AN ASSESSMENT OF STRENGHT PROPERTIES OF VETIVER GRASS ROOTS IN RELATION TO SLOPE STABILIZATION

Diti Hengchaovanich and Nimal S. Nilaweera[1]

Introduction

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 (Grimshaw 1994 ; Yoon 1994). 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. It has been and will be used to stabilize several road embankments of the East-West Highway and some other road projects. Simultaneously, attempts have been made to analyze the effects of vetiver root on slope stabilization and erosion control. This paper discusses the tensile root strength of vetiver and its contribution to soil strength through experiments on tensile root determinations and root-permeated soil shearing, which are a part of ongoing research especially designed to access both root strength properties and morphological parameters of roots in relation to slope stability and erosion control

---

[1] Erocon Sdn. Bhd., Kual Lumpur, Malaysia

Tensile Root Strength or Vitiver Grass

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.

The ultimate root tensile force against the root diameter plot for the vetiver roots is presented in Fig. 1. The power regression analysis of the relationship between the ultimate root tensile force and the root diameter provides the best fit with the following equation:

$$F_1 = 46.93\, d^{1.4217} \qquad (1)$$

where is F_1 - ultimate tensile root force, and

d - the root diameter

This power regression function can be used to predict the ultimate tensile force of a vetiver root with known diameter. A comparison of tensile resistance of vetiver roots with those of some hardwood species is made in Fig. 2. 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 (1986), Nilaweera (1994), and Burroughs and Thomas (1977) respectively. The comparison clearly indicates that the tensile resistance of vetiver roots is as high as that of the hardwood 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, F_1, should be proportional to d^2. According to the function given by Equation (1), F_1 is proportional to $d^{1.4217}$ implying that the tensile root strength decreases with the increase in root diameter. Figure 3 illustrates the actual relationship between tensile root strength and root diameter. The tensile root strength, T_S, decreases with the increasing root diameter, d, following the power regression relationship.

$$T_S = 59.80\ d^{-0.5785} \qquad (2)$$

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. According to Fig. 3, 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 hardwood roots, the average tensile strength of vetiver grass is very high. Even though some hardwood 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.

Direct Shear Tests on Vetiver 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 shear box, a hydraulic jacking system, a proving ring and dial gages. The shear box was made of 8 mm thick steel plates capable of 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 (Fig. 4).

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.

Table 1. Shear strength increase in soil profile due to root penetration of two-year-old vetiver plants with spacing 15 cm in a hedgerow of 50 cm length

Depth (m)	D_R (kg/m^3)	A_R (mm^2)	A_r/A X 10^{-4}	Δ_S (kN/m^2)	% Δ_S	Δ_S(kN/m^2)
0.25	1.522	331.0	3.31	8.92	90.2	5.39
0.50	0.701	176.2	1.76	4.17	39.3	4.73
0.75	0.521	137.8	1.38	3.46	34.6	5.02
1.00	0.378	106.8	1.07	2.61	26.3	4.89
1.25	0.181	71.2	0.71	1.94	19.0	5.45
1.50	0.135	51.6	0.52	1.28	12.5	4.96

D_R – bulk weight of root in unit soil volume, A_R – root area on shear surface,
A – area of the shear surface, Δ_S – shear strength increase in soil due to roots,
Δ_S - shear strength increase in soil due to 1 cm^2 root area.

The test results were processed in order to obtain the relationship between the shear stress and shear displacement for each test. Figure 5 presents the shear-stress versus shear-displacement curves, 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 root-free soil at a particular depth is defined as the shear strength increase in soil due to the presence of vetiver roots (Δ_S).
According to the test results, it is obvious that the penetration of vetiver 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 1. The Δs value decreases with in depth from 8.90 kN/m^2 at 0.25 m depth to 1.82 kN/m^2 at 1.50 m depth depending on the number of roots penetrating through the shear surface. A comparison of the variation of Δs and the root cross-sectional area on the shear surface in given in Fig. 6 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. The shear strength increase due to 1 cm^2 root area (Δ_s) is calculated for each test depth and presented in Table 1. The Δ_s value varies very slightly with an average of 5.1 kN/m^2 for the analyzed root-penetration depth.

Discussion

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 (Wu, 1976). 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 into an increase in shear strength in the soil as expressed by the following equation :

$$\Delta s = t_R\,[\cos\theta \tan\phi + \sin\theta] \qquad (3)$$

Where are: θ – angle oe shear distortion

ϕ – angle of internal friction

t_R – 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 (T_R) by the fraction of the soil cross-section occupied by roots, or the root area ratio (A_R/A).

Using T_R = 75 MPa, ϕ = 30º and θ = 30º, the increase in the shear strength in the soil due to vetiver root was calculated for each test depth and tabulated in Table 2 with experimental results.

Table 2. The experimental and computed Δ*s* values at variable depths.

Depth,m	Δ*s*,kN/m² (experimental)	Δ*s*,kN/m² (computed)
0.25	8.92	24.83
0.50	4.17	13.20
0.75	3.46	10.35
1.00	2.61	8.03
1.25	1.94	5.33
1.50	1.28	3.90

The computed Δ*s* values are about 3 times as high as the values obtained from the field experiments. The disparity between Δ*s* values obtained from experiments and computation 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 of vetiver 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 Δs 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 compute the shear strength increase directly, an estimation of shear-strength increase can be made by dividing the computed values by a factor of 3 for vetiver-root-permeated soil with the angle of internal friction of 30º. 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 vetiver roots (Fig 7). The value Δs increases linearly with the root area ratio in the order of 2.7×10^4 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.

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-wide hedgerow spacing these Δs values can be used directly at relevant depth intervals throughout the slope. However, for greater hedgerow spacings 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/m^2 at 2 m depth below the vetiver hedgerow takes place.

Conclusion

The tensile root strength properties of vetiver grass in association with its inherited morphological root characteristics improve the resistance of soil slopes to shallow mass stability and surface erosion. The tensile strength of vetiver roots is as strong as, or even stronger than, that of many hardwood 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 hardwood roots.

Compares to hardwood vegetation, the smeller average root diameter of vetiver furnishes a very high mean tensile strength (75 MPa), indicating that vetiver grass is more effectual in root reinforcement in soil slopes. 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 the root penetration of a 2-year-old vetiver hedgerow with plant spacing of 15 cm varies from 90% at 0.25 m depth to 1.25 % at 1.50 m depth. The shear-strength increase in soil due to vetiver roots can be approximated by using the average tensile root strength and the existing root area occupied by vetiver 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.

References

Abe, K ; and M. Iwamoto. 1986. An evaluation of tree root effect on slope stability by tree root strength. J. Japanese Forest. Soc.68: 505-510.

Burroughs., E.R. ; and Thomas, B.R.. 1977. Declining root strength in Douglas fir after felling as a factor in slope stability. Research Paper INT-190, Intermountain Forest and Range Experiment Station, US Forest Service, Ogden, Utah, USA.

Grimhaw, R.G. 1994. Vetiver grass-Its use for slope and structural stabilization under tropical and semi-tropical conditions. Proc. Int Conf.on Vegetation and Slopes, Oxford, England

Nilaweera, N.S. 1994. Effects of tree roots on slope stability: The case of Khao Luang Mountain
area, Southern Thailand. Doctoral Dissertation, Diss. No. GT-93-2, Asian Institute of Technology, Bangkok, Thailand

Yoou, P.K. 1994. Important biological considerations in use of vetiver grass hedgerows (VGHR)
for slope protection sna stabilization. Proc. Int. Conf. on Vegetation and Slopes, Oxford, England