)
No shear failure was observed for any sample
a = stem count on extraction date for both trays b = measure of rate of change of new stem growth for an interval of approximately 4 days (between counts)c = samples extracted from mature plant colony

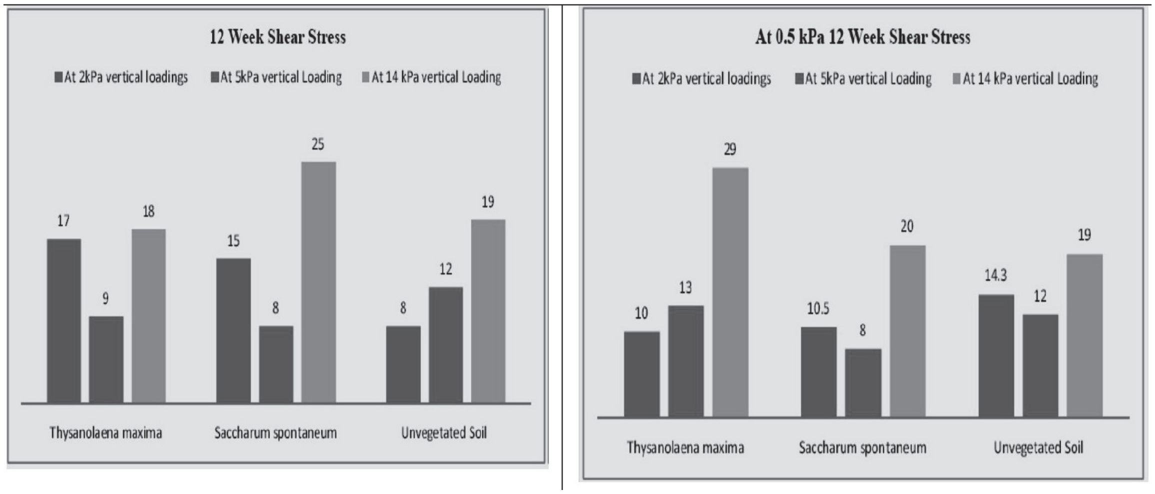


Fig.9: Shear stress after 12 week

Table 8 summarizes direct shear data after twelve weeks of growth. The S*accharum spontaneum* samples were taken from a pre-grown matured colony, where the subsurface material was comprised of little soil media and virtually nothing other than an intertwined system of its roots. There was no shear failure exhibited for any sample. The shear response increase was measured. The highest terminal value obtained was 29 kPa for the 300 psf (14 kPa) normally loaded direct shear test on *Thysanolaena maxima*, and the range covered 18 kPa of increasing shear response. The lowest terminal value obtained was 8 for the 40 psf normally loaded direct shear test on both vegetated samples, and the ranges covered 7 kPa and 5 kPa of increasing shear response for *Thysanolaena maxima* and, S*accharum spontaneum* respectively. Shear stresses were recorded at 0.5 in of horizontal displacement for comparison. The highest value obtained for this parameter was 29 kPa, which occurred for the 300 psf (14 kPa) normally loaded direct shear test on *Thysanolaena maxima* . The lowest value obtained for this parameter was 8 kPa, which occurred for the 40 psf normally loaded direct shear test on S*accharum spontaneum. Thysanolaena maxima* had an average growth rate of 7stems per approximately 4 days. Stem count growth was not tracked on S*accharum spontaneum*, because the samples came from a pre-grown source. The average dry AGB masses were 13.60 and 21.45 g for *Thysanolaena maxima* and S*accharum spontaneum*, respectively.Figure9 showed that S*accharum spontaneum* has maximum shear stress and *Thysanolaena maxima* has minimum.At 0.5kPa *Thysanolaena maxima* has maximum shear stress while unvegetated soil has minimum stress.The tensile strength of roots depends on the plants species, root diameter, age, site conditions (e.g. moisture) and season. Root tensile strength usually decreases with increasing diameter. The increase in shear strength of soil with increasing biomass content (weight of dry living roots per soil volume) has been found to be roughly linear. After the photosynthetic portion are cut down, the live root mass and the shear resistance decrease rapidly. Large roots can resist great total tensile forces simply because of their size but their anchorage value lies with their resistance to bending and shear. Small diameter roots are flexible with a high tensile strength. Large diameter roots are stiff, resisting shear and bending. Small roots act to generate a strong friction zone between soil and root. Large roots act as unbending anchors. This combination of root sizes allows plants to stand[46]. Immediate vegetation is necessary for wide mesh systems to ensure a sufficient filter effect and protection against surface erosion. It is the small roots which provide great tensile strength for a given cross-sectional area. Greater root tensile strength per cross-sectional area lies in smaller roots, while greater root stiffness lies with larger roots. Both rooting depth and length maximize root / soil friction, mass of soil held above the roots, and resistance to failure. The process of shear stress may have a significant impact on both the growth and distribution of a large biomass population. Detachment of biomass from the soil grains could act to keep the biomass concentrations lower in the area of high shear. Detailed analysis of the shear stress at the field scale is impractical since that would require knowing the flow field everywhere at the pore scale. Principles used in flocculation studies [47]can be used to study the shear of biomass from soil particles and it can act as indicator of high shear stress.

Shear Strength Benefit Index

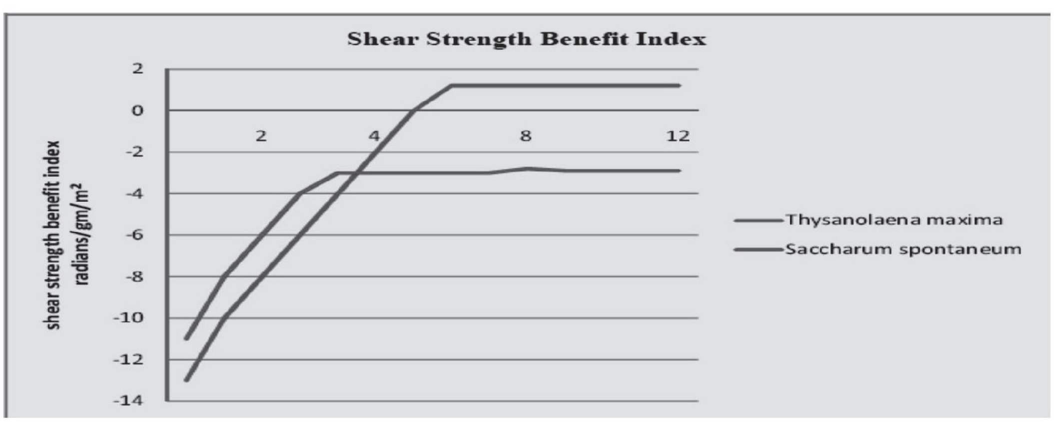
Comparing data for the two species to the control samples, an increase in soil stability correlates positively to an increase in time. From the four-week growth scenario, comparing test results between that of the vegetated SRCs to the soil control samples, shear stresses are higher for the soil control samples by a significant amount compared to that of the vegetated counterparts of both plant species. For the eight-week growth scenario, *Thysanolaena maxima* begins to outperform S*accharum spontaneum,* and the differences in shear stresses of the vegetated samples relative to the soil control samples are beginning to be positive. For the final growth scenario, although S*accharum spontaneum* is predominantly weaker than the soil control sample, the relative differences are smaller yet than for any other time-series; *Thysanolaena maxima* by this point has outperformed the soil control sample almost entirely.

Figure 10 is a plot representing the benefits observed in shear strength as a result of vegetative root systems with respect to the time after planting in weeks. Both species are shown on the plot; *Thysanolaena maxima* is in blue, and i S*accharum spontaneum* s in red.

The shear strength benefit index, X, is expressed in units of radians per gram divided by the planting surface area in square meters and was calculated for each growth scenario as follows

$X = (m_{SRC} - m_{SOIL}) / AGB$

Where: X = shear strength benefit index [radians/g] per planting surface area in square meters



Weeks after Planting
Fig. 10: Shear Strength Benefit Index

mSRC = relationship of increase in shear stress to effective stress for vegetated soil-root composite [radians], as defined below m_{SOIL} = relationship of increase in shear stress to effective stress for soil control sample [radians], as defined below

$m = \tan^{-1}(\Delta\tau / \Delta\sigma)$

Where: Äô = change in shear stress for dataset

$\Delta\sigma$ = change in effective stress for dataset

Field Investigation

To evaluate the shear strength properties of an actual area was visited and samples were obtained in situ.

Table 9: Shear strength increase in soil profile due to root penetration of two-year-old plants with spacing 15 cm in a hedgerow of 50 cm length

Depth(m)	DR(kg/m3)	AR(mm^2)	Ar/AX 10^{-4}	$\Delta S(kN/m^2)$	% ΔS	$\Delta S(kN/m^2)$
0.25	1.487	350.0	3.11	8.63	89.9	5.19
0.50	0.691	182.2	1.69	4.07	40.1	4.77
0.75	0.513	148.8	1.18	3.34	36.1	5.12
1.00	0.401	111.6	1.11	2.77	25.9	4.99
1.25	0.200	74.3	0.82	1.89	19.9	5.65
1.50	0.142	55.6	0.57	1.18	13.2	5.06

DR – bulk weight of root in unit soil volume, AR – root area on shear surface,
A – area of the shear surface, ÄS – shear strength increase in soil due to roots,
DS - shear strength increase in soil due to 1 cm^2 root area.

Root Area

The test results were processed in order to obtain the relationship between the shear stress and shear displacement for each test. Figure 11 presents the relation between root depth and soil shear strength It has been observed that root depth is inversely proportional to increase in soil shear strength. Root depth decrease shear strength increase. Each plot representing the relationships for root-permeated and root-free soils for each 0.25 m of depth up to 1.5 m of root penetration. The difference between the maximum shear stress of root-permeated soil and that of rooftree soil at a particular depth is defined as the shear strength increase in soil due to the presence of roots (ΔS).

According to the test results, it is obvious that the penetration of roots in a soil profile increases the shear strength of soil significantly. For each test depth, the shear strength increase, the corresponding root cross sectional area, and the bulk root weight per unit volume of soil were determined and tabulated in Table 9. The Δs value decreases with in depth from 8.90 kN/m2 at 0.25 m depth to 1.82 kN/m2 at 1.50 m depth depending on the number of roots penetrating through the shear surface. A comparison of the variation of Äs and the root cross-sectional area on the shear surface in given in Figure 11 for the depth of root-penetration. The vetiver root penetration of a 2-year-old hedgerow with 15 cm plant spacing can increase the shear strength of soil in an adjacent 25-cm-wide strip by 90% at 0.25 m depth. At 0.5 m the shear strength increase is about 39% and is then gradually reduced to 12.5% at 1.50 m depth. In the present study, the shear-strength increase in the soil by the root penetration of a vetiver hedgerow at different depths of up to 1.5 m was determined for a 0.5 m wide strip of soil across the slope. In general, for a 1 m-

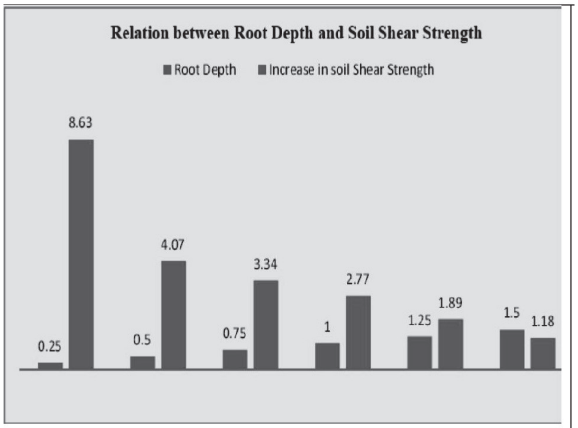


Fig.11: Relation between Root Depth and Soil Shear strength

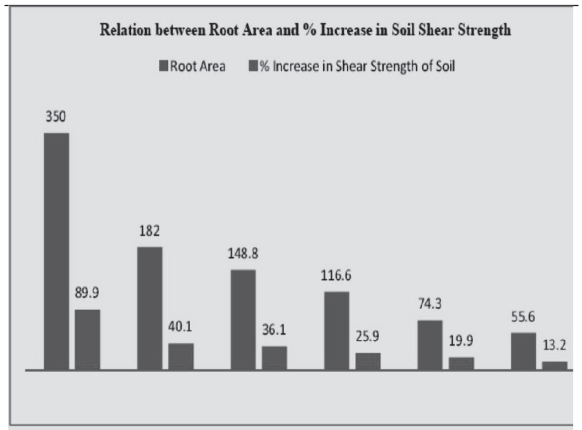


Fig. 12: Relation between Root Area and % increase in Soil Shear strength

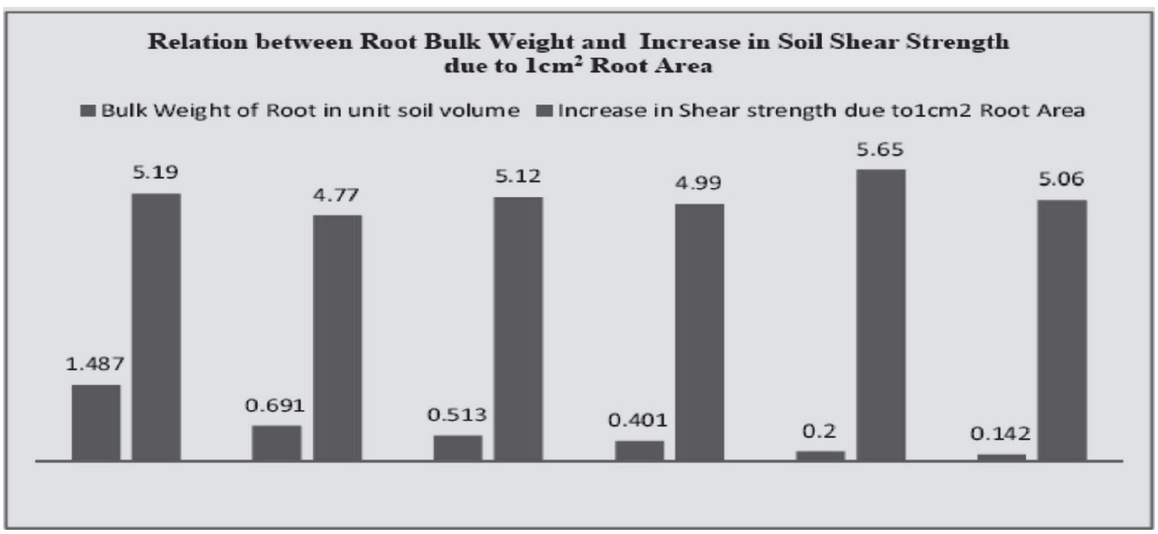


Fig.13: Relation between Root Bulk Weight and Increase in Soil shear Strength due to 1cm^2

wide hedgerow spacing these Δs values can be used directly at relevant depth intervals throughout the slope. However, for greater hedgerow spacing the Δs values should be corrected according to the pertaining areas of influence. It was unable to investigate the influence of vetiver roots on the shear strength of soil below 1.5 depth due to the difficulties encountered during excavation and the setting-up of testing equipment. Field evidences indicate that a gradual and slow decrease in root penetration with depth after the upper most 0.5 m where a rapid decrease in root penetration occurs. According to the trend of the Δs decrease with depth it can be predicted that a shear-strength increase of about 1 kN/m2 at 2 m depth below the vetiver hedgerow takes place.

The ultimate tensile root forces versus root diameter relationships for Japanese ceder, Dipterocarpus alatus, and Rocky Moutain Douglas fir were obtained from early works of Abe and Iwamoto[48], Nilaweera[49], and Burroughs and Thomas[50] respectively. The comparison clearly indicates that the tensile resistance of vetiver roots is as high as that of the other vegetation, sometimes even higher, contrary to the fact that it is a grass species. The tensile strength of the root is defined as the ultimate tensile root force divided by the cross-sectional area of the unstressed root. If the tensile root strength is constant for vetiver roots, the ultimate tensile force, F1, should be proportional to d2. The actual relationship between tensile root strength and root diameter. The tensile root strength, Ts, decreases with, the increasing root diameter, d, following the power regression relationship.

Similar relationships were reported from many previous works on hardwood roots. This phenomenon implies that stronger, finer roots provide higher resistance than larger diameter roots with comparatively low tensile strength for a given root cross-sectional area of species. The tensile strength of vetiver roots varies from 180 to 40 MPa for the range of root diameter of 0.2-2.2 mm. The mean tensile strength is about 75 MPa at 0.7-0.8 mm root diameter which is the most common diameter class for vetiver roots. Compared to many hard wood roots, the average tensile strength of vetiver grass is very high. Even though some hard wood roots provide higher tensile strength values than the average tensile strength of vetiver roots in the root diameter class of 0.7-0.8 mm, their average tensile strength values are lower since the average root diameter is much higher than that of vetiver roots.

Relation between root bulk weight and increase in soil shear strength due to $1cm^2$ is presented in figure 13.The shear strength increase due to 1 cm2 root area (Δs) is calculated for each test bulk weight presented in Table 9. The maximum increase in shear strength at the 0.200 kg/m^3 bulk weight of root in unit soil volume.There are slight difference in increasing soil shear strength at different bulk weight of root.It has been observed that bulk weight of root in unit soil volume has no direct effect on increasing soil shear strength. Furthermore, the correlation of Δs with the root area ratio and bulk root weight per unit of soil volume clearly indicate linear relationships which can be used to predict the shear strength increase in soil due to roots . The value Δs increases linearly with the root area ratio in the order of 2.7 x 104 for vetiver grass. The relationship between the Δs and bulk root weight per volume unit of soil indicates some positive intercept of shear-strength increase owing to the nature of roots and root penetration with depth. At shallower depths, the fractions of root weight given by obliquely oriented roots and by the roots terminating before the shear zone are higher than those at deeper levels. Therefore, at shallow depths the root weight is not directly proportional to the Δs value. As a consequence, a positive intercept in the relationship between the Δs value and the bulk root weight per area unit of soil appears though the intercept should be theoretically zero. For a known root-area ratio or a known bulk weight of roots per volume unit of soil, these relationships can be used to predict the Δs value instead of rather difficult and expensive direct shear tests. Carefully extruded root systems of vetiver plants by water jetting can be used to determine the root area and the root weight at different depths of root penetration.

Biotechnical reinforcement occurs in relatively shallow soil layers. The rooting depths of herbaceous plants is less than 0.5 m, that of trees and bushes less than 3-5 m. Therefore, normal stress is small and an increase in surcharge (surface load of the vegetative cover and the stored water) is almost negligible. In this range of normal stress the Coulomb approximation of the shear curve differs considerably from the Mohr envelope curve, and the angle of internal friction changes quickly (Figure 14).

The Mohr curve should therefore be used for quantifications of plant root effects on soil shear resistance, since it is more accurate than the Coulomb curve in the range of small normal stresses.

“??” is not constant, but decreases with depth, and is zero in soil horizons without root reinforcement. An increase in cohesion due to soil suction under unsaturated soil water conditions is only temporary and should not be considered(Figure 15). “??” depends on the tensile strength of the roots and the soil material (the friction between root surface and soil material). Roots that contribute to an increase of shear strength must cross the sliding plan. By displacement of the soil within the shear zone, tensile stress is mobilized in the roots. The roots act like anchors. Root stress components tangential to the sliding plane are shear forces. Stress components in a right angle to the shear surface increase the normal stress in the sliding plane. It is assumed that the roots are anchored sufficiently on both sides of the sliding plane so that failure is caused by rupture of the root and not by pulling them out from the soil. Further assumptions are: (1) the root is in a right angle to the sliding plane before shearing, (2) the tensile strength is completey mobilized, (3) the roots do not change the angle of internal friction of the Soil (Figure 16).

The disparity between observed values and previous work can be attributed to assumptions made on the root reinforcement model and the nature of root specimens used in the tensile tests. During shearing of root-permeated soil, the tensile strength of each and every root was not mobilized completely as assumed in the model. Some roots were pulled out completely or partly by a rupture at a finer point below the shear surface providing a lower resistance to shearing than expected. Even though the root penetration is generally vertical, as assumed in the model, some root orientations oblique to the shear surface can give rise to lower shear-strength increase in soil. In actual conditions, the root crookedness, jointing and the presence of young roots yield lower Äs values than those expected from straight, unbranched and mature root which are stronger than the former. Thought the adaptation of the root reinforcement model does not favour the shear strength increase directly, an estimation of shear-strength increase can be made by dividing the values by a factor for root-permeated soil with the angle of internal friction of 30º. Measuring the shear strength properties of these generas can show how plant roots can act to stabilize soil against erosive action by providing benefits to shear strength. Roots of, *Vetiveria zizanioides* as well as the roots of the other species studied, have demonstrated the ability to strengthen soil against shear stresses applied by the presence of external forces something that could have a drastic effect on erosion rates overall. The results showed that the tensile force of plant increased significantly with the increasing root diameter. The vertical roots penetrate the slip surface to work against failure. This situation assumes that the tensile strength of roots becomes fully mobilized if the roots are deeply embeded into the soil. The tensile force of plant root increased with increasing root diameter with a slope angle ranging from 30 to 40°. However, tensile force of roots decreased slightly with increasing slope angle. It also showed that the tensile force increased significantly with increasing width-height ratio of leaves. These plants showed a significant result to protect the experimental prototype slopes. Plant roots with an increased diameter also played an important role in preventing landslides in the prototype slope. Further research could bring significant results in using the plant on the slope of the real world to prevent landslides.

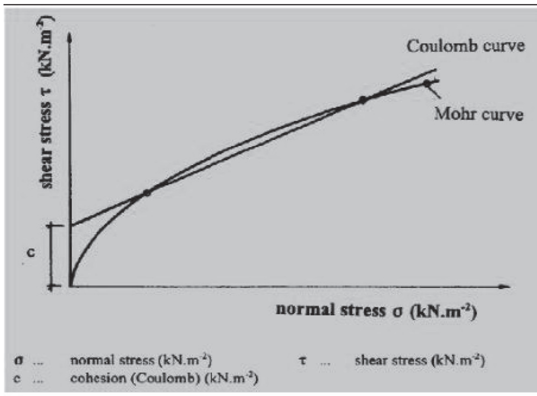


Fig. 14: Mohr and Coulomb shear curve

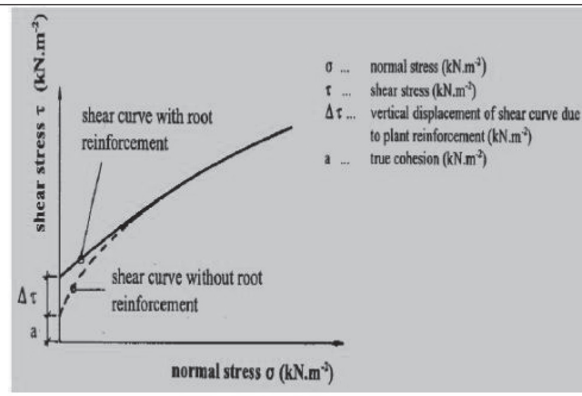


Fig. 15: Shear curves with and without plant root reinforcement

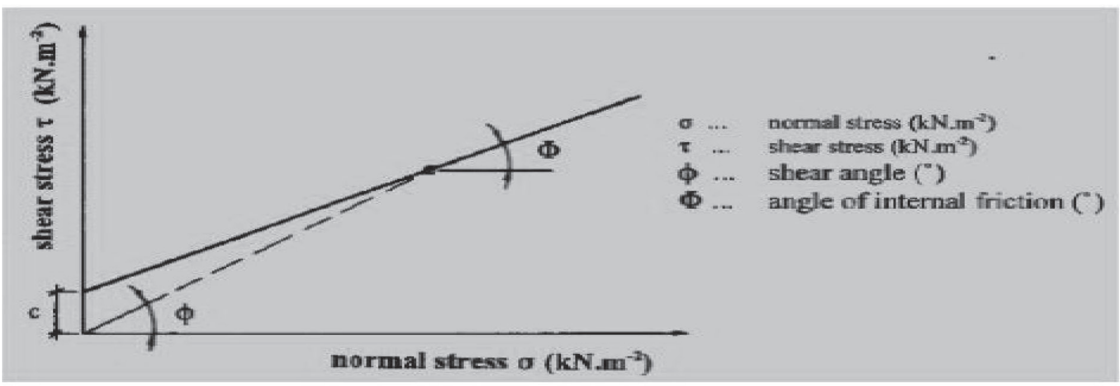


Fig. 16: Shear angle and angle of inner friction

Conclusions

In adverse climate, change is taking place and natural catastrophes, e.g. resulting from storms, flooding and landslides, are becoming more frequent, it is necessary to find effective and economical methods to reduce soil mass movement on a large scale. The reinforcement of soil by vegetation is a highly promising solution with regard to reducing superficial landslide risk and erosion on both natural and man-made slopes. All these three plants are ecofriendly, cost effective and with great economic values have an important role in civil engineering.The tensile root strength properties of *Thysanolaena maxima*, S*accharum spontaneum* in association with *Vetiveria zizanioides* and their inherited morphological root characteristics improve the resistance of soil slopes to shallow mass stability and surface erosion. *Thysanolaena maxima*, S*accharum spontaneum* and *Vetiveria zizanioides* were of interest to understand the influence of time after planting for which the roots would begin to exhibit behavior that could provide soil stabilization benefits. Erosion occurs as a result of applied shear stresses in soils, and it is believed that plant roots can stabilize soil by increasing shear strength. Soil-root composites vegetated with roots of *Thysanolaena maxima* were able to handle higher shear stresses than S*accharum spontaneum*. Although exhibiting lower shear strengths than their unvegetated counterparts in the 4-week growth scenario, both species were seen to approach higher soil stability by the 12-week growth scenario. *Thysanolaena maxima* handled higher shear stresses than the soil control sample after 8 and 12 weeks. Shear strength benefit index analyses shows improvement characteristics for both species with *Thysanolaena maxima* out performing S*accharum spontaneum* throughout all growth periods. The tensile strength of vetiver roots is as strong as, or even stronger than, that of both plant roots which have been proven positive for root reinforcement in soil slopes. The root tensile strength of vetiver decreases with the increase of root diameter as in the case of hard wood roots. The penetration of fine and strong vetiver roots in a soil profile can increase the shear strength of soil significantly at shallow depths. The shear-strength increase in soil due to roots can be approximated by using the average tensile root strength. The existing root area occupied by roots on a potential shear surface at a certain depth or by using the relationships of shear-strength increase in the soil versus the root- area ratio or the bulk weight of root per volume unit of soil. Together all these three plants are very effective as reinforcer for the prevention of soil erosion. Reinforcement is provided by both thin and coarse roots, the former acting more as tensile elements within the soil matrix, whereas large diameter roots can also act as tendons or anchors connecting planted surface layers to underlying or adjacent stable soil zones.

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