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SOIL REINFORCEMENT WITH COMBINATION ROOTS SYSTEM: A CASE STUDY OF VETIVER GRASS AND *ACACIA MANGIUM WILLD*

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ABSTRACT: This paper focussed on the effect of combination root reinforcement system on soil slope stability. Consequently, an attempt was made to study the effect of Vetiver grass roots in combination with *Acacia Mangium Willd* roots on shear strength of soil. To assess the mechanisms of root anchorage and root reinforcement within two years growth period, the plants were pulled out to determine their pullout resistance as well as their penetration into the soil. In addition, large scale field direct shear tests were carried out on both rootless and root reinforced soil. A composite soil-root system was developed to evaluate the contribution of combination root reinforcement to shear strength. Subsequently, the results revealed that there are significant root reinforcement effects of 1.5 times increase by Vetiver grass and 3.0 times increase by Acacia tree in the soil shear strength root reinforcement in the slope stabilization scheme. Consequently, this paper proposed the critical zone and selected soil moisture content to calculate the strength increment of the combination root reinforcement soil system for successful slope stabilization.

Keywords: Slope stability, combination roots system, *Acacia Mangium Willd*, vetiver grass

INTRODUCTION

Vegetation helps stabilize slopes by providing root strength and by modifying the saturated soil water regime. Plant roots can anchor through the soil mass into fractures in bedrock, can cross zones of weakness to more stable soil, and can provide interlocking long fibrous binders within a weak soil mass. In deep soil, anchoring to bedrock become negligible and lateral reinforcement predominates. Slope instability is one of the natural hazards causes lost of life, economic and natural resources damages. A natural slope is different from a man- made slope in that the effects of vegetation and soil variability play an important role in their stability (Wu et al, 1979).. The main effect of vegetation on slope stability is generally considered to be mechanical stabilization due to the response of roots. This effect is applied through the strength and the distribution of roots within the soil. The mechanical reinforcement provided by root networks is one of the most important stabilizing factors, as roots are strong in tension but weak in compression and conversely soil is strong in compression but weak in tension. A soil that contains roots therefore has increased shear strength due to the production of a reinforced matrix, which is stronger than the soil or roots separately.

Although the root system has been used worldwide, few studies described the engineering of combination root system. In this study, the effect of root diameter on the tensile strength of roots was established. To obtain the contribution of root tensile strength to the shear strength of soil, large scale direct shear tests were performed in 0.5 x 0.5 x 0.5 m^3 root permeated soil blocks along with root free soil blocks with same soil properties. The difference between the shear strength values of root permeated and root free soils, the shear strength increase due to the presence of roots, were then analyzed with the root area ratio, root diameter, and eventually with the root tensile strength to elaborate the significance of root tensile strength of combination species and its influence in soil strength increase.

BENEFITS OF ROOT REINFORCEMENT

Deep-root woody vegetation, however, increases soil strength by root reinforcement and also by the buttressing and soil arching between plants. Root

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reinforcement increases the cohesion and can be added to the numerator of the factor of safety equation (Gray and Leiser, 1982). Buttressing is provided by firmly anchored tree trunk. Arching occurs when soil attempts to move through and around a row of trees. If the rows are staggered, the buttressing and arching affects a large proportion of the slope.

Woody plants providing a high concentration of deeply penetrating flexible roots with high tensile strength are most effective for slope stability. Soil shear strength increases with the bulk weight of roots per unit volume, which can be also be expressed as the ratio of the area of the roots to the area of the sliding surface. Based on in-situ shear test data of sandy residual soil on granitic slopes forested with Douglas Fir, Gray and Leiser (1982) concluded that root-area ratios in the range of 0.05% to 0.10% increase soil shear strength 0.07-0.14 kg/cm^2.

In a study of shallow land sliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range, the influence of roots reinforcement on shallow land sliding has been established through mechanistic and empirical studies. In the study areas, landslides tend to occur in areas of reduced root strength, suggesting that to make site-specific prediction of landslide occurrence slope stability analyses must account for the diversity and distribution of vegetation in potentially unstable terrain (Joshua et al, 2003).

PLANT SPECIES

There may be few or no native species available that grow readily in such soil and area conditions. On the other hand, it may be possible to find exotic species that are well adapted to these conditions. These also may serve as a pioneer or nurse cover that sufficiently modifies the area so that native species can become established. Pioneer plants are the first to invade and establish. These pioneer plants modify the side sufficiently for plants in later succession stages to gain a toehold.

An immense variety of plants can be used for re-vegetation purpose. The trick is to decide which types of plants are compatible with area conditions and well suited for achieving stabilization goals. Two types of pioneer plants were selected in this research that includes Vetiver grass and *Acacia Mangium Willd.*

VETIVER GRASS

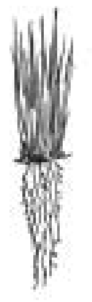

Fig. 1 Vetiver grass

The species belongs to the grass family (Graminae) which is most common in Thailand. Vetiver is a tropical plant which grows naturally and referred to in scientific term as *Vetiveria Zizaniodes*. It has a vigorous, strong, long, and massive fibrous root system that can penetrate up to 3 m underground depending on soil condition as shown in Fig. 1. Moreover, because of its dense and massive root system underground, it offers better shear strength increase per unit fibre concentration in the soil than for tree roots.

In Thailand, Vetiver grass can be found growing in a wide range of area from highlands to lowlands in various soil conditions. These species appears in a dense clump and grow fast. The clump diameter is about 300 mm and the height is 500 to 1500 mm. Vetiver roots are important as a temporary cover. Most grass has fibrous roots which spread out from the underground part of the culms and hold the soil in a horizontal pattern. The roots that penetrate vertically into the soil are not deep. In contrast, the roots system of Vetiver grass does not expand horizontally but penetrates vertically deep into the soil, whether it to be the main roots, secondary roots or fibrous roots (Chaipattana Foundation, 1996)

Vetiver grass has been promoted and researched extensively in Thailand with considerable success. As a consequence, it is being used in a range of applications including; combating of soil erosion, in farming and forestry, and most significantly as stabilization hedges on slope stability for engineering purposes. Vetiver grasses have been planted at 1.5 m intervals in testing area.

ACACIA MANGIUM WILLD

Acacia Mangium Willd is being evaluated and considered as one of the major fast growing species used in reforestation programs throughout Asia and the Pacific. Due to its rapid growth and tolerance of very poor soil, *Acacia Mangium Willd* is playing an increasing role in efforts to sustain natural ecosystems.

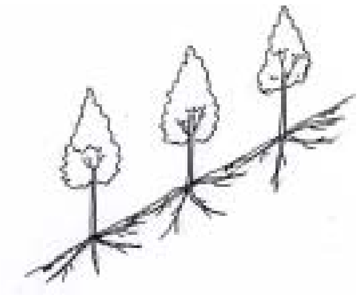

Fig. 2 *Acacia Mangium Willd*

Acacia Mangium Willd is native to Australia, Indonesia and Papua New Guinea (PIER, 2003). *Acacia Mangium Willd* is widely planted in Thailand as a pioneer tree and for reforestation. It has rapid early growing, and can attain a height of 30 m and stem diameter of over 600 mm. *Acacia Mangium Willd* is very fast growing tree and seems to prefer moist to wet sites. Its root that crosses from the unstable soil to the rest of the slope can provide reinforcement and can distinguish into two types namely: basal root and lateral root as shown in Fig. 2. Lateral roots are found near the stump, root systems commonly and extend laterally to neighbouring trees or several trees spacing away. It is common for root networks to grow laterally or parallel to the slope. These roots interweave, holding soil blocks together (Burroughs and Thomas, 1977), and creating a continuous net of roots which span potential failures. While the vast majority of the lateral roots are concentrated near the soil surface (Abe and Iwamoto, 1986), basal roots can extend down to bedrock. If these roots penetrate in bedrock cracks, the basal roots can anchor the soil to the slope.

CONCEPT OF COMBINATION ROOTS SYSTEM

This research work uses the combination roots of Vetiver grass and *Acacia Mangium Willd*. The magnitude of root strength in a potential soil mass will increase with the amount and extent of adjacent root network. In other words, the distribution of trees surrounding a potential landslide site controls the apparent cohesion owing to root strength. Vetiver grass can effectively be used for soil erosion control. Its roots are fibrous roots, small in diameter and fruitful of water. Vetiver grass roots can penetrate deep into the ground and can reinforce and increase the shear strength of roots reinforce soil in only certain level such as soil erosion control. The *Acacia Mangium Willd*’ s roots are harder and stronger than the Vetiver roots and can penetrate horizontally and vertically. Buttressing is provided by

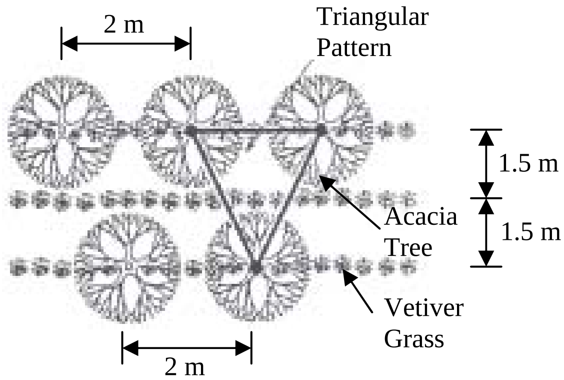

Fig. 3 Triangulation plants pattern

Fig. 4 Vetiver grass roots dominated

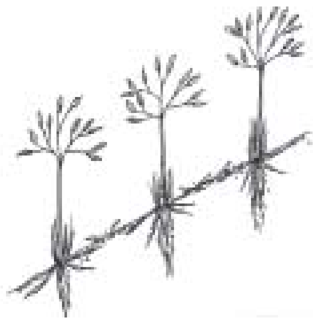

Fig. 5 Combination roots system of Vetiver grass and Acacia tree

Fig. 6 *Acacia Magium Willd* dominated

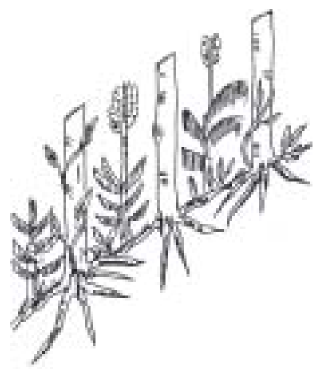

Fig. 7 *Acacia Mangium Willd* and Indigenous plants

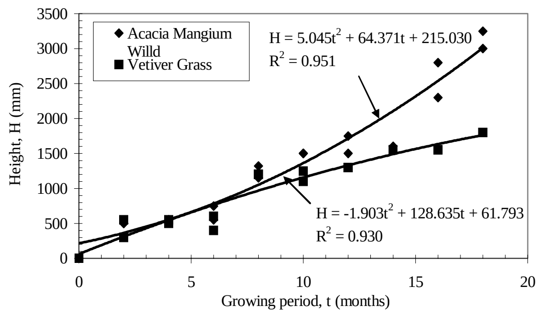

Fig. 8 Relationship between growth rate of species and growth periods

firmly anchored tree trunk or large diameter shrubs. Arching occurs when soil attempts to move through and around a row of trees (Gray and Leisre, 1982). If the tree rows are staggered, the buttressing and arching function influence large areas of the slope. Therefore, the Acacias were planted in the triangular pattern with spacing of 2.0 m while the Vetiver grasses were planted in a row with spacing of 1.5 m as shown in Fig. 3.

In first period of time, the Vetiver grass which can grow faster than the *Acacia Mangium Willd*, dominate the shear strength of root permeated soil and protect the slope as shown in Fig. 4. In second period, the Acacia will grow up and its roots can spread and intervening to Vetiver grass. The effectiveness of the combination roots dominate the shear strength of rooted soil as shown in Fig. 5. In the third period of time, the Acacia grow faster and dominated the strength of soil. The Vetiver grass was covered by the shade of Acacia tree and gradually disappeared as shown in Fig. 6. In the fourth stage, the indigenous species will recover and their roots including *Acacia Mangium Willd* intervenes each other as shown in Fig. 7. Due to the hard and strong root of the Acacia tree, the soil is further reinforced.

GROWTH RATE

Observations were made on the growth rate of two selected species. Both Vetiver grass and *Acacia Mangium Willd* were used to study root distribution in field trial at King Mongkut's Institute of Technology North Bangkok, Prachinburi Campus which is located in the eastern part of Thailand. The soil properties were obtained as shown in Table 1. Every 2 months, the growth rate of plant was monitored by measuring their height and diameter. The result revealed that the growth rate of Vetiver grass and Acacia tree increased as growing period increased. Within 2 years, the growth rate of Vetiver grass increased from 200 mm to 1000 mm, an increase of 80% and maintained constant thereafter. In contrast, the Acacia tree still increased its height and its diameter from 5 mm at the beginning to 12 mm. The relationship between the growth rates growing period during two years of two species is shown in Fig. 8. From the beginning to 4 months, the growth rate of Vetiver grass seems to be higher than Acacia tree. However, after 4 months the growth rate of Acacia tree was higher than Vetiver grass because the Acacia tree attained a height of 3000 mm compare to 1500 mm for Vetiver grass. The height of Vetiver grass increased from 30 mm to 180 mm which is 6 times from the beginning. While the average height of Acacia tree increases from 50 to 325 mm which is 6.5 times from the original height. The average of *Acacia Mangium Willd* root distribution increased from 100 to 500 cm or 5 times from the original dimensions. The average of Acacia tree root distribution increased from 100 to 3000 mm which is 30 times. The diameter of clump of Vetiver increased from 5 to 14 mm or 1.8 times. While the average stem diameter of *Acacia Mangium Willd* increased from 5 mm to 60 mm or 12 times. The average root length of Vetiver grass increased from 5 to 45 mm which is 9 times from the beginning while the average root length of Acacia tree increased from 10 to 250 mm which is 25 times from the beginning.

Table 1 Index properties of the soil

Properties	
Specific Gravity, Gs	2.64
Dry unit weight of soil, t/m^3	1.85
Optimum moisture content,%	11.02
Liquid Limit,%	27.55
Plastic Limit,%	16.40
Classification	SP

Fig. 9 Large scale field pullout test

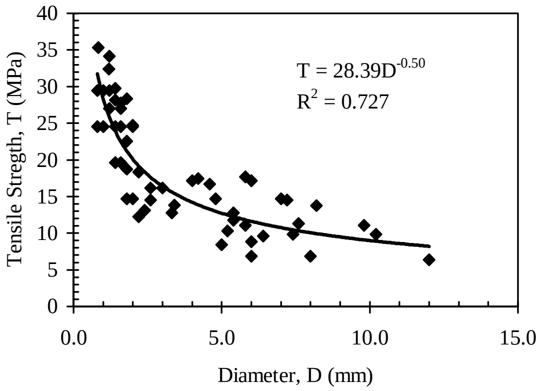

Fig. 10 Relationship between root tensile strength and Acacia tree root diameter

LARGE SCALE PULLOUT TEST

The pullout test measured the maximum resistance when a root is pulled out from the soil. Pullout strength is composed of tangential friction or adhesion between soil and roots, and is influenced by root bending, branching, root hairs, and the tensile strength at breakages. Figure 9 shows large scale pullout test. Pullout tests were conducted for both Vetiver grass and Acacia tree roots in every 2 month until 2 years.

TENSILE STRENGTH OF ROOTS

The tensile strength of roots can be obtained from pullout tests. Estimates of root tensile strength can be converted to apparent root cohesion or adhesion (quantified with units of stress) by dividing the tensile force due to root strength by the surface area within the soil thickness across which the root penetrated (Wu, 1995). The roots of Vetiver grass and *Acacia Mangium Willd* with diameter greater than or equal 1 mm were tested. The maximum force reached before breakage was recorded. Diameter of root was measured using callipers. The variation in root tensile strength with root diameter of *Acacia Mangium Willd* is shown in Fig. 10. Root tensile strength varies approximately from 8 to 28 MPa for root diameters ranging from 1 to 12 mm. The relationship between root tensile strength and diameter can be expressed in the form of power relationship expressed by:

$$T = 28.39D^{-0.50} \quad (1)$$

where T is root tensile strength in MPa, D is root diameter in mm.

Figure 11 shows the relationship between tensile strength and root diameter of Vetiver grass. Root tensile strength was approximately from 14 to 44 MPa for root diameters ranging from 0.2 to 1.3 mm. The relationship between root tensile strength and root diameter which is a power relationship is expressed by:

$$T = 16.95D^{-0.60} \quad (2)$$

Tensile strength reduced with diameter because the diameter of root depended on sponge shell while fiber core and strength of root depended only on the inner core of the root.

MODULUS OF ELASTICITY OF ROOTS

Modulus of elasticity of Vetiver grass roots decreased in the range of 420 to 140 MPa with the increase of root diameter as shown in Fig. 12. A power relationship between modulus and diameter of Vetiver grass roots is expressed by:

$$E = 194D^{-0.84} \quad (3)$$

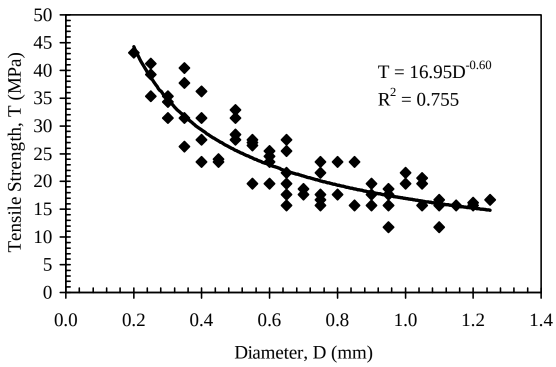

Fig. 11 Relationship between root tensile strength and Vetiver grass root

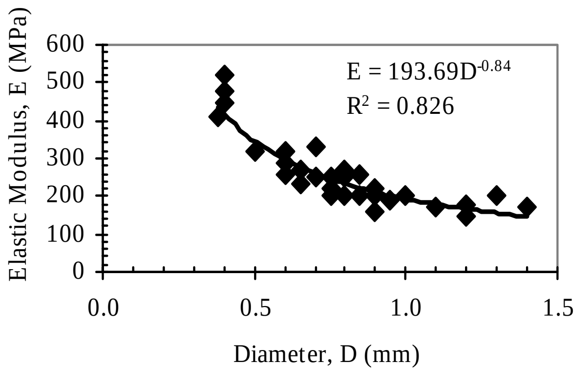

Fig.12 Modulus of elasticity of Vetiver grass roots

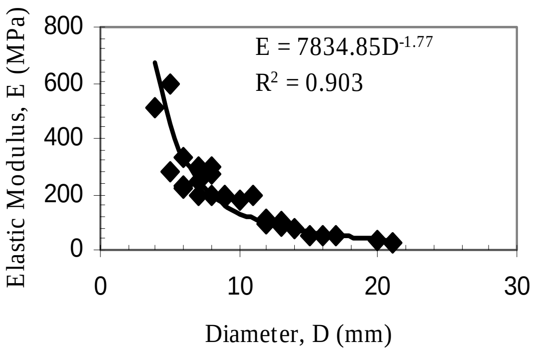

Fig. 13 Modulus of elasticity of *Acacia Mangium Willd* roots

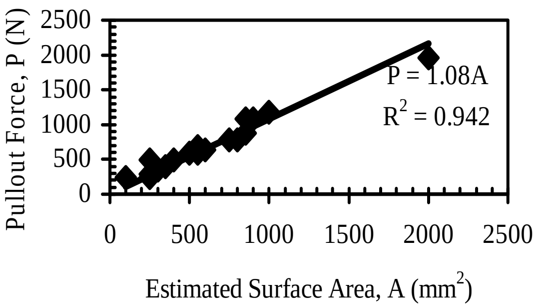

Fig.14 Relationship between pullout force and estimated surface area of *Acacia Magium Willd* roots

where E is modulus of elasticity of root in Mpa and D is root diameter, mm.

Similarly, the *Acacia Mangium Willd* roots also decreased in the range of 670 to 40 MPa with the increase in root diameter as shown in Fig. 13. A power relationship between modulus and diameter of *Acacia Mangium Willd* roots is expressed by:

$$E = 7835D^{-1.77} \tag{4}$$

where E is modulus of elasticity of root in Mpa and D is root diameter, mm

From the test results it can be concluded that modulus of elasticity of root decreased as root diameter and growing period increased because the diameter of root depended on sponge outer shell while the fiber core and modulus of elasticity of root depended only on the inner core of the root.

PULLOUT RESISTANCE OF ROOTS

In the composite materials, such as a soil reinforced by root fibers, loss of root cohesion can also occur by debonding failure or root slippage, when that the pullout resistance of the bond between the root and soil is less the root tensile strength. From laboratory experiments, Waldron and Dakessian (1981) concluded that the root slippage rather than breakage was the limiting condition of root reinforcement for fine-grained soils. The pullout force, P, required to break the soil-root bond, μ, along a length of root, L, for dry conditions can be approximated as:

$$P = \pi D \mu L \tag{5}$$

where D is the root diameter, and πD is the perimeter of the root (e.g. Ennos 1990). Field experiment by Anderson et al. (1989) and Riestenberg (1994) support the relation express by Eq. 5.

The pullout strength of roots was used to analyze the maximum resistance when a root is pulled out of the soil. Tsukamoto (1987) and Abe and Iwamoto (1986) reported that pullout strength could be predicted by root diameter and was independent on slope conditions and root type. Pullout strength was composed of tangential friction between soil and roots, and was influenced by root bending, branching, root hairs, and the tensile strength at breakages. The pullout tests were conducted on both Vetiver grass and *Acacia Mangium Willd* trees in the field every two months. The development of radial cracks for *Acacia Mangium Willd* trees has been observed. On the other hand, only slight radial cracks can be observed in the Vetiver grass because its roots normally penetrate downward. The relationships between pullout force and estimated surface area of *Acacia Mangium Willd* tree root are presented in Fig. 14. The relationship is linear and expressed by:

$$P = 1.08A \tag{6}$$

where P is the pullout force in N and A is the estimated surface area in mm^2

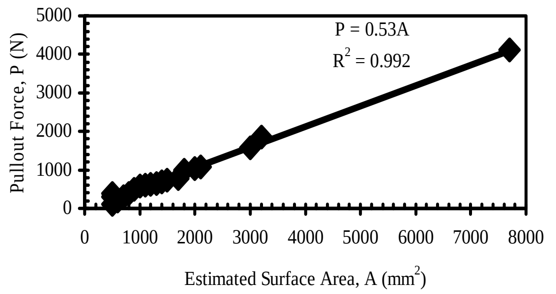

Fig. 15 Relationship between pullout force and pullout force of Vetiver grass roots

Similarly, the relationships between pullout force and estimated surface area of Vetiver grass root are presented in Fig. 15. The relationship is linear and expressed by:

$$P = 0.53A \tag{7}$$

The pullout force increased as estimated root surface area increased which depend largely on penetration of roots into soil. The longer the growing periods of the species, the higher the pullout resistances of the roots are obtained.

PULLOUT FORCE VERSUS ROOT COHESION

From pullout test, root cohesion can be obtained by dividing the pullout force with the estimated surface of roots. It was found that the root cohesion increased as pullout force increased. Besides, it can be concluded that root cohesion also increased as growing period increased which lead to effectiveness holding of roots to surrounding soil. Consequently, root cohesion will be added to soil cohesion and shear strength of soil will increase. The relationship between pullout force and estimated surface area of *Acacia Mangium Willd* root is presented in Fig. 16. The relationship is a power

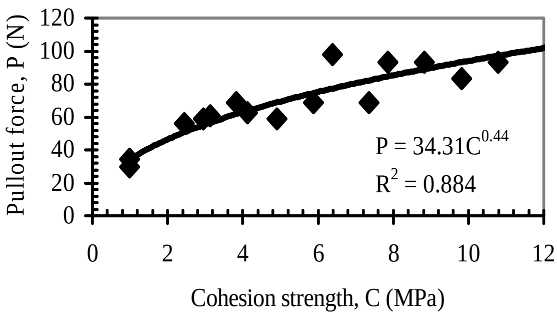

Fig. 16 Relationship between cohesion strength and pullout force of *Acacia Magium Willd* roots

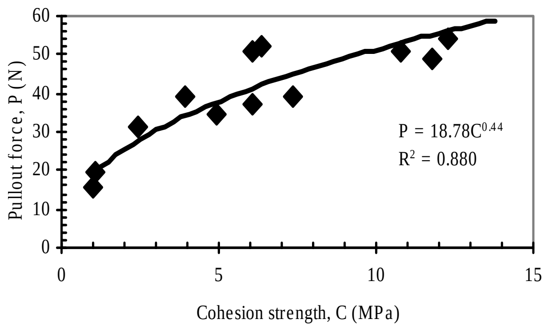

Fig. 17 Relationship between cohesion strength and pullout force of Vetiver grass roots

expression as follows:

$$P = 34.31C^{0.44} \tag{8}$$

where P is the pullout force in N and C is root cohesion in MPa.

The relationship between pullout force and estimated surface area of Vetiver grass root is presented in Fig. 17 and is given below:

$$P = 18.78C^{0.44} \tag{9}$$

Fig. 18 Large scale direct field shear test

LARGE SCALE DIRECT SHEAR TEST

The strength of soil with roots is difficult to measure directly. A large scale shear box was performed to measure the contribution of Vetiver grass roots and Acacia tree roots to the strength of soil in the testing area. Prior to the test the grass or the tree was cut at ground level. Then, trenches were excavated around a soil block, approximately 1 m square and 0.5 m deep, to isolate it

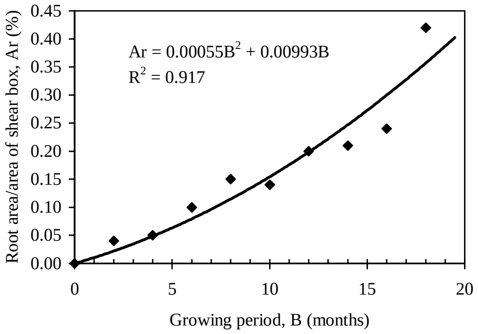

Fig. 19 Relationship between area ratio and growing periods of combination root system

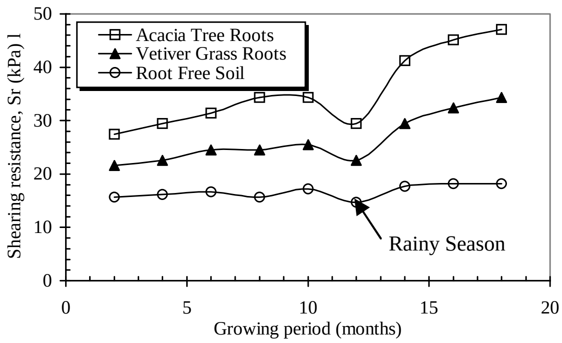

Fig. 20 Relationship between shearing resistance and growing periods of combination root system

from the surrounding soil. The shear box test of 100 x 300 x 300 mm was employed as shown in Fig. 18. The shearing force was applied by hydraulic jacks that acted on steel plates placed against the wall of the rear trench. Large scale direct shear tests were conducted in 3 locations including under the Acacia tree, between the Acacia tree, and in a row of Vetiver grass as previously shown in Fig. 3.

AREA RATIO OF ROOT COMBINATION SYSTEM

Area ratio refers to the proportion of section area of roots along shearing plane area of soil in shear box of 500 mm x 500 mm. Relationship between area ratio of combination root reinforcement system at 100 mm. depth from ground surface and growing periods is shown in Fig. 19. It was found that area ratio increased as growing period increased. The relationship is a power expression given by the following equation:

$$Ar = 0.00055B^2 + 0.00993B \qquad (10)$$

where Ar is the area ratio in percent and B is the growing period in months.

The increase area ratio corresponds to increasing pullout force and root adhesion that enhances the slope stabilization of root reinforced soil.

SHEAR RESISTANCE OF COMBINATION ROOT SYSTEM

Data from field shear tests are important for evaluating the appropriateness of combination soil root reinforcement concept. During 18 months of research, field direct shear tests were conducted in 3 locations, namely: a) in root free soil, b) under the *Acacia Mangium Willd* tree, and c) between the *Acacia Mangium Willd* and a row of Vetiver grass as previously shown in Fig. 3. Relationship between shearing resistance and growing periods of combination root system is shown in Fig. 20. The shearing resistance of root free soil varies from 15 to 18 kPa. The lower value occurred due to high moisture content in the soil during the rainy season. The shear resistance of root free soil was influenced by soil moisture content in different seasons.

The shearing resistances of combination root reinforced soil were influenced by both *Acacia Mangium Willd* root and Vetiver grass root. The shearing resistance of combination root reinforced soil slightly increased from 21 to 26 kPa as growing period increased from 2 months to 10 months. At 12 months the shearing resistance decreased from 26 to 22 kPa due to high moisture content in soil during rainy season and dramatically increased to 22 to 26 kPa at 18 months. The shearing resistance of shear resistance of combination root reinforced soil increased by 54 % from the initial value. In comparison, the shearing resistance of combination root reinforced soil is higher than root free soil by 47% at 2 months and increased to 88% at 18 months.

The shearing resistances of *Acacia Mangium Willd* tree root reinforced soil in the area under the *Acacia Mangium Willd* tree were also measured. This testing area was influenced by strong root of *Acacia Mangium Willd* tree. The test results show that the shearing resistance of *Acacia Mangium Willd* tree root reinforced soil slightly increased from 27 to 34 kPa as growing period increased from 2 months to 10 months and decreased to 29 kPa at 12 months due high moisture content from rain. The shearing resistance increased from 29 to 47 kPa at 18 months. The shearing resistance of combination root reinforced soil increased by 71 % from the initial values. The test results revealed that the shearing resistance of *Acacia Mangium Willd* tree root reinforced soil is higher than root free soil by 86% at 2 months and increased to 166% at 18 months. The shearing resistance of root reinforcement soil increased as the growing periods increased with proper selected plant species. *Acacia Mangium Willd* tree and Vetiver grass are plant species that can be adopted soil slope stabilization.

In a study near Cincinnati, Ohio, tree roots increased the factor of safety against shallow sliding nine fold. The sliding surface in this case was the contact between bedrock and colluviums. The average shear strength contributed by tree roots penetrating the contact was determined to be about 6 kPa. In forest areas, colluviums-mantled were stable up to 35°, whereas deforested slopes were subject to sliding at 12° to 14° (Rienstenberg and Sovonick-Dunford, 1983).

CONTRIBUTION OF ROOT REINFORCEMENT

The ability of plant roots to strengthen the soil mass is well known. The inclusion of plant roots with high tensile strength increased the confining stress in the soil mass by its closely spaced root matrix system. The soil mass is bound together by the plant roots and the shear strength is increased. The contribution of root reinforcement to shear strength is considered to have the characteristics of added cohesion or adhesion (Wu et al., 1979). Soil-root shear strength is directly proportional to root cohesion. This means a soil with high root cohesion will increase the soil-shear strength, adding to slope stability. Roots of plants increase soil cohesion by binding to soil particles. The number, depth, size, and growth patterns of roots affect the soil cohesion. A few models quantify the interaction between the roots and the soil matrix such that root cohesion is limited by the thread strength of the roots themselves, not the bond between root and soil. This procedure is adopted and the following equations for determining the increase in shear strength from Wu (1976), Waldron (1977), and Wu et al. (1976).

Assuming the root cross the shear zone perpendicularly and the ultimate tensile strength (T_r) is mobilized, the total tensile root strength of a given species per unit area of soil, t_r, is expressed as:

$$t_r = \sum T_{ri} \,(A_{ri}/A_s) \tag{11}$$

where (A_{ri}/A_s) is the root area ratio or proportion of root cross-sectional area to soil cross-sectional area (A_s), and n is the number of roots in area (A_s). The ratio of the total cross-sectional area of all roots to soil cross-sectional area is expressed by A_r/A_s. In Fig. 21, the schematic diagram of elastic roots is shown extending

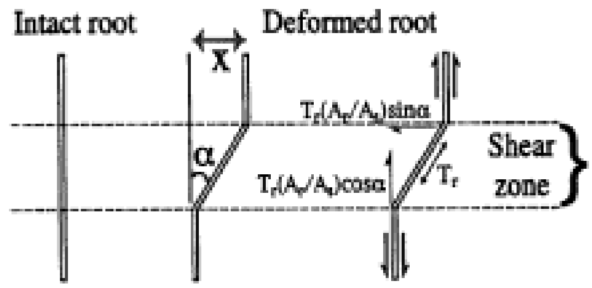

Fig. 21 Cross sections of roots across the shear zone on the root reinforcement model

perpendicularly across a shear zone, displaced laterally by an amount X, and distorted by angle of shear, α. The mobilization of tensile resistance in the fibers in the soil can be translated into a tangential component ($t_r\cos\alpha \tan\phi'$) and a normal component ($t_r\sin\alpha$). Expressed as a reinforcement strength per unit area of soil, the root, C_R, cohesion is:

$$C_R = t_r(\cos\alpha\ \tan\phi' + \sin\alpha) \tag{12}$$

Sensitivity analyses indicate that the values of ($\cos\alpha \tan\phi' + \sin\alpha$) in Eq. (12) can be approximated as 1.2 for $25^o<\phi'<40^o$ and $40^o<\alpha<70^o$ (Wu 1976; Wu et al. 1979). In addition, experimental direct shear tests on dry, fiber-reinforced sand by Gray and Ohashi (1983) indicate that the greatest reinforcement occurs when a fiber is oriented at 60^o with respect to the deformation zone. It is unclear how saturated conditions may alter α and relative fiber reinforcement. Equation (11) is modified to determine the root cohesión arising from root reinforcement of a given each species. Schmidt et al (2001) employed the following model:

$$C_R = 1.2\Sigma\ T_{ri}(A_{ri}/A_s) \tag{13}$$

Greater values of C_R arise from high-strength root threads, larger diameter roots, and (or) increased root densities.

Mechanisms of shear strength increase include: 1) fiber deforms when shearing occurs, 2) deformation causes fiber to elongate, provided there is enough interface friction and confining stress to lock the fiber in place and prevent slippage, and 3) fiber elongation mobilizes tensile strength in fiber. The tangential component of the tensile force directly resists shear, while the normal component increases the confining stress on the shear plane. (see Fig. 21)

On the basis of the field observations, laboratory research, and previously published research by Schmidt et al. (2001), the following assumptions were made:

1) The tensile strength of individual root fibers is fully mobilized (not just bond failure between the soil and root). The calculation of root cohesion includes only those roots in landslide scarps which broke as a result of landslide, evidence that their strength was fully mobilized.

2) The effective internal friction angle, ϕ', is unaffected by root reinforcement. Although laboratory analyses by Endo and Tsuruta (1969) substantiated assumption 2, it is unclear how scale effect modify the contribution to the soil mass frictional strength in the field.

3) All broken roots failed simultaneously. During land sliding, it is unlikely that all roots are simultaneously loaded to their ultimate tensile strength, hence we may overestimate root cohesion in the landslides characterized by slow deformations where roots progressively fail over time.

4) Roots are flexible and are initially oriented perpendicular to the shear zone (Fig. 21). Laboratory tests reveal that the reinforcing fibers oriented perpendicular to a shear zone provide reinforcement comparable to that of randomly oriented fibers (Gray and Ohashi 1983)

5) Root cohesion increases are directly proportional to A_r/A_s. Field measurements of root extraction force (Anderson et al. 1989; Riestenberg 1994) and laboratory analyses on the effects of roots on shearing resistance (Kassiff and Kopelovitz 1968; Waldron and Dakessian 1982; Gray and Ohashi 1983) substantiated this assumption, as root reinforcement expresses a positive relationship with root cross-sectional area. The results of Gray and Ohashi (1983) indicated that shear strength increases are directly proportional to A_r/A_s, whereas Jewell and Wroth (1987) and Shewbridge and Sitar (1989) argue that the strength increase in reinforced soil is slightly nonlinear. That is, we may overestimate root cohesion at sites with high root densities (values of A_r/A_s >0.005).

6) The potential effect of pore-water pressure on C_R is neglected. Any variation on C_R arising from changes in surface tension in the unsaturated zone is also neglected.

7) Root cohesion neglects the bending moments of the individual root threads. Experiment by Shewbridge and Sitar (1990) indicated that the methods based on the development of tension within the reinforcing fibers (neglecting bending moment) are sufficient to represent root reinforcement.

The focus of this research is on that of C_R, the strength added to soil from roots. To address this, the tensile strength, root diameter and root density were measured for selected species. Since the mechanical effect of plant roots is to increase the cohesiveness of the soil mass, root reinforced soil shear strength (S_r) can be considered as equivalent to an apparent cohesion of the soil known as apparent root cohesion (C_R). Typical values of apparent root cohesion range from 1 kPa to 17.5 kPa (Coppin and Richards, 1990). These values were obtained from the studies of several investigators using different techniques including back-analysis, direct shear test, root density information combined with vertical root model equations, and back-analysis combined with root density information. The values of apparent root cohesion (C_R) are dependent on the type of vegetation and field soil conditions.

Wu et al. (1979) incorporated the effects of vegetation in slope stability analysis by using conventional limit equilibrium method. In limit equilibrium methods, the shear strength (Sr) of the soil along a potential slip surface is assumed to be fully mobilised at the point of failure (τ). The Mohr-Coulomb equation is used to describe the shear strength of the soil:

$$Sr = \tau = c' + (\sigma\text{-}u) \tan \phi' \qquad (14)$$

where c' is the effective cohesion; σ is the total stress; u is the pore water pressure; ϕ' is the effective internal friction angle. By incorporating the effect of root reinforcement due to combination root system, Eq. (14) becomes:

$$Sr = \tau = (c' + C_{R1} + C_{R2}) + (\sigma\text{-}u) \tan \phi' \qquad (15)$$

where C_{R1} is the apparent Vetiver Grass root cohesion and C_{R2} is the apparent Acacia Tree root cohesion

The apparent root cohesions (C_{R1},C_{R2}) can be incorporated in infinite slope analysis to increase the factor of safety (FOS). In the field the shear stress of root free soil at 16 months period is 19.62 kPa while the shear stress of Vetiver grass penetrated soil is 29.43 kPa which is 1.5 times higher than the former. Besides, the shear strength of soil reinforced with both Vetiver grass roots and Acacia tree roots at the same period of time is 58.86 kPa which is 3 times higher than root free soil. The results indicated that the roots of Vetiver grass and Acacia gree can improve the stability of soil slopes.

CONCLUSIONS

Vetiver grass and Acacia tree roots were studied in improving the stability of slopes. The observations made during monitoring of field trial indicate that combination root reinforced system could be expected on slope where roots penetrated into the soil. Soil was therefore held by roots, and consequently, significant soil strength increased as growing period increased. To assess the root reinforcement in the field, pullout and direct shear tests were done. Most roots directly affecting slope stability are about 10 mm in diameter and less than 100 mm in diameter. Roots reinforcement has been considered as equivalent to an increase in apparent soil cohesion. In this research, only the effect of roots within the shear zone was considered. Vetiver grass and its roots increase quickly for about 8 months, and then remain nearly constant while *Acacia Mangium Willd* tree has rapid early growth, and continue growing to a height of 30 m. Individual roots become stronger as they become larger. In the final stage, the *Acacia Mangium Willd* roots with Vetiver grass roots interweave and enhanced further the shearing strength of combined root reinforced soil including: 1) Vetiver Grass root increased soil strength by 1.5 times and 2) Acacia tree root increased soil shear strength by 3 times.

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