LABORATORY INVESTIGATION OF VETIVER ROOT REINFORCEMENT FOR SLOPE PROTECTION

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Abstract
Soil bioengineering is an environmentally friendly method which employs vegetation to contribute sloping terrain by reinforcing the soil. The vegetation can contribute to slope stability with two effects: mechanical and hydrological. Vetiver grass (\textit{Vetiveria nemoralis} A. Camus), a perennial grass that had been promoted to help conserve the soil and runoff by the World Bank in the 1980s, has been developed to become an important soil bioengineering tool. This paper demonstrates the effect of vetiver root matrix on the soil slope focusing on the mechanical reinforcement. The vetiver grass specimens grown under one year were used in this study. The investigation program includes root observations and direct shear tests. The growing rate of the vetiver roots and the root area ratios were observed during the tests. The cohesion and angle of internal friction of root-reinforced soils were determined from a standard direct shear and a large direct shear apparatus. The results indicated that the roots of vetiver grass were fast growing. Shear strength of the root-reinforced soil was significantly increased because of roots bundling as well as the increased number of root hair. Electron microscopic results revealed that the bundling and adhesion contributed from large surface area of root hair can help to improve the slope stability by increasing shear strength of the soil.

Keywords: Laboratory tests, root area ratio, shear strength, cohesion, electron microscope

1. Introduction
Landslide is one of the most widespread earth processes, which involve the failure of sloping earth material. Landslide is considered one of the important problems in geotechnical engineering. This is because landslide is usually among the most costly natural hazards in terms of human life and economic loss. In recent years, the natural slope instability has increasingly occurred, especially in the tropical monsoon zone such as Southeast Asian countries. There are several factors that could cause natural slope failure, such as geological activity, hydrological influence and human interference, but seepage and rainfall are the main factors.

To increase the slope stability, several engineering methods have been used such as: soil nails, retaining structure, geosynthetic reinforcement and shortcrete. However, these methods are costly and may not be suitable for natural slopes. In ancient times, the use of vegetation in soil slopes and earthen covers for landfill has been recognized and it is also well-known that the effect of vegetation plays an important role in increasing soil slope stability. Soil
bioengineering is an environmentally friendly alternative that uses vegetation for improving slope failure. There are two main contributions that vegetation could have to the slope stability, i.e. hydrological and mechanical processes). Firstly, changing through the soil moisture regime and drawing the water from the soil via evapotranspiration (Ali and Osman, 2008) could induce the soil suction. Secondly, the roots of vegetation could enhance the slope stability by increasing the shear strength of the soil (Gray and Sotir, 1996; Wu et al., 1979). The role of vegetation on slope stability has been defined by Greenway (1978), Coppen and Richards (1990) and Wu (1995). In addition, this method is applied against the shallow failure, as well as the soil surface erosion in the natural slopes.

Vetiver grass (Vetiveria nemoralis A. Camus), a perennial grass that had been promoted to help conserve the soil and runoff by the World Bank in the 1980s, has been developed to become an important soil bioengineering method. (Grimshaw, 1994; Greenfield, 1996). Recently, the Chaiapattana Foundation and the Office of the Royal Development Projects Board, Thailand, have promoted the use of vetiver grass for soil and water conservation for many royal projects in Thailand. Vetiver grass is a kind of vegetation that is very fast growing and requires low maintenance. The length of vetiver roots was observed to grow up to 2.0-3.5 m (Chinapan et al., 1997). The vetiver roots can penetrate deeply into the ground to form a net-like barrier capable of filtering silt and stabilizing topsoil. Normally, in the regions with prolonged and heavy rainfall, the shallow failure is a typical failure mode of the soil slope and it always occurs 1.0-3.0 m in depth from the surface (Au, 1998; Gray and Leiser, 1982). Hence, the shallow failure from the natural slope could be protected by the rooting depth of the vetiver grass which interlocks with the soil particles against the slope collapsed. Planting this vetiver grass requires a simple technology and it is low cost to do the maintenance. Some previous researchers have performed the tensile root strength properties of vetiver grass for the resistance to shallow failure and surface erosion (Hengchaovanich and Nilaweera, 1996).

This paper aims to present an investigation program of the vetiver root-reinforced system for slope stabilization using laboratory techniques. The growing rate of the vetiver roots and the root-area ratios were observed by direct measurement and image processing techniques, respectively. The shear strength of vetiver root-reinforced soils was determined using a standard direct shear test for single vetiver and a large direct shear test for a group of vetiver. Thus, the increase in soil shear strength from vetiver-root fibre can be proved.

2. Root Observation

In soil bioengineering approach, choosing the suitable vegetation is the first important step. Vetiver grass ecotypes have been selected based on the soil type and the environment which could help them to survive for a long period of time. Thailand’s Land Development Department (LDD, 1998) declared that the roots of vetiver grass can penetrate deeper into the ground; so it is suitable for arid areas. However, the research on engineering aspects of vetiver grass is still limited and undergoing. In this study, two species of vetiver grass, which are highland vetiver (Vetiveria nemoralis A. Camus) and lowland vetiver (Vetiveria zizanioides L. Nash), were selected as supported by Thailand’s Land Development Department.

For root observation, the vetiver specimens were planted in hydroponic conditions. Each single vetiver root was grown in a container with a liquid nutrient (without soil). An air pump was also installed in the container to provide oxygen into the mineral nutrient solutions as shown in Figure 1. This experiment can be used to investigate the growing rate of vetiver roots without damaging the roots. The measurement of the length of root and the radius of
root bundle were carried out for each specimen continuously for 6 months. Figure 2a,b show the observation of vetiver roots for highland and lowland specimens at 3 months, respectively.

![Root observation](image)

**Figure 1.** Vetiver specimens planted in hydroponic conditions

(a) Highland vetiver root at 3 months  
(b) Lowland vetiver root at 3 months  

**Figure 2.** Root observation

The values of root length and root bundle diameter from the hydroponic vetiver specimens were observed and measured continuously from 2 to 6 months. The relationship between the length of roots and the radius of root bundles are presented in Figure 3a,b for highland and lowland vetiver specimens, respectively. The growing rate of roots can be determined from a plot of length of roots with respect to time as shown in Figure 4 for both highland and lowland vetiver specimens. According to the results, it can be indicated that the roots of the vetiver have spread the radius of roots bundle up to 1.7 cm and the length of the roots can grow up to 180 cm within 6 months. Based on the results, the radius of roots bundle of highland vetiver specimen is slightly larger than lowland vetiver specimen, while the lengths of the roots are almost the same. The average growth rate of roots is approximately 30 cm/month. As shown in Figure 4, the current study of vetiver has shown a slightly higher growth rate of vetiver when comparing to the data from Kaewsaeng (2000). The difference is probably caused by planting conditions and measurement methods. It is noted that the data
from Kaewsaeng (2000) was observed from the specimen planted in the soil and the root measurement required plant removal.

(a) Highland vetiver

(b) Lowland vetiver

Figure 3. Relationship between the length of roots and radius of roots bundle

Figure 4. Comparison of growing rate of vetiver roots

3. Root Area Ratio

Moreover, the root observations of the group vetiver roots can be defined by a root area ratio. The term ‘root area ratio’ refers to the fraction of the total cross-sectional area of a soil that is occupied by roots (Gary and Sotir, 1996). The root area ratio plays an important role for the contribution of root fibers on shear strength when it is directly defined by the cross-sectional area in the shear plane. However, the root area ratio measured in the plane perpendicular to the root-growth direction is very difficult to determine and it also varies with depths. The parallel plane measurement of the root area ratio, which is easier to observe and represents an average of root fibre contribution in the soil, was used in this study.

Alsheimer and Hughes (2007) reported the technique of using image processing to observe root distribution in a large direct shear specimen. The photographs of root and soil were taken with a digital camera and transferred to binary image via the histogram function of Photoshop
software. The black and white pixels of the image could be distinguishably counted between soil and root. The ratio between the pixels of root and total pixels can be loosely defined as a root area ratio. Figure 5a is a photo of 6-month highland vetiver specimen which was taken by a digital camera. Figure 5b is the binary image, converted from a digital photograph, which has presented the method to estimate the root area ratio based on the colour in the image. For example, the white and black colours represent the soil and void space, respectively; on the other hand, the grey colour represents the root area. Hence, the root area ratio can be defined by the total pixels of roots and total pixels. Table 1 shows the results of the average root area ratio of the group vetiver at 6 months for both highland and lowland.

![Image](image-url)

**(a) Root photograph**

**(b) Binary image processing**

**Figure 5.** Determination of root area ratio for the 6 months group highland vetiver

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Water content (%)</th>
<th>Bulk density (kg/m³)</th>
<th>Root area ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soil</td>
<td>20.85</td>
<td>1.030</td>
<td>0</td>
</tr>
<tr>
<td>Lowland 6 months</td>
<td>25.49</td>
<td>1.110</td>
<td>3.36</td>
</tr>
<tr>
<td>Highland 6 months</td>
<td>24.86</td>
<td>1.103</td>
<td>4.56</td>
</tr>
</tbody>
</table>

### 4. Shear Strength of Root

#### 4.1 Sample Preparation

In this study, the reinforcement of the vetiver root systems was studied using direct shear tests in the laboratory. The laboratory tests were chosen instead of field tests; hence, the vetiver samples can be simply prepared and the density and water content of the soil can be controlled (see Table 1). Two types of specimens were prepared in this study, i.e. single and group vetiver. The vetiver grasses were prepared by planting into the soil. The soil used in this study was collected from a typical slope area. The chemical properties of the soil were tested and reported in Table 2. As the results show, the various nutrients have remained relatively high and are similar to those used for planting purposes. In other words, this kind of soil can be used for cultivation on the agriculture land.

<table>
<thead>
<tr>
<th>Test</th>
<th>Value</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalinity-Acidity (pH)</td>
<td>6.7</td>
<td>Medium</td>
</tr>
<tr>
<td>Organic matter (O)</td>
<td>12.13%</td>
<td>High</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>61 mg/kg</td>
<td>High</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>7,859 mg/kg</td>
<td>High</td>
</tr>
</tbody>
</table>
Magnesium (Mg) | 974 mg/kg | High  
Potassium (K) | 1,996 mg/kg | Very high

(a) Single vetiver specimen for direct shear test  
(b) Group vetiver specimen for large direct shear test

**Figure 6.** Sample preparation for direction shear tests

Single vetiver specimens, which were planted in the plastic bag and put in the PVC tube (150 mm wide, 600 mm long), were prepared for the standard direct shear test. Figure 6a shows the schematic of planting vetiver grass for single specimens. Four tested samples were prepared by cutting at the upper part from top to bottom with 20 mm thickness for each tested sample to fit with the direct shear box as shown in Figures 6a and 7a. For the group specimen, the vetiver grass slips were prepared by planting in a 300 mm cubic wooden box. Nine vetiver specimens were planted with a spacing of 75 mm as shown in Fig 6b. These group vetiver specimens were prepared for the large direct shear test. Three tested samples were prepared for the test by trimming to fit with large direct shear mould of 300 mm x 300 mm x 200 mm as shown in Figure 7b. In addition, this group of vetiver grass was prepared for image processing to define the root area ratio as well. It is noted that the group vetiver specimens were planted in the same soil that was used to prepare for the single vetiver specimen.
4.2 Direct Shear Test for Single Specimens

Four-month-old highland and lowland vetiver specimens were prepared for the standard direct shear test. To observe the increase of shear strength from the vetiver root reinforcement, the bare soils with the same density and water content associated with each specimen were prepared for direct shear tests as well. A 60 mm diameter cylindrical mould was used to perform the direct shear test for the 4-month old single specimens. The tests were performed by following the ASTM D3080 standard with the shear rate of 1.5 mm/min. The normal stresses of 10, 20, 50 and 100 kPa were applied for each test. All specimens were sheared until they reached the peak point or started showing the fairly constant shear stress or the maximum horizontal displacement of 6 mm. The shear strengths of the highland and lowland vetiver root-reinforced soils and the bare soils were obtained as presented in Figure 8a. The cohesion intercept and the friction angle were determined according the Mohr-Coulomb failure criterion as summarized in Table 3. The presence of the vetiver roots has improved the strength of the soil. As the results show, the vetiver grass could increase the cohesion of shear strength approximately by 1 kPa for lowland vetiver and almost 6 kPa for highland vetiver. Similarly, Ali and Osman (2008) reported the increasing of cohesion of shear strength of soil by vetiver roots. The results show that the cohesion of shear strength of soil was increased around 11 kPa from the average values of 1 m depth of rooted zone.

4.3 Large Direct Shear Test for Group Specimen

Similarly, 6-month-old group highland and lowland vetiver specimens were prepared for the large direct shear test. The large direct shear apparatus was chosen to perform direct shear tests for the group vetiver specimens. The tests were performed following the ASTM D3080 standard which used 30, 50 and 75 kPa to apply for the normal stresses by the hydraulic pressure system through the top plate of the machine. The side friction between the sample and the shear box was minimized by applying some oil. All the data from the displacement transducer and load cell are acquired by an automatic data logging system. All samples were sheared to reach the maximum horizontal displacement at 50 mm. The large direct shear test results are plotted in Figure 8b. The cohesions and friction angles were determined based on Mohr-Coulomb failure criterion as presented in Table 3.
Table 3. Results of direct shear tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen</th>
<th>Shear strength parameters</th>
<th>Increase in cohesion (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard direct shear test</td>
<td>Bare soil</td>
<td>$c = 6.8$ kPa; $\phi = 22.8^{\circ}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4-month-old single vetiver lowland</td>
<td>$c = 7.7$ kPa; $\phi = 29.7^{\circ}$</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>4-month-old single vetiver highland</td>
<td>$c = 13.7$ kPa; $\phi = 28.8^{\circ}$</td>
<td>5.9</td>
</tr>
<tr>
<td>Large direct shear test</td>
<td>Bare soil</td>
<td>$c = 2.5$ kPa; $\phi = 21.8^{\circ}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6-month-old group vetiver lowland</td>
<td>$c = 5.1$ kPa; $\phi = 28.4^{\circ}$</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>6-month-old group vetiver highland</td>
<td>$c = 8.5$ kPa; $\phi = 29.2^{\circ}$</td>
<td>6.0</td>
</tr>
</tbody>
</table>

4.4 Electron microscope observation

While it is clear that the main roots and secondary roots when bundled up are responsible for the overall strength of the root system, in fact, it is the adhesion between the soil and the root hairs that determine the failure during the pull out during shear event. It can be simply explained by the diagram in Figure 9.

Figure 9. Interface friction between soil and root (Redrawn after Gray and Sotir, 1996)

In order to understand the macroscopic adhesion effect of vetiver grass root system, such as cohesion, root-soil interaction needs microscopic observation in order to link the behaviors and responses across different length-scales. According to Gray and Ohashi (1983), simple uniform distribution of interface friction between soil and roots could be directly related to the minimum root length $L_{\text{min}}$ required to prevent root-soil slippage:
\[ L_{\text{min}} = T_R D / 4 \tau_b \]  

where \( T_R \) is the tensile strength of the root, \( D \) is the root diameter and \( \tau_b \) is the limiting bond interface friction stress between root and soil (Gray and Ohashi, 1983). The contribution of interfacial friction plays an important role during the pulling and slipping of the root system from soil. In particular, the root hairs are of the order of micron level and their interfacial area is contributing significantly to the friction due to their increased surface area. Root hairs are generally dense towards the end of the vetiver grass, near the root cap. One particular function is to facilitate root penetration as these root hairs serve as anchorage points so that the root tip could penetrate deeper into the soil. The very same anchorage mechanism also provides adhesion between the root itself and the soil during shear and catastrophic pull out events which could be directly linked cohesion term in Mohr-Coulomb failure criterion framework.

Figure 10a shows a typical root tip of vetiver grass. The morphology is rough and wavy which may indicate the tissue scars as well as regeneration of new tip skin as the tip penetrated into the soil. The width of the micrograph is approximately 100 microns. The diameters of vetiver grass’ main roots range from 0.2 to 2.2 mm (Hengchaovanich and Nilaweera, 1998). The root hairs are located towards the end of the main and secondary roots. The area has high density of root hairs and therefore is responsible for the interface friction, as shown in Figure 10b. The high density and small diameters suggest a large interfacial area and is the direct indication of the increased interfacial strength.

5. Conclusions
According to the root observation and the direct shear test results, it can be indicated that the root system of vetiver can increase the shear strength of the soil by mechanical reinforcement. These results can confirm a significant contribution of the vetiver root to slope stability. The conclusions of this study are as follows:
1) The roots significantly affect the increase in the shear strength of soil. The shear strength of the root-reinforced soil depends on the root length and the root area ratio.
2) According to the root observation results, the growth rate of vetiver roots is relatively high compared to others (Lyr and Hoffmann, 1967). The maximal depth development of vetiver root system could go up to 200 cm in the first year and the average daily increment of the roots is approximately 10 mm.

3) The direct shear test results indicate that the vetiver roots significantly enhance the soil shear strength especially on the cohesion in the order of 1 to 6 kPa. This result agrees well with the observation by Ali and Osman (2008). However, the increases of cohesion are different depending upon the type and age of vetiver as well as the type of tested specimen.

4) The increase of shear strength from vetiver root can be alternatively explained using electron microscope technique. The root hairs are of the order of micron level and their interfacial area is contributing significantly to the friction due to their increased surface area. This mechanism provides adhesion between root and soil during shear which could be directly linked cohesion term in Mohr-Coulomb failure criterion framework.

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