Engineering characterization of Vetiver system for shallow slope stabilization

A. Jotisankasa, Department of Civil Engineering, Kasetsart University, Jatujak, Bangkok, Thailand, 10900, fengatj@ku.ac.th
T. Sirirattanachat, Department of Civil Engineering, Kasetsart University, Jatujak, Bangkok, Thailand, 10900, teerapat.geotechnical@gmail.com
C. Rattana-areekul, Department of Civil Engineering, Kasetsart University, Jatujak, Bangkok, Thailand, 10900, ccra_ging@hotmail.com
K. Mahannopkul, Department of Civil Engineering, Kasetsart University, Jatujak, Bangkok, Thailand, 10900, krairoj@gmail.com
J. Sopharat, Department of Plant Science, Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla, Thailand, 90112, jessadaso@gmail.com

Abstract

The Vetiver system (VS) has proven to be very effective in mitigating erosion and shallow slope instability, provided it is applied correctly. Nevertheless, quantitative studies of how much contribution the VS really provides to slope stabilization in the field are still relatively scarce. This study outlines an approach for such purposes, including laboratory tests, field observation as well as numerical analysis. Laboratory tests include root & soil mechanics characterization, such as tensile strength, as well as direct-shear testing and permeability tests of root-reinforced soil sample. This, together with field observation of root quantity by means of mini-rhizotron, enables quantification of root-area ratio and the root cohesion that exists in actual slopes. It can be seen from a test site in Surathani, South Thailand, that after the Vetiver was invaded by the local species and its roots decayed, the root area ratio decreased significantly leading to loss in root cohesion and decreased factor of safety. This thus emphasizes the importance of frequent maintenance of the Vetiver in practice in order to sustain long-term slope stability. Also based on studies using numerical simulation, the VS appeared to have mainly beneficial effects for slope of 26° gradient (1V:2H). However, when applying the VS on very steep slope (>60°, 2V:1H), practitioner should exercise certain cautions, especially for the case of easily degradable rock such as claystone, since there could be theoretical adverse effect of increased infiltration through root zone, amount to 10% reduction in factor of safety.

Keywords: slope stabilization, erosion control, engineering properties, shear strength, infiltration

1. Introduction

Slope failure and erosion problems have increasingly become more frequent around the world, causing damage to infrastructure, farmlands, and sometimes leading to loss of people’s lives. Soil-Bio engineering or the use of vegetation to prevent shallow slides and erosion has been historically applied in many parts of the world. Recently, this green approach has received more attention among practitioners and researchers worldwide due to its relatively low cost, aesthetic and environmental value, as well as sustainability.

Vetiver grass (Chrysopogon zizanioides or formerly, Vetiveria zizanioides) have been used extensively in many tropical and sub-tropical countries for shallow slide stabilization and erosion control (e.g. Hengchaovanich, 1998, Truong et al., 2008). Normally, planted as hedgerows parallel to the slope contour, Vetiver grass has a very dense fine vertical root system that penetrates as deep as 3-4 meter in some applications, making
it very effective for slope stabilization, reduction of runoff erosive energy and sediment trap. Its application ranges from soil-water conservation, slope stabilization as well as pollution-control at landfills. Its popularity is due to the ease of use, tolerance, low-cost and effectiveness where applied correctly. For example, in Thailand, the Vetiver grass was successfully implemented for erosion control and slope stabilization along the Yadana gas pipeline right-of-way zone running from Myanmar to Thailand (Tansamrit, 2003).

However, there are many aspects of influence of vegetation on slope stability as shown in Figure 1, some of which are beneficial and some can be destabilizing. For example, canopy interception of rainfall and evapotranspiration will reduce pore water pressure leading to increase in shear strength. Root fibers reinforce the soil mass, thus increasing its shear strength too. However, vegetation-covered and root-permeated ground surface are normally of higher permeability and infiltration rate (see e.g. Styczen & Morgan, 1995) This increased infiltration would lead to lower run-off and consequently less erosive energy which is understandably beneficial for erosion control (e.g. Curtis & Claassen, 2007). Yet, it may also bring about increase in pore water pressure which would subsequently destabilize the slope. In particular, Vetiver grass, which is considered one of the deepest roots amongst all plants, in theory, may provide a pathway for water infiltration to a greater depth. Nevertheless, a recent study by Rahardjo et al. (2014) suggested that the Vetiver grass tended to act as slope covers to minimize the infiltration of rainwater into slopes. This aspect is thus still an unresolved issue and may be related to bio-degradation of the Vetiver roots with time. In practice, there are still some concerns of the theoretical risk of increased infiltration and destabilizing effect due to Vetiver grass on very steep slope. In 2011, H.M. the king Bhumibol of Thailand, the great patron of Vetiver applications, even suggested practitioners to exercise certain caution when applying Vetiver on steep slopes and encouraged researchers to investigate into this aspect.

Figure 1. Various effects of vegetation on slopes (Coppin & Richard, 1990)

2. Research methodology and theoretical background

In order to quantify the beneficial effects of Vetiver system as well as the theoretical risk of its misuse, systematic characterization of engineering properties of Vetiver system in relation to slope stability needs to be carried out. These can be categorized into two groups: mechanical and hydraulic. The mechanical effects of Vetiver system on slope are mainly beneficial, normally through reinforcement. Traditionally, the contribution of the Vetiver
root reinforcement on shear strength of soil is quantitatively expressed using the “soil cohesion due to root reinforcement”, or “root cohesion”, $c_r$. The value of root cohesion can be estimated using Equation (1) (Wu et al., 1979)

$$c_r = t_R \left[ \frac{A_R}{A} \right] (\sin \theta + \cos \theta \tan \phi')$$  \hspace{1cm} (1)

where $t_R =$ mobilized root tensile stress, $\frac{A_R}{A} =$ Root area ratio or ratio between root and total area; $\theta =$ Shear distortion angle in the shear zone. It is noted that the mobilized root tensile stress, $t_R$, is dependent on the modes of failure that could occur in root-reinforced soils, such as fiber-break mode, fiber-stretch mode, and fiber-slip mode (Gray & Sotir, 1996). In reality, a combination of these three failure modes would occur when root-reinforced soil is sheared. Practically, it could be reasonable assumed that the mobilized root tensile stress, $t_R$, would be a function of the ultimate root tensile strength, $T_R$.

Shear strength ($\tau$) equation for variably saturated soil with root reinforcements can be expressed as (2);

$$\tau = c' + c' + \sigma_n \tan \phi' - u_w \tan \phi''$$  \hspace{1cm} (2)

where, $c'= $ effective cohesion, $\sigma_n= $ normal stress, $\phi'= $ effective angle of shearing resistance, $u_w= $ pore-water pressure (positive or negative), $\phi''= $ angle of shearing resistance due to pore-water pressure or suction, which may vary linearly with suction (for unsaturated case, $u_w<0$, and $\phi'' = \phi^b$, but for saturated case, $u_w>0$, then $\phi'' = \phi'$).

The value of pore-water is largely governed by the hydraulic properties of the ground, and evapotranspiration. During rainfall, water infiltration will saturate the soil and thus increases the pore-water pressures. Major hydraulic properties of the soil, that control infiltration rate, consist of the permeability and soil-water retention curve as well as ground-surface roughness coefficient.

In effect, evapotranspiration due to Vetiver will tend to reduce the pore-water pressure, $u_w$, thus increasing shear strength of the ground, $\tau$, and improving slope stability. However, this evapotranspiration effect of reducing pore-water pressure may not be effective during the period of heavy rain and near saturated air-humidity, when plant stomata tend to close.

Based on the known root cohesion and pore-water pressure, the stability of the slope can then be estimated using Limit Equilibrium method based on slope gradient and soil properties. One of the more simplified expressions is that of infinite slope as follows,

$$F = \frac{c' + c' + (\gamma z \cdot \cos^2 \beta) \tan \phi' - u_w \tan \phi''}{\gamma z \cdot \sin \beta \cdot \cos \beta}$$  \hspace{1cm} (3)

where $\beta$ is the slope gradient, $z$ is depth of failed soil mass, $\gamma$ is soil’s total unit weight, and $F$ is the factor of safety, which indicate stability of slope.

A major challenge in quantifying the engineering properties of Vetiver system lies with the temporal variation of its in-situ properties. Unlike construction materials such as concrete or reinforced steel bars, plants are living things and thus their root distribution (normally expressed as root area ratio, $RAR = \frac{A_R}{A}$) can be seasonal, either develops or degrades with time and maintenance conditions. This essentially means that the important
engineering parameters such as “root cohesion”, $c^r$, permeability or soil-water retention curves, will not necessarily be constant throughout the design life.

This study thus combines various laboratory and field techniques along with numerical simulation in order to address some gaps in our understanding of the engineering behaviour of the Vetiver system in relation with slope stability. Figure 2 illustrates such approach employed in this study. This concept is similar to the Soil Mechanics triangle, as proposed by John Burland, popularly used in geotechnical engineering field. Each part of this study will be described in the following.

Figure 2. Research approach in this study

3. Root tensile strength and soil cohesion due to root reinforcement

One of the pioneer research into engineering properties of Vetiver has been conducted by Henchaovanich & Nilaweera (1996) and Hengchaovanich (1998). According to these early works, the tensile strength, $T_R$, of Vetiver root is found to be about 1/6 of the tensile strength of steel bar. More recently, Sungwornpatansakul and his groups have conducted comprehensive research on tensile strength of Vetiver grass of many sub-species as shown in Figure 3 (e.g. Sungwornpatansakul & Rajani, 2006, Voottipruex & Sungwornpatansakul, 2003). It could be seen that the tensile strength from Sungwornpatansakul & Rajani (2006) tests appeared to be lower than that of Hengchaovanich (1998). This is expected to be because the specimens of Hengchaovanich (1998) were taken from fully grown Vetiver (2 years old) in the field, while tests of Sungwornpatansakul & Rajani (2006) were on Vetiver grass, a few months old, grown in PVC tube in laboratory. These tension tests were all conducted in a stress-controlled condition.

In the current study, an improvement has been made on the root tension test equipment such that tension was applied in a strain-controlled manner. In this way, the obtained stress-strain curve and peak stress will be more reliable as abrupt failure (that normally occurred in stress-controlled tests) could be avoided. A portable loading frame was modified for tension testing of root specimen as shown in Figure 4. A significant improvement has been made on the technique for gripping the root specimen to loading frame. In this work, liquid latex rubber was coated at both ends of root specimen to avoid damage to roots and to avoid slip failure at the gripping location. As shown in Figure 3, the
results of current tests using this technique showed a higher tensile strength than previous tests especially for smaller root diameter (<0.3mm) range. This is expected to be due to better gripping method and strain-controlled condition in current study. Since this current study was carried out on laboratory-grown Vetiver, it appeared reasonable that the tensile strength obtained was closer to those of Sungwornpatansakul & Rajani (2006) than that of Hengchaovanich (1998).

![Graph showing tensile strength vs root diameter for different studies](image)

**Figure 3.** Tensile strength of Vetiver roots, a) compared with previous studies, b) current study

For analysis and design of slope, engineers need information on the soil cohesion due to roots to calculate the factor of safety. According to Equation (1), it can be seen that the root cohesion, \( c^r \), can be expressed as a function of root area ratio, \( RAR = \frac{A_R}{A} \). It can also be expressed as a function of root bio-mass per unit volume of soil, \( \rho_R \). Equation (4) thus expresses the rate of increase in cohesion due to root percentage in two forms, using either \( k \)-parameter or \( a \)-parameter.

\[
c^r = k \left( \frac{A_R}{A} \right) = a \cdot \rho_R \tag{4}
\]

Early works by Hengchaovanich (1998) suggested the increase of shear strength (kPa) due to grass root, \( a = 6-10 \text{ kPa/kg/m}^3 \), of root mass/unit volume of soil. Similarly, Sungwornpatansakul & Rajani (2006) found that the \( k \) value was about 60kPa/% bulk root area.
Nevertheless, there were some research questions regarding the influence of moisture conditions on the contribution of root to shear strength. In particular, most of the previous works were conducted on sample in moist unsoaked conditions (natural moisture content). In this study, a new large direct shear as developed by Sukpunya & Jotisankasa (2013) was employed to investigate the shear strength of Vetiver root-reinforced soil in water-submerged or soaked condition as shown in Figure 5.

Another major development has been made that by using transparent acrylic tube as sample holder, the distribution of root area ratio could be studied during shear. Figure 6 shows test results of strength of sandy soil (classified as SC, or clayey sand, using Unified Soil Classification System) with and without Vetiver roots (Surathani sub-species) in soaked condition. This SC soil was taken from a landslide site of Ban Natum in Suratthani, South of Thailand. Root-mass was expressed as both wet mass (roots taken at the end of test) and dried mass (roots dried in oven at 105°C overnight). The rate of increase in strength due to root biomass, \( a = 1.9 \text{ kPa/kg/m}^3 \) of dried root/unit volume of soil in this study, which is about only one-third the value from tests of Hengchaovanich (1998) which were tested in natural (unsoaked) field condition. This smaller value obtained in current study could be due to the reduced friction between soil and root and the reduced tension strength of root in submerged condition as well as the different age of Vetiver roots.
Figure 6. Test results of large direct shear on Vetiver-reinforced soil in soaked condition from current study

4. Permeability and soil-water retention curve of root-reinforced soils

This part of study focuses on the influence of Vetiver root on soil’s permeability and soil-water retention curve. Only highlights of the test results will be given here. In total, three major soil types were selected for investigation, namely clayey Sand (SC), low plasticity Silty soil (ML), and high-plasticity Clay (CH). The SC soil was taken from a landslide site of Ban Natum in Suratthani, South of Thailand, the ML soil taken from another landslide in Uttaradit, North of Thailand, while the CH clay was taken from Bangkok area. The soils were compacted to 80% standard Proctor inside a transparent acrylic mold with 10cm diameter and 15 cm height. Each of these samples were planted with Vetiver grass and waited until the vetiver reached a certain age of zero to eight months before testing. The study was aimed at determining relationship between the permeability and root area ratio.

Experimental set-up as shown in Figure 7 was used for the instantaneous profile tests (e.g. Fredlund & Rahardjo, 1993, Jotisankasa et al., 2010) for permeability function and soil-water retention curve tests. The side root-area-ratio could be calculated by drawing the root pattern on the transparent sheet attached to side of the mold and performing image analysis in Matlab computer programme. Also the bulk root-area-ratio, $RAR_B$, was also calculated based on the bio-mass of the root as follows,

$$RAR_B = \frac{R}{\rho_R}$$

where $\gamma_R$ is the unit weight of root = 641 kg/m$^3$, and $\rho_R$ is the biomass of roots per unit volume of soil, kg/m$^3$. 

\[ y = 1.8662x \]
\[ R^2 = 0.9779 \]
\[ y = 0.3544x \]
\[ R^2 = 0.8242 \]
Figure 7. (a) Instantaneous profile tests on soil with vetiver for soil-water retention curve and permeability function determination and (b) example of interpreted root distribution on side of specimen

Figure 8 shows the test results plotted between permeability (or hydraulic conductivity) and the bulk root area ratio. Evidently the general trend is that the soil’s permeability of ML and CH soils increases a little by the presence of Vetiver roots for the bulk root-area-ratio less than 1%. This initial increase in permeability of the soil may be due to loosening effect on the soil structure from planting process. As the root area ratio exceeds 1%, the permeability started to decrease and became about 10 times smaller when the root area ratio reached 1.2-1.5%. This can be explained by the fact that there had been some macro pores in the compacted CH and ML soils that were later filled with roots once root growth reaching a certain level. The overall influence of Vetiver roots in this study seems to decrease the permeability of the CH and ML soils once fully grown and hence preventing infiltration into slope for these soils. As for SC soils, however, the trend is still not so clear, as there was decrease in permeability for soil with roots in some cases while increase in permeability for others.

This observation however only applies to the Vetiver less than 8months old. For older Vetiver, there could be effects of root decay and rejuvenation that comes into play. This aspect will be covered in the next section on field observation.

Figure 8. Variation of saturated permeability with bulk root area ratio
5. Field application of low-cost minirhizotron for Vetiver root study

It is of great importance to study the distribution of Vetiver roots in the field to validate the observations made in the laboratory and try to extrapolate some of the results further in real-life situations. In this regard, the minirhizotron device is used to study the root distribution in the field. The minirhizotron system is a simple method for observing fine roots which intersect the surface of a transparent tube buried in the soil and root zone. It provides a non-destructive and in-situ method to study fine roots. The transparent tubes are inserted in the soil either vertically or at an angle 45° (e.g. Vamerali et al., 2012).

The device used in the current study is developed by Sopharat et al. (2013) as shown in Figure 9. They modified the USB camera with aluminium rods that was easily connected to a portable computer as a simple minirhizotron camera. The image acquisition through transparent acrylic tube (103 and 110 mm inner and outer diameters, respectively) is directly stored to the computer hard disk via USB cable. Each snapshot corresponds to an area of 5 x 6 cm. The installation technique needs a good contact between soil and surface of transparent tube to reduce the probability of roots following the soil-tube interface. The tube must contact the soil tightly enough to minimize voids at the soil-tube interface. In this study, image analysis was carried out using Matlab algorithm in order to calculate the value of side Root-Area-Ratio, $RAR_S$, defined as ratio between area of the apparent roots on the side and the total area.

This minirhizotron device was installed next to vetiver grass on top of 45° slope consisting of colluvium sandy soil in Ban-Natum site, Surathani province. Photos of roots were taken during two periods, i.e. March 2013, and November 2014. During the latter time, vetiver grass disappeared from the slope due to invasion from native species as shown in Figure 10. The photos of roots taken from both periods are shown in Figure 11. The presence of roots for November 2014 case appeared to reduce significantly due to decay of the Vetiver roots especially at shallower depth, while at greater depth, some roots still were present since the decay process may be slower. It could be seen that the new roots of native species that took over started to penetrate downwards, though these were still at early stage and seemed marginal. Some trace of voids could also be observed around the decayed root zone. This could provide potential path for seepage in the future.

![Figure 9. The minirhizotron camera: PSU-Minirhizotron-1](image-url)
Figure 10. Field root study using the minirhizotron at Ban-natum, Suratthani

Figure 12 shows the calculated variations of side root area ratio, root cohesion and factor of safety with depth based on the interpreted root distribution for both periods of March 2013, and October 2014, using Equations 1, 2, 3 & 4. It can be seen that after the Vetiver was invaded by the local species and its roots decayed, the root area ratio decreased significantly leading to loss in root cohesion and decreased factor of safety. This thus emphasizes the importance of frequent maintenance of the VS in practice in order to sustain long-term slope stability. For example, guidelines provided by Truong et al. (2008) for maintenance of the VS should be strictly followed, e.g. watering, replanting, cutting, weed control, fertilizing, etc. Inter-planting using appropriate species, such as Arachis pintoi in between Vetiver hedgerows as proposed by Sanguankaeo et al. (2003), can also be used.

6. Numerical analysis

Rainfall-induced slope failure involved complex interaction between rainfall, infiltration and shearing of soil leading to limit state of equilibrium along critical slip surface. Its analysis thus requires a numerical method in order to take into account all these factors into consideration. Jotisankasa et al. (2014) employed Finite Element Method for modelling seepage and Limit Equilibrium method to calculate slope stability of hypothetical slopes stabilized with Vetiver. The study was intended to explore both advantage and potential risk of Vetiver grass that induced increased hydraulic conductivity on slopes. Two hypothetical slopes with gradient of about 27° and 60° were considered. For both cases, the slopes were modelled with and without Vetiver row in order to compare the effects of Vetiver on stability. It was assumed that the Vetiver zone had hydraulic conductivities 2times the value of original soil. Material properties used in this analysis were based on past studies by Jotisankasa & Tapparnich (2010) and were representative of...
residual soils derived from weathered argillaceous rock (Shale and Mudstone) from Uttaradit province where wide-spread shallow landslides took place in 2006. Highlights of this study are given in the following.

Figure 11. Interpreted root distribution from Minirhizotron (a) March 2013, (b) October 2014

Figure 12. Calculated side root area ratio, root cohesion and factor of safety based on interpreted root distribution.

6.1 Variably saturated seepage

Infiltration behavior of slope was studied using Richard’s and continuity equation as shown in (4).

$$\frac{\partial}{\partial x} \left[ k_x \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_y \frac{\partial h}{\partial y} \right] + Q = m_w \left[ \frac{\partial u_w}{\partial t} \right]$$  (4)
where, $k_x$ and $k_y$ is the permeability in x and y direction respectively, $h$ = total hydraulic head, $Q$ = applied boundary flux, $u_w$ = pore water pressure, and $m_w$ = gradient of the soil-water characteristic curve. The purpose for solving equation (4) is to determine the distribution of pore water pressure in response to rainfall infiltration, which would then be used in slope stability calculation as in Equations (2) & (3) using Limit Equilibrium method.

6.2 Case Study 1: Natural Slope (2:1, H:V)

For case study 1, the modeled slope, as shown in Figure 13, consists of top soil (0.2m in thickness), which is underlain by residual soils (1&2) and bedrock. The total depth from ground surface to bedrock is 2 metre. The slope gradient is about 26.6 degree, which is similar to the condition of failed natural slope in Uttaradit province, Northern Thailand (Jotisankasa & Tapparnich, 2010).

As explained earlier, the slope was modelled with and without Vetiver row in order to compare the effects of Vetiver on stability. As shown in Figure 13, for the with-Vetiver case, the Vetiver root zone had the depth of 2 meter (i.e. rooted down to bedrock) and width of 0.2 m. The spacing between Vetiver row was 1 meter (in horizontal direction) and the total length of slope was 29 meter. As for the without-Vetiver case, the slope profile was the same as for the with-Vetiver case, except that there was no Vetiver root zone in the modeled slope.

![Figure 13. Slope geometry and finite element mesh for case study 1 (with vetiver rows)](image)

![Figure 14. Pore water pressure after 12 hours of rain (43 mm of rain) for case 1 (with and without Vetiver)](image)
Seepage analysis was conducted in this study using the SEEP/W finite element software. For the initial condition, the steady state analysis was performed with the flux boundary condition at the upper surface specified as $1.077 \times 10^{-7}$ m/s (300 mm/month), which was the average monthly rainfall during rainy season in Thailand. During transient analysis, the upper boundary condition was specified as $1 \times 10^{-6}$ m/s (86.4 mm/day) and the period of rainfall continued for 48 hours, equal to 172.8 mm of rain in total.

Pore-water pressure distributions for slopes with and without Vetiver rows are compared at the location top of slope as shown in Figure 14. For slope with Vetiver rows, the root zone appeared to conduct water to a greater depth, resulting in slightly lower pore water pressure from zero to 0.5 m depth, while having marginally greater pore pressure at greater depth. By and large, there is not much significant difference between the pore water pressure of 26° slopes with or without Vetiver.

The values of pore water pressure variation with time were then used in stability calculation to determine the change of factor of safety with accumulated rainfall as shown in Figure 15. The slope without Vetiver grass appeared to fail (FS=1) when the total rainfall reached about 120-170 mm and the slope with Vetiver rows was always of higher factor of safety throughout. It can be said that the increased cohesion due to roots more than offsets the higher permeability of root zone that may induce deeper infiltration into slopes, at least for the case of 26° slope.

6.3 Case Study 2: Cut Slope (1:2, H:V)

For case study No 2, the modeled slope had a gradient of about 60 degree and the FEA mesh are as shown in Figure 16a. This slope was typical of cut slopes in weathered rock in Thailand. The Vetiver row was assumed in each 2-meter high bench and the root zone was 0.2 m wide and only 0.8 m deep. The shear strengths used in calculation are typical of weathered weak claystone. Figure 16b shows the pore water pressure from transient seepage analysis at 24 hours (accumulated rain of 86.4 mm) for both Vetiver and no Vetiver cases. It can be seen that, with assumed increased permeability zone due to Vetiver hedgerows on slope, groundwater can infiltrate to a greater depth through the root zone, resulting in higher pore water pressure in the slope.

Based on this pore water pressure distribution, slope stability analyses were performed for both cases (with & without Vetiver) at different accumulated rainfalls and the results are shown in Figure 17. It can be seen that the factor of safety for the slope with Vetiver is about 10% lower than the slope without Vetiver. This is due to the increased pore water pressure in the root zone.
pressure induced from increased infiltration through the root zone. It was observed that the failure surface extended deeper than the root zone of the Vetiver and hence it can be said that the influence of the root reinforcement in this case does not contribute to the stability.

![Figure 16. Finite element mesh for Case study 2 and typical pore-water pressure (kPa) in slope.](image)

![Figure 17. Factor of safety and accumulated rain for 60° cut slope with and without Vetiver rows.](image)

Various assumptions made in this study still need to be explored further to confirm the validity of this finding. In particular, the actual depth of the Vetiver roots in the field that can penetrate the bedrock still needs to be confirmed. Still based on this model, it can be concluded that for natural soil slope with gradient 26°, the 2-metre deep Vetiver roots may increase the pore water pressure only slightly and the stability of the soil would be mainly improved by reinforcement of the roots. However, for a weathered rock slope of about 60°, the 0.8 m deep Vetiver roots could potentially provide a pathway for water infiltration, increased the pore water pressure and thus reduced the factor of safety of the slope by about 10%. This reduction in stability due to root-zone infiltration can be still considered a theoretical risk of vegetation’s adverse effect on slope steeper than 60°. When applying the VS on very steep slope (>60°), practitioner should therefore exercise certain cautions, especially for the case of easily degradable rock such as claystone. In such cases of extreme steep slope, engineering structures, such as retaining wall, geo-synthetics, or other methods of reinforcements should be employed in combination with the VS.
7. Conclusion

In order to quantify the beneficial effects of Vetiver system as well as the theoretical risk of its misuse, systematic characterization of engineering properties of Vetiver system in relation to slope stability has been carried out. This study involved both mechanical and hydraulic aspects by ways of laboratory and field techniques along with numerical simulation. It was demonstrated that the moisture conditions of the soil play an important role on the contribution of root to soil’s shear strength. Based on test results using a new large direct shear, the rate of increase in strength due to root biomass, \( \alpha = 1.9 \text{ kg/m}^3 \) of dried root/unit volume of soil for soaked condition, which is about only one-third the value from tests of Hengchaovanich (1998) which were tested in natural (unsoaked) field condition.

The overall influence of Vetiver roots in this study seems to decrease the permeability of the high plasticity clay and low plasticity silt once fully grown to eight months old and hence preventing infiltration into slope for these soils. As for clayey sand, however, the trend is still not so clear, as there was decrease in permeability for soil with roots in some cases while increase in permeability for others. This observation however only applies to the Vetiver less than 8months old. For older Vetiver, there could be effects of root decay and rejuvenation that comes into play as observed in the field using Minirhizotron technique. It can be seen from a test site in Surathani, South Thailand, that after the Vetiver was invaded by the local species and its roots decayed, the root area ratio decreased significantly leading to loss in root cohesion and decreased factor of safety. This thus emphasizes the importance of frequent maintenance of the Vetiver in practice in order to sustain long-term slope stability.

Based on studies using numerical simulation, the VS appeared to have mainly beneficial effects for slope of 26\(^{\circ}\) gradient (1V:2H). However, when applying the VS on very steep slope (>60\(^{\circ}\), 2V:1H), practitioner should exercise certain cautions, especially for the case of easily degradable rock such as claystone, since there could be theoretical adverse effect, amount to 10% reduction in factor of safety.

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