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INVESTIGATION OF MECHANICAL PROPERTIES AND ROOT ARCHITECTURE OF PLANTS AND SOIL PHYSICAL PROPERTIES FOR SOIL SHEAR STRENGTH

Nazi Avani[1*] and Habibah Lateh[2]

[1]Environmental Studies, School of Distance Education, University Sains Malaysia, 11800 USM Penang, Malaysia.[*]E-mail: avani.nazi@yahoo.com
[2]Professor, School of Distance Education, University Sains Malaysia, Penang, Malaysia. E-mail: habibah@usm.my

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Abstract

The use of vegetation as slope cover becomes an alternative solution for slope stabilization instead of using shotcrete cover. Use of vegetation is a way to reduce the impact of engineering works and increase the landscape quality. Although the use of vegetation to reduce slope failure is common around the world during the last decades, but in Malaysia there is still lack of such studies. Therefore, to answer the question whether the existence of tropical trees increase the soil shear strength against slope failure and measuring the amount of increase, the soil engineering properties of two tropical species were studied. Eight trees of similar age of *Acacia mangium* and *Macaranga tanarius*, were selected along the East-West highway, Malaysia. The direct shear tests were used to analyze the effect of tree roots on soil mechanical properties. Soil and root properties such as moisture and bulk density with and without root and root architecture of two species were analyzed. The results showed that the existence of roots increases soil shear strength and this is higher in soil sample with *M. tanarius* roots which increases it with about 11 % to 44 % while *A. mangium* trees increase soil shear strength with about 7 % to 27 %. The soil particle size in *M. tanarius* samples shows higher coarse grain size, therefore, the higher soil shear strength could be explained. The results showed that there is a negative correlation between soil moisture and soil shear strength and a positive correlation between soil bulk density and soil shear strength. The root architecture of *M. tanarius* with VH-type also imply the higher soil shear strength compare with *A. mangium*. In conclusion, *M. tanarius* root and soil properties implied higher soil shear strength of soil samples compared to *A. mangium*.

Key words: engineering properties, root architecture, soil and root properties, soil bulk density, soil cohesion, soil shear strength.

Introduction

Soil stabilization using roots in woody shrubs and trees, and root reinforcement of sloping ground is one of the least recognized measures. A summary of engineering influences of vegetation used to stabilise sloping ground (Norris and Greenwood 2006) include additional effective cohesion due to the vegetation; tensile reinforcement force by the existence of roots; soil strength changes due to moisture removal by the vegetation; pore water pressure changes due to the existence of roots.

Utilization of bio-engineering on slopes and road cuttings depicts the use of vegetation for protection of river banks and slopes. Bio-engineering combines understanding of engineering principles with knowledge of vegetation and its interaction with soil. Understanding plant root functions and soil-root interaction is the first step to improve bioengineering techniques and use of living plants instead of industry materials to stabilize slope and therefore to construct sustainable future.

The presence of vegetation can significantly affect water level in the soil and also the pore pressure of water (Greenwood et al. 2004). Vegetation has two main effects on the slope stability. By its hydrological effect, vegetation can increase the capacity of water infiltration and reduce water content in the soil and also with evapotranspiration increase the effective soil cohesion and the effective soil cohesion enhances by increasing in reinforcement effect (Das et al. 2017b). By mechanical effect the presence of vegetation roots crosses the potential failure slip surface, provides a tensile force which is an additional restrain on the potential slip (Burylo et al. 2011). Use of vegetation for slope stabilization has lower initial construction cost and needs just regular observation and maintenance. Hence, bio-engineering offers an alternative solution instead of using a conventional massive structure for slope stability and shallow landslide (Leung et al. 2015).

Krzeminska et al. (2019) monitored the hydrological and mechanical effects of selected Norwegian species (trees, shrubs and grass) on stream bank stability in Norway. Soil shear strength and porosity, soil moisture, groundwater level and stream water level were monitored in this study. They conducted that there is no significant difference between grass and shrub plots but they found lower soil moisture and porosity, and higher soil shear strength within the tree plots.

Cebada (2017) calculated the mechanical effects of 17 different species in Nepal on slope stability. Out of the 17 plant species in the study, two were grasses, two bamboos, five shrubs and eight trees. The results showed that use of grasses, like *Thysanolaena maxima* (Roxb.) resulted in increased factor of safety (FOS). *Vitex negundo*L. showed the highest FOS among shrubs. *Salix tetrasperma* Roxb. provides better reinforcement due to its root cohesion. They concluded that a combination of species rather than monoculture provides good protection against slope failure.

Some authors such as O'Loughlin and Ziemer (1982), Sonnenberg et al. (2010) and Ali et al. (2012) agreed that mechanical functions of roots are more accepted than hydrological functions regarding slope stability. Even though, plant roots reduce the pore water pressure, but it is obviously accepted that mechanical functions effect directly on slope stability and decide whether or not the slope is stable or fail during shear stress. Simon and Collison (2002) showed that the hydrological effect of riparian vegetation increases slope stability by only 29 %, but in contrast the mechanical effect increases the stability about 53 %. Abernethy and Rutherfurd (2001) also mentioned that the mechanical benefit of vegetation can be more than the hydrological.

Ali (2010) mentioned that more information is still needed on Malaysian plant roots system regarding to slope stability. Information on the nature and on their performance of Malaysian species for bio-engineering purposes is poor. In case of below-ground performance, there are few studies on root system architecture of exotic or native tree species. This is due to the fact that study on root system is time-consuming as they are below-ground, especially for large trees, and also root system is in direct collaboration with soil conditions therefore the comparisons would be difficult.

One of the limiting factors in the use of biotechnology of environmental engineering is lack of knowledge about the characteristic of root systems. Therefore, knowledge on their morphological and mechanical properties of different plant species is an effective parameter to select an appropriate slope stability species. The main objective of this study is to investigate the effect of vegetation roots of two broadleaf species on soil shear strength. In this study, we would like to answer the question whether the existence of *Acacia mangium* Willd. and *Macaranga tanarius* (L.) Müll. Arg. root system in soil increases the soil shear strength or not. And if yes, how much they can increase the soil shear strength.

Material and Methods

Study area

The study area is located along the East-West Highway of Malaysia. It is one of the major roads in the northern part of Peninsular Malaysia between N 05°27′32.0″ E 101°07′42.3″ and N 5°42′11.15″ E 101°49′54.74″. The length of the highway is 119 km which links two districts namely Gerik in Perak and Jeli in Kelantan. The climate of the study area is humid and annual mean precipitation is 1957.5 mm. The minimum altitude is 283 m above the sea level. The type of soil is clayey with a mixture of sand and gravel. The geology of the area consists of granite, schist, phyllite, slate and limestone, meta-volcanic, mylonit, amphibole schist, thick bedded to massive quartzite with thin phyllites interbed (Lloyd et al. 2001) (Fig. 1).

In this study, investigated species are *Acacia mangium* (Malay name: Mangium) and *Macaranga tanarius* (Malay name: Mahang). The studied species were selected based on the following factors/criteria to select slope stability species (Stokes et al. 2008):

- Fast growing plant species (*M. tanarius* and *A. mangium*);

- Small species with a low canopy (*M. tanarius*);

- Self-renewal ability (*A. mangium*);

- Nitrogen fixing plants (*A. mangium*) improve soil materials with their nodulation functions; strong resistance; have a beneficial effect on soil resistance and infertility and soil and water conservation;

- No study about the effect of its root on soil cohesion and also it is the common species in Malaysia (*M. tanarius*) (Zakaria et al. 2008).

Methodology

Soil mechanical tests

Direct shear box test

The soil shear strength is its resistance to shearing stress. For engineering situations such as investigating slope stability or cuts, the shear strength data are needed. Soil derives its shear strength from two parameters, internal friction angle and cohesion.

One of the oldest and cheapest tests for soil is a direct shear test. The shear strength is done in the laboratory by a direct shear device. Fan and Su (2008) and Zhang et al. (2010) mentioned the

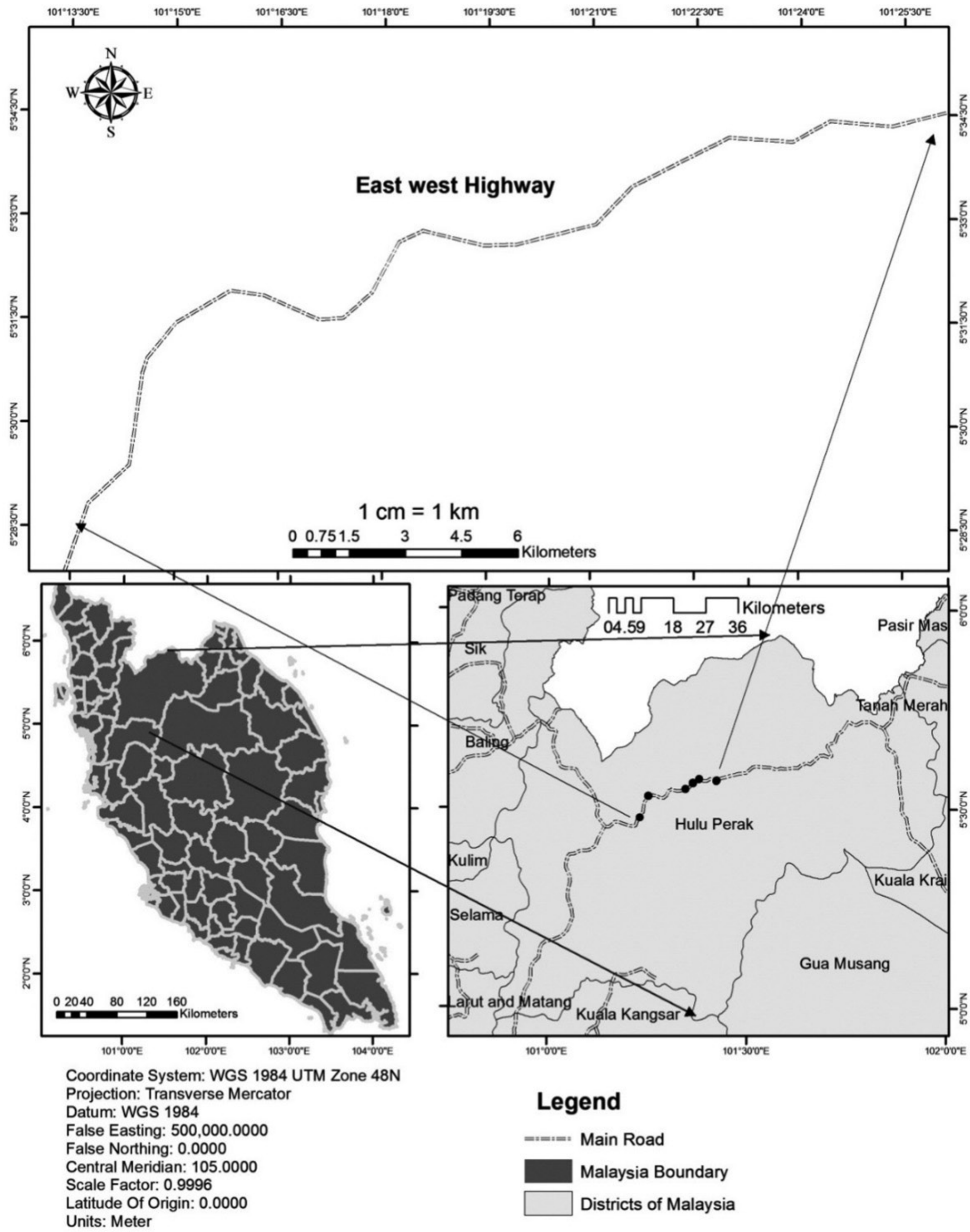


Fig. 1. Location of the study area.

low cost and direct visual process as the advantages of this test. The other advantages mentioned by Ali and Osman (2008) are: samples at different depth can be investigated; uniform soil sample can be prepared and saturation of each sample can be obtained. The biggest disadvantage is that the shear plane is assumed.

Shear strength is measured by continuing the displacement of soil particles and the resistance of soil to this shifting. Two loads are applied in soil particles in the direct shear test. A normal stress (vertical) is applied and held stable, and then a shear stress is applied until rupture.

In direct shear test equipment, soil specimen is placed in a metal box which splits into two halves horizontally. Through a metal plate, vertical force (normal stress) is applied and continues. By moving one half of the box relative to the other one, shear force is applied to failure in the soil.

The procedure of soil direct shear test

Firstly, the area of the shear box was measured, then the top and bottom of shear box were fixed together and set in contact. Then shear box was placed in the machine and the normal force with three loads – 10 kg, 20 kg and 40 kg, were applied. After that the motor was started (0.25 mm/min). Data of horizontal displacement, vertical displacement and shear load were recorded by data logger. Reading was continued until the soil failed.

To determine soil mechanical properties, soil cohesion and internal friction angle, three undisturbed samples of rooted soil and non-rooted soil (for each soil sample with and without root) at 30 cm soil depth were taken by manually pushing the cylinder with a known volume (63.4 mm diameter × 20 mm height). Strain-controlled direct shear test machine was used (Direct/Residual Shear Apparatus, MCR 2110/1, Geotechnical laboratory, University Sains Malaysia). The undisturbed soil samples were placed in a shear testing device under the three normal loads. A lateral displacement was applied at 0.25 mm/min until failure occurred and the peak shear force was noted (Fig. 2).

Fig. 2. The process of undisturbed soil sampling and analyzing with direct shear box machine.

Data processing

The collected 3 soil samples from each profile of trees at 30 cm soil depth, and the direct shear test under 10, 20 and 40 kg vertical pressure was carried out. A lateral displacement was applied at 0.25 mm/min until failure occurred and the peak shear force was noted. When 3 data of peak shear strength were measured, were plotted to find the relationship between vertical pressure and shear strength, therefore the intercept of the line is soil cohesion and the linear slope is tan ϕ.

The soil engineering properties (soil cohesion and internal friction angle) were measured based on Coulomb equation (1).

$$\tau = \sigma \cdot tan\ \phi + C, \tag{1}$$

where: τ is soil shear strength, KPa; ϕ is the internal friction angle, degree; C is the cohesion, KPa.

The normal stress (σ) in KPa, is given by equation (2).

$$\sigma = [(9.81 \cdot m) \cdot 1000^{-1}] \cdot A^{-1}, \quad (2)$$

where: m is the mass of frame loadings and loads weights (kg) (in this study the frame weight is 4.476 kg); 1 kg $_{force}$ = 9.81 N; A is the soil area (the area of shear box = 0.003157 mm^2).

Soil physical tests

Soil moisture content, specific gravity and particle size of samples with and without roots were determined in this study. For analyzing the moisture percentage of a soil sample, it is necessary to weight the container with and without soil and then dry it in oven at 105 °C for 24 h. Soil specific gravity is necessary for some tests such as: porosity, soil particle size and soil saturation. The pycnometer method was used to calculate the soil specific gravity. Particle size distribution is a necessary test that presents the relative portions of soil particle size. Then it is possible to determine that soil consists mainly of gravel, sand, silt or clay particles. There are two methods to analyze soil particle size namely, mechanical analysis and hydrometer methods.

Root architecture

Since the end of 1990s, coarse root architecture was measured by new devices and techniques such as volume location and semi-automatic 3D digitizing. Root architecture can be achieved by classifying individual roots in several types (Danjon and Reubens 2008). Based on general form and branching pattern, Yen (1987) classifies root architecture in five types, such as H-type, VH-type, M-type, V-type and R-type (cited in Reubens et al. 2007). Fan and Chen (2010) state that the VH- and H-types are introduced to be used in slope stability application, whereas the M-type and H-type are introduced for use in soil reinforcement and restoration as well as erosion control.

Leung et al. (2015) mentioned that soil reinforcement which caused by vegetation roots depends on root architecture.

Results

Soil physical results

Table 1 shows the result of soil physical tests, soil moisture content, specific gravity bulk density and soil type of rooted and non-rooted soil sample.

Table 1. The average meaning of parameters.

Soil physical tests / Sample	Soil moisture, %	Specific gravity, g/cm^3	Initial bulk density, mg/m^3	Soil type
A. mangium	25.41625	2.32	0.796375	sandy-silt
M. tanarius	27.155	2.20625	0.80125	silty-sand
No root	21.945	2.29375	0.8275	silty-sand

Soil mechanical results

The relationship between shear stress and normal stress of undisturbed soil samples with and without root is shown in Figure 3.

Table 2 shows the cohesion and internal friction angle of soil samples with *A. mangium* and *M. tanarius* roots as well as soil without root.

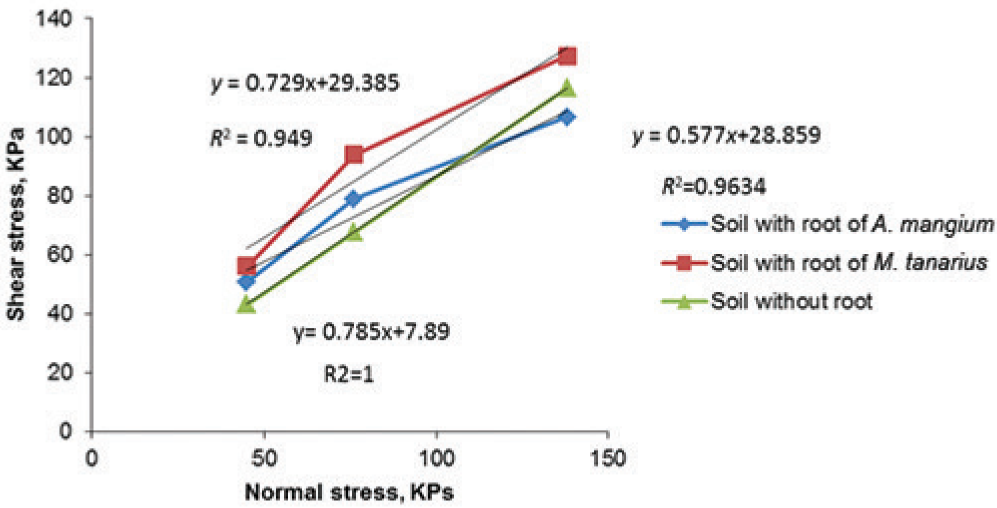


Fig. 3. The relationship between shear stress and normal stress.

Table 2. The mechanical properties.

Sample	Soil cohesion (*C*), KPa	Internal friction angle, °
A. mangium	28.859	30
M. tanarius	29.385	36.12
Non-rooted soil	7.8935	38.15

Soil shear strength increased due to the existence of roots

Soil shear strength is the maximum shear stress that soil can carry without rupture. The shear strength of soil (τ, KPa) is directly related to the normal stress (σ, KPa) acting in shear zone, assuming that other factors are certain. The Mohr-Coulomb law shows the relationship between soil shear strength and normal stress – based on equation (1).

The composite cohesion comes from not only soil particles but also the interaction between soil and roots. Therefore, the cohesion can be defined as integrated cohesion by equation (3).

$$C = C_s + C_r, \qquad (3)$$

where: C_s is the soil cohesion and C_r is root cohesion.

Table 3 shows the integrated cohesion C, root cohesion C_r and internal friction angle of soil with *A. mangium* and *M. tanarius* root and soil without root to calculate soil shear strength.

Table 3. Indexes of shear strength.

Index of shear strength/ sample	Soil and root cohesion (*C*), KPa	Root cohesion (C_r), KPa	ϕ, °
Plain soil	7.9	-	38.15
A. mangium	28.9	21	30
M. tanarius	29.4	21.5	36.12

Indexes of shear strength in Table 3 can be used to calculate shear strength of rooted and non-rooted soil samples with Mohr-Coulomb equation – refer to equation (2).

According to Coulomb model the shear strength is proportional to the normal stress; therefore, shear strength will be valid for any normal stress. Table 4 shows the amount of soil shear strength (τ, KPa) with normal stress (σ) of 44.98 KPa.

Table 4. Shear strength calculated (σ = 44.98 KPa).

Samples	ϕ, °	C, KPa	τ, KPa
Plain soil	38.15	7.9	43.23
A. mangium	30	28.9	54.86
M. tanarius	36.12	29.4	62.22

One-way analysis of variance was used to determine the significant difference between shear strength of plain soil and soil with *A. mangium* and *M. tanarius* roots. The results showed that there is a significant difference between shear strength of plain soil and soil with roots (under 10 kg normal load) ($F_{2.21}$ = 5.140, p < 0.05).

Post hoc comparisons using Tukey HSD test showed that the mean value of soil shear strength of *M. tanarius* (M = 62.22 KPa) is significantly different than soil shear strength of plain soil (M = 43.23 KPa; p < 0.05). However, the mean value of soil shear strength of *A. mangium* (M = 54.86 KPa) did not significantly differ from plain soil (p = 0.152) as well as mean value of soil shear strength of *M. tanarius* (p = 0.444).

According to Figure 4, under vertical pressure of 10 kg, the shear strength of soil samples with *M. tanarius* roots is significantly higher than that without roots. It shows that shear strength of soil with *M. tanarius* roots is higher than *A. mangium* root samples; even a significant difference is not identified.

Table 5 shows the amount of shear strength of rooted and non-rooted soil samples with normal stress of 76.05 KPa.

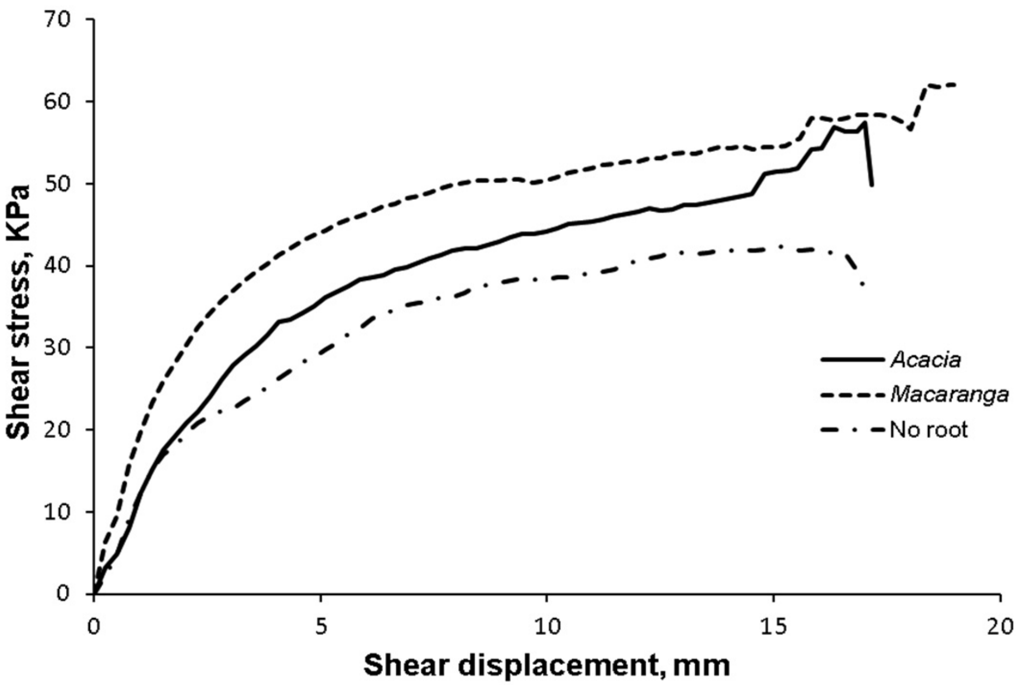


Fig. 4. Relationship between shear stress and shear displacement of rooted and non-rooted soil samples (applying normal stress of 44.98 KPa).

Table 5. Shear strength calculated (σ = 76.05 KPa).

Samples	ϕ, °	C, KPa	τ, KPa
Plain soil	38.15	7.9	67.63
A. mangium	30	28.9	72.80
M. tanarius	36.12	29.4	84.89

One-way analysis of variance was used to determine the significant difference between shear strength of plain soil and soil with roots. The results showed that there is no significant difference between shear strength of plain soil and soil with *A. mangium* and *M. tanarius* roots (under 20 kg normal load) ($F_{2.21}$ = 2.983; p = 0.072). With normal stress of 76.05 KPa, the relationship between shear stress and shear displacement of rooted and non-rooted soil samples is shown in Figure 5.

Table 6 shows the amount of shear strength of rooted and non-rooted soil samples with normal stress of 138.19 KPa.

Table 6. Shear strength calculated (Normal stress = 138.19 KPa).

Samples	ϕ, °	C, KPa	τ, KPa
Plain soil	38.15	7.9	116.45
A. mangium	30	28.9	108.68
M. tanarius	36.12	29.4	130.24

One-way analysis of variance was used to determine the significant difference between shear strength of plain soil and soil with *A. mangium* and *M. tanarius* roots. The results showed that there is no significant difference between soil shear strength of samples (under 40 kg normal load) ($F_{2.21}$ = 2.028; p = 0.157). The relationship between shear stress and shear displacement of rooted and non-rooted soil samples under normal stress of 138.19 KPa is shown in Figure 6.

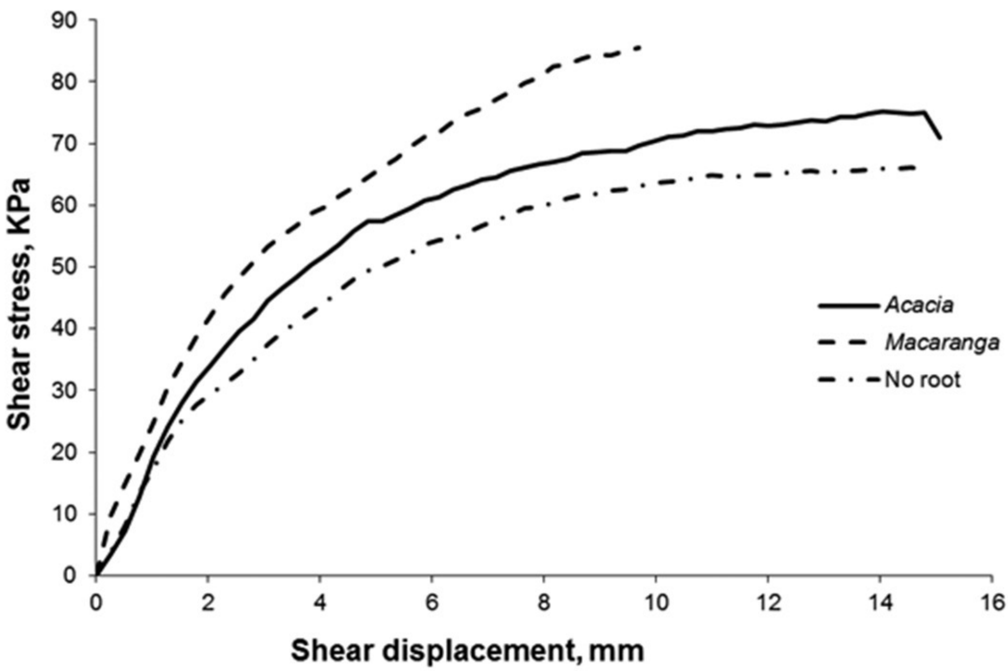


Fig. 5. Relationship between shear stress and shear displacement of rooted and non-rooted soil samples (applying normal stress of 76.05 KPa).

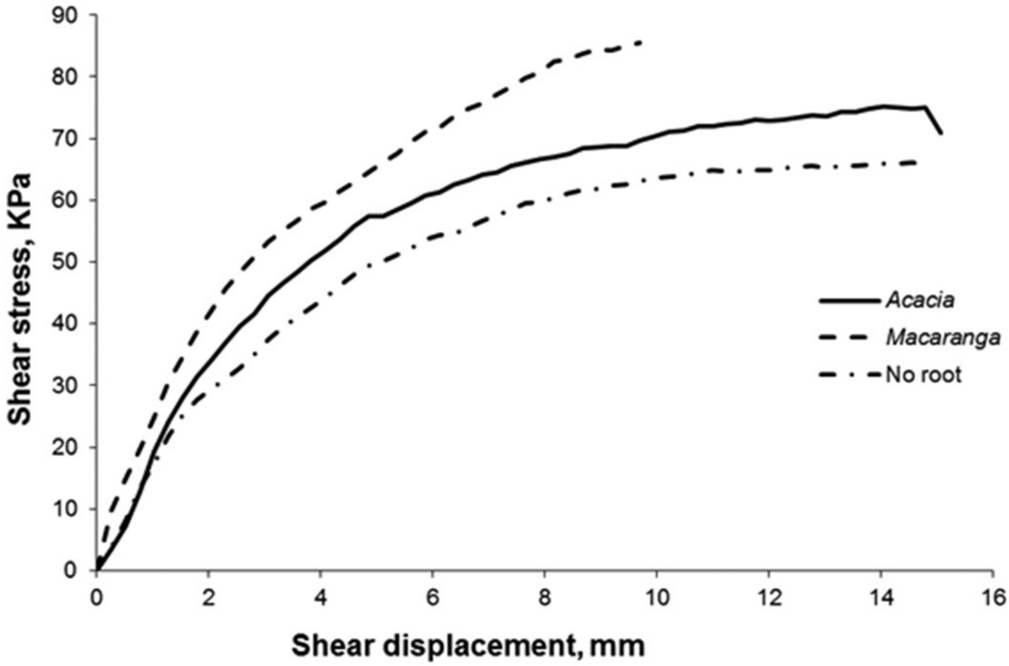


Fig. 6. Relationship between shear stress and shear displacement of rooted and non-rooted soil samples (applying normal stress of 138.19 KPa).

Soil shear strength and soil physical properties

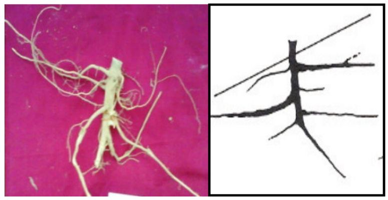
The relationship between soil moisture content and soil shear strength in soil samples with roots and samples without roots shows that there is a negative correlation between soil shear strength and soil moisture. The relationship of soil shear strength and soil moisture for soil sample with *M. tanarius* roots is $y = -0.49 \cdot x + 75.75$ and for soil sample with *A. magnum* roots is $y = -0.48 \cdot x + 67.11$ and for soil sample without roots is $y = -0.33 \cdot x + 50.47$.

The relationship between soil bulk density and soil shear strength in soil samples with *A. mangium* and *M. tanarius* roots and samples without roots shows that there is a positive correlation between soil shear strength and soil bulk density. The relationship of soil shear strength and soil bulk density for soil sample with *M. tanarius* roots is $y = 98.2 \cdot x – 16.5$ and for soil sample with *A. magnum* roots is $y = 57.2 \cdot x + 9.1$ and for soil sample without roots is $y = 58.5 \cdot x – 5.2$.

Root architecture

Table 7 shows the root growth pattern in two studied species based on Yen (1987) which is VH-type (*M. tanarius*) and H-type (*A. mangium*).

Table 7. Root growth pattern of two species.

Species	Root pattern growth	Root growth type
M. tanarius		VH-type (this research)
A. mangium		H-type (Ali 2010)

Discussion

Soil mechanical properties of rooted and non-rooted soil

Many authors around the world have used the laboratory and *in situ* shear tests on root permeated soil blocks to analyze the mechanical properties of soil with and without roots (Operstein and Frydman 2000; Docker and Hubble 2008; Askarinejad and Springman 2014; Fan and Tsai 2016; Das et al. 2017a, 2017b; Lateh and Avani 2018; Raj et al. 2018; Maffra et al. 2019).

Two parameters of soil mechanical properties, soil cohesion and internal friction angle influence on soil shear strength which studied by many researchers to find out which one increase soil shear strength. For instance, the soil shear strength of rooted and non-rooted soil samples of *Robinia pseucdoacacia* L. with a triaxial compression test was studied by Zhang et al. (2010). They found that roots have more impacts on the soil cohesion than the soil friction angle. They argue that due to the presence of root, one index of soil shear strength (soil cohesion) increases and the other factor (friction angle) may increase or decrease. Abdullah et al. (2011) state that the friction angle of soil has no significant effect on soil shear strength of three studied species compared to bare soil. The study shows that the cohesion of soil with roots is significantly higher than those without roots and this amount is significantly higher for *Leucaena leucocephala* (Lam.) de Wit. It could be due to the differences in root growth pattern which follows tap root system with long vertical root in *L. leucocephala.* Ali and Osman (2008) claim that the soil shear strength increases by increasing soil cohesion due to the presence of the plant roots in the soil and the effect of soil internal friction angle is negligible. They analyzed increased soil shear strength of four different species namely: *Vetiveria zizanoides* (L.) Roberty, *Leucaena leucocephala*, *Bixaorellana* L. and *Bauhinia purpurea* (L.) Benth. Their results show that shear strength (soil cohesion) increases in *L. leucocephala* more than that of the other species. O'Loughlin and Ziemer (1982) also mention that the existence of Beech roots in soil increase the soil cohesion from 3.3 to 6.6 KPa compared to non-rooted soil samples and the effect of roots on internal friction angle is negligible.

On the other hand, some other authors such as Frei (2009), Graf et al. (2009), Jiao et al. (2010), Davoudi (2011) and Askarinejad and Springman (2014), mentioned that an increase in the internal friction angle of soil caused increase in the soil shear strength. Frei (2009) and Graf et al. (2009) stated that an increase in the soil shear strength of moraine with alder trees (*Alnus incana* (L.) Moench) is due to an increase of the internal friction angle of soil from 34.3° to 39.4° without any change in soil cohesion. Jiao et al. (2010) showed that the internal friction angle of soil sample with more roots is larger than that of soil samples without roots. This is due to the roots which increase the friction of the soil and therefore increases soil friction angle. The study found that the existence of the roots destroys the connections of clay particles and therefore diminishes the soil cohesion. He claims that in the direct shear test, the internal friction angle of soil contributes mainly to the root anchorage force. Therefore, roots can increase the friction angle and produce resistance to shear stress.

Askarinejad and Springman (2014) showed that the existence of *Avena sativa* L. roots in soil increase the soil internal friction angle compared to non-vegetated soil and in overall increase the soil shear strength. Davoudi (2011) also showed that the existence of Willow root in the soil increase internal friction angle of soil, and in overall increase soil shear strength.

Slope stability improvement is provided by increasing the apparent root cohesion and rooting depth (Chok et al. 2004). Many studies have shown that the increase in soil shear strength is usually attributed to an increase in the apparent soil cohesion (Operstein and Frydman 2000, Ali and Osman 2008). In agreement with other authors, Pollen-Bankhead et al. (2009) also found that the effect of tree roots (Tamarisk and Russian-olive) on soil shear strength increases the soil cohesion without any changes in soil internal friction angle.

Other authors such as Tang et al. (2007) and Chen and Loehr (2008) found an increase in both soil cohesion and internal friction angle of clayey soil reinforced with polypropylene and sandy soil respectively. Tengbeh (1989) also claim that grass roots increase the soil shear strength parameters (both soil cohesion and internal friction angle) of sandy clay loam soils, but for clay soil, it only increases soil cohesion. Maffra et al. (2019) also evaluate the roots influence on the shear strength of a clay soil and a sandy soil. They found that in the sandy soil, roots influenced the shear strength by increasing the cohesion value with 234 %, while in the clay soil with 32 % and the internal friction angle with 14.4 %.

The result of this study is in agreement with those who claim that the shear strength of soil increases due to the increase in soil cohesion. Therefore, this research is in agreement with Operstein and Frydman (2000), Ali and Osman (2008), Pollen-Bankhead et al. (2009), Lin et al. (2010), Davoudi (2011), Abdullah et al. (2011). According to the results, the soil cohesion of samples with roots for both species is higher than that without roots. The results show that the amount of soil cohesion of *M. tanarius* is more than *A. mangium*.

In conclusion, Veylon et al. (2015) suggested that the impact of root on soil shear resistance whether by increasing soil cohesion or internal friction angle depends especially on species. On the other hand, Chok et al. (2004) mentioned that slope stability improvement is provided by increasing the apparent root cohesion (additional soil cohesion due to root). To understand the root function on soil shear strength, root system knowledge is required because this complex biological structure is unknown to the engineers. It is necessary to upgrade the engineering knowledge of vegetation such as additional soil cohesion due to the existence of root, vegetation interacts with soil, water, and climate, which many engineers are not familiar with the use of vegetation as an engineering material.

Soil shear strength

It is observed that the shear strength of soil permeated roots is higher than that without roots (figs 5, 6 and 7) (except for *A. mangium* soil samples with normal stress of 138.19 KPa; Fig. 6). Therefore, the study question has been answered and revealed that the existence of roots in soil will increase the shear strength of soil. The shear strength of soil increases about 44 % due to the existence of *M. tanarius* tree roots and this amount for *A. mangium* tree roots is about 27 % under normal stress of 44.98 KPa compared to non-reinforced soil with roots (Table 4). Therefore, *M. tanarius* roots increase shear strength of soil much more than that of *A. mangium* roots. Cazzuffi et al. (2006) also used big shear box machine to compare the effect of grass roots on soil shear strength compared with non-rooted soil samples. They found that Vetiver and Elygrass roots shows higher soil shear strength compared the other species. These differences could be explained by differences in root systems and environmental situation.

By increasing the normal stress to 76.05 KPa, the soil shear strength of rooted soil with *M. tanarius* increases to about 25.52 % and for *A. mangium* roots about 7.64 % compared to non-reinforced soil with roots (Table 5). With normal stress of 138.19 KPa, the results show that the soil shear strength with *M. tanarius* roots increased about 11.84 % and for *A. mangium*, the soil shear strength decreases to about -6.67 % (Table 6, Fig. 6).

The shear stress-displacement curve for studied species and plain soil under 10 kg normal load is shown in Figure 8. The maximum shear stress-displacement point is significantly higher in soil permeated roots of *M. tanarius* than that those without root ($p < 0.05$, ANOVA). It is observed that *M. tanarius* has higher displacement before it achieves the maximum shear strength, it means high resistance towards the force applied before it losses the strength. This result is in agreement with Fan and Tsai (2016) who showed that the shear stress-displacement peak of soil samples without root occur before the peak shear strength of soil with *L. leucocephala* roots.

Docker and Hubbel (2008) showed the relation between shear stress *versus* shear displacement of four tree species (*Acacia floribunda* (Vent.) Willd, *Casuarina glauca* Sieber, *Eucalyptus elata* Dehnh. and *Eucalyptus amplifolia* Naudin) in Australia as well as soil without roots. They show that when soil samples without roots reach its peak strength, resistance of soil samples with roots is still increasing. They state that all species demonstrate higher soil shear strength compare to non-rooted soil, but *A. floribunda* shows a greater amount compared to other species.

Fan and Su (2008) mentioned root efficiency (RE) (the role of roots in shear strength of root permeated soil) in their research which comes from the increase in soil shear strength divided by shear strength of root-free soil. Referring to this study, the root efficiency of *A. mangium* (with higher normal stress) is below than zero, therefore it shows that the efficiency of *A. mangium* roots to increase shear strength of soil with higher normal stress is not applicable.

Soil mechanical properties and root architecture

The result of internal friction angle showed difference between two studied species (internal friction angle of soil with *A. mangium* roots is 30°, and with *M. tanarius* roots is 36.12°). Therefore it showed that *M. tanarius* roots can increase the shear resistance more than *A. mangium* as they increase the internal friction angle more. Zhang et al. (2010) state that roots can meaningfully produce resistance to the shear stress with increase the internal friction angle.

The differences in internal friction angle of two species refer to the differences in root pattern. As the root system of *A. mangium* is H-type (Ali 2010) in which most of the roots grow horizontally, but *M. tanarius* roots growth type is VH-type (this research) whereby roots grow horizontally and vertically, therefore, the friction between root and soil increased. Saifuddin and Osman (2014) describe the VH-type root system as: strong tap root which lateral roots extended in a low orientation with horizontal plane. Zhang et al. (2010) stated that roots in horizontal or vertical forms reinforce soil in one direction, but roots in cross form reinforce soil in two directions. Therefore, trees with cross form roots are expected to reinforce soil and slope stabilization more than other root pattern forms. Abdullah et al. (2011) also mentioned that the root growth pattern in *L. leucocephala* which follows tap root system with long vertical root caused higher soil shear strength compared to other species. Riestenberg (1994) also compared the root architecture of two species namely: maple sugar and white ash, and mentioned that sugar maple with lateral roots which do not develop a tap root cannot stabilize deep seated landslides, while white ash with developed roots in first centimeters depth and a tap root which penetrate in depth can stabilize deep seated landslides. Several species according to their enhancement in slope stability were ranked by Cebada (2017) and they concluded that *Vitex negundo* (shrub) and *Acacia catechu* (L.) Willd. (tree) has represented the highest rank among other species due to the fact that their root system develops a tap root with extensive lateral roots which can increase soil cohesion.

According to Tengbeh (1989), cohesion increases by increasing root amount in the soil, therefore, the differences in soil cohesion may be due to the differences in root profile. On the other hand, soil cohesion increases linearly with an increase in root cross-sectional area at the shear plane.

Soil shear strength and physical properties of soil

The results show that with increasing soil moisture, the value of soil shear strength decreases. This result is in agreement with Zhang et al. (2010), Veylon et al. (2015) and Dhawale and Harle (2017) which show that water content in soil decrease the soil shear strength.

The results of soil bulk density show that by increasing it the amount of soil shear strength increases. Rahardjo et al. (2014) mention that the soil with higher coarse grain particles shows higher shear strength due to an increase in contact pressure between particles. As the soil particle size in M. tanarius soil samples shows higher coarse grain size, therefore, the higher soil shear strength could be explained.

Conclusions

The results show that the soil engineering properties (cohesion and internal friction angle) for both species in this research increase compared to non-rooted soil sample. This increase is more in soil with *M. tanarius* roots than *A. mangium* roots. Soil shear strength improves by the presence of roots in the study area and this amount is higher in *M. tanarius* than *A. mangium*. The result of this study is useful to protect the areas prone to slope failure with the increase of soil shear strength using the studied two categories of plants. The roots of these two plants show considerable mechanical properties that can contribute in protecting slope soil erosion.

In this research, for *A. mangium* at higher normal stress, maximum shear strength is less than that of soil samples without root. This result may be attributed to the position of soil cores collected in relation to slope angle and root architecture as well as soil moisture. Root system architecture can be driven by slope angle and knowing the upslope and downslope region of the sampled core may influence the maximum shear stress. If upslope cores are placed in the shear assembly with shear force acting in a relative upslope direction, roots are likely to be in compression and therefore exhibit lower values of shear stress. Ideally, cores should be sheared in a downslope direction to ensure that: a) soil will be sheared in the direction of most likely failure; b) roots will take up stress more quickly and, therefore, more likely to show root derived reinforcement at relative low levels of displacement (strain). It is therefore important to consider sample orientation when analyzing the effect of soil sampling position on maximum soil shear strength. Therefore, it is suggested as a further research topic.

The soil moisture of samples without root has higher amount compare to soil samples with root and it is shown that with higher normal stress in soil sample with *A. mangium* roots, the amount of maximum shear strength is less than soil sample without roots. It may be due to less soil moisture in soil sample without roots which can resist more when the normal stress increased. However, there is not a proper study to represent the relationship between maximum shear strength and soil moisture according to different normal stress, therefore further studies in this matter is needed.

Due to the lack of knowledge and information regarding the root systems of common tropical species and their effect on soil shear strength, this subject is an important research area for further studies to applicate soil bioengineering techniques instead of civil engineering works in slope stability projects.

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References

Abdullah M.N., Osman N., Ali F.H. 2011. Soil-root shear strength properties of some slope plants. Sains Malaysiana 40(10): 1065–1073.

Abernethy B., Rutherfurd I.D. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrological Processes 15(1): 63–79.

Ali F. 2010. Use of vegetation for slope protection: Root mechanical properties of some tropical plants. International Journal of Physical Sciences 5(5): 496–506.

Ali N., Farshchi I., Mu'azu M.A., Rees S.W. 2012. Soil-root interaction and effects on slope stability analysis. Electronic Journal of Geotechnical Engineering 17: 319–328.

Ali F.H., Osman N. 2008. Shear Strength of a Soil Containing Vegetation Roots. Soils and Foundations 48(4): 587–596.

Askarinejad A., Springman S. 2014. Centrifuge modelling of the effects of vegetation on the response of a silty sand slope subjected to rainfall. Computer Methods and Recent Advances in Geomechanics, September: 1339–1344.

Baets S.De, Torri D., Poesen J., Salvador M.P., Meersmans J. 2008. Modelling increased soil cohesion due to roots with EUROSEM. Earth Surface Processes and Landforms 33(13): 1948–1963.

Burylo M., Hudek C., Rey F. 2011. Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France). Catena 84(1–2): 70–78.

Cazzuffi D., Corneo A., Crippa E. 2006. Slope stabilisation by perennial 'gramineae' in Southern Italy: plant growth and temporal performance. Geotechnical & Geological Engineering 24(3): 429–447.

Cebada D.P. 2017. Assessment of the Role of Vegetation as Part of Ecosystem – Based Risk Reduction Measures Used for Shallow-Landslides in Rasuwa District, Nepal. Master Thesis, University of Twente. 68 p. Available at: https://webapps.itc.utwente.nl/librarywww/papers_2017/msc/aes/pantle-cebada.pdf

Chen C., Loehr J. 2008. Undrained and drained triaxial tests of fiber-reinforced sand. Proceedings of the 4th Asian Regional Conference on Geosynthetics, Shanghai, China: 114–120.

Chok Y., Kaggwa W., Jaksa W., Griffiths D. 2004. Modelling the effects of vegetation on stability of slopes. 9th Australia-New Zealand Conference on Geomechanics, Auckland: 391–397.

Das G.K., Budhaditya H., Garg A., Ng C.W.W., Lateh H., Avani N. 2017a. Bivariate probabilistic modelling of hydro-mechanical properties of vegetated soils Manuscript. Advances in Civil Engineering Materials 6(1): 235–257.

Das G.K., Hazra B., Garg A., Ng C.W.W., Asce F. 2017b. Impact of Hydrological and Mechanical Correlations on the Reliability of Vegetated Slopes. American Journal of Applied Scientific Research 3(4): 1–13.

Davoudi M.H. 2011. Influence of Willow Root Density on Shear Resistance Parameters in Fine Grain Soils using in situ Direct Shear Tests. Research Journal of Environemntal Aciences 5(2): 157–170.

Dhawale V.R., Harle S.M. 2017. Influence of Different Soil Properties on Shear Strength of Soil : A Review. American Journal of Applied Scientific Research 2(6): 87–90.

Danjon F., Reubens B. 2008. Assessing and analyzing 3D architecture of woody root systems, a review of methods and applications in tree and soil stability, resource acquisition and allocation. Plant and Soil 303(1–2): 1–34.

Docker B.B., Hubble T.C.T. 2008. Quantifying root-reinforcement of river bank soils by four Australian tree species. Geomorphology 100(3–4): 401–418.

Fan C.-C, Chen Y.-W. 2010. The effect of root architecture on the shearing resistance of root-permeated soils. Ecological Engineering 36(6): 813–826.

Fan C.-C., Su C.-F. 2008. Role of roots in the shear strength of root-reinforced soils with high moisture content. Ecological Engineering 33(2): 157–166.

Fan C.-C., Tsai M.-H. 2016. Spatial distribution of plant root forces in root-permeated soils subject to shear. Soil and Tillage Research 156(March): 1–15.

Frei M. 2009.Validation of a New Approach to Determine Vegetation Effects on Superficial Soil Movement. PhD thesis, Eidgenössische Technische Hochschule – ETH

Zürich, No 18455. 6 p.
Graf F., Frei M., Boll A. 2009. Effects of vegetation on the angle of internal friction of a moraine. Forest, Snow and Landscape Research 82(1): 61–77.
Greenwood J.R., Norris J.E., Wint J. 2004. Assessing the contribution of vegetation to slope stability. Geotechnical Engineering 157(4): 199–207.
Jiao Z., Wang D., Xie H., Zhang J., Guo L. 2010. Experimental analysis of shear strength of undisturbed soil in leucaena forest in Jiangjia Ravine, Yunnan, China. Journal of Mountain Science 7(4): 386–395.
Krzeminska D., Kerkhof T., Skaalsveen K., Stolte J. 2019. Effect of riparian vegetation on stream bank stability in small agricultural catchments. Catena 172: 87–96.
Lateh H., Avani N. 2018. The Use of vegetation to reduce Landslide hazards in Malaysia. International Journal of Engineering and Technology 7(4): 480–483.
Leung F.T.Y., Yan W.M., Hau B.C.H., Tham L.G. 2015. Root systems of native shrubs and trees in Hong Kong and their effects on enhancing slope stability. Catena 125(February): 102–110.
Lin D.G., Huang B.S., Lin S.H. 2010. 3-D numerical investigations into the shear strength of the soil-root system of Makino bamboo and its effect on slope stability. Ecological Engineering 36(8): 992–1006.
Lloyd D., Anderson M., Hussein N., Jamaludin A., Wilkinson P. 2001. Preventing landslides on roads and railways: a new risk-based approach. Civil Engineering 144(3): 129–134.
Maffra C., Sousa R., Sutili F., Pinheiro R. 2019. The Effect of Roots on the Shear Strength of Texturally Distinct Soils. Floresta e Ambiente 26 (3): 1–11.
Norris J., Greenwood J. 2006. Assessing the role of vegetation on soil slopes in urban areas. In Proceedings of the 10th IAEG International Congress: 1–12.
O'Loughlin C.O., Ziemer R.R. 1982. The Importance of Root Strength and Deterioration Rates Upon Edaphic Stability in Steepland Forests. Proceedings of IUFRO Workshop P.1.07-00 Ecology of Subalpine Ecosystems as a Key to Management, 2–3 August, Oregon State University, Corvallis, Oregon: 70–78.
Operstein V., Frydman S. 2000. The infuence of vegetation on soil strength. Ground Improvement 4(2): 81–89.
Osman N., Barakbah S.S. 2006. Parameters to predict slope stability-Soil water and root profiles. Ecological Engineering 28(1): 90–95.
Pollen-Bankhead N., Simon A., Jaeger K., Wohl E. 2009. Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona. Geomorphology 103(3): 363–374.
Rahardjo H., Harnas F.R., Indrawan I.G.B., Leong E.C., Tan P.Y., Fong Y.K., Ow L.F. 2014. Understanding the stability of Samanea saman trees through tree pulling, analytical calculations and numerical models. Urban Forestry & Urban Greening 13(2): 355–364.
Raj S., Atma S., Budhaditya P., Ajit H., Ankit S., Zhu G.H. 2018. Stochastic modelling of relative water permeability in vegetative soils with implications on stability of bioengineered slope. Stochastic Environmental Research and Risk Assessment, Springer Berlin Heidelberg 32(12): 3541–3559.
Reubens B., Poesen J., Danjon F., Geudens G., Muys B. 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: areview. Trees 21(4): 385–402.
Riestenberg M.M. 1994. Anchoring of Thin Colluvium by Roots of Sugar Maple and White Ash on Hillslopes in Cincinnati. Landslides of the Cincinnati, Ohio, Area. U.S. Geological Survey, Bulletin 2059-E. United States Government Printing Office, Washington. 25 p.
Saifuddin M., Osman N. 2014. Evaluation of hydro-mechanical properties and root architecture of plants for soil reinforcement. Current Science 107(5): 845–852.
Simon A., Collison A.J.C. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27(5): 527–546.

Sonnenberg R., Bransby M.F., Hallett P.D., Bengough A.G., Mickovski S.B., Davies M.C.R. 2010. Centrifuge modelling of soil slopes reinforced with vegetation. Canadian Geotechnical Journal 47(12): 1415–1430.

Stokes A., Norris J.E., Van Beek L.P.H., Bogaard T., Cammeraat E., Mickovski S.B., Jenner A., Jenner A, Di Iorio A., Fourcaud T. 2008. How Vegetation Reinforces Soil on Slopes. In: Slope Stability and Erosion Control: Ecotechnological Solutions: 65–118.

Tang C., Shi B., Gao W., Chen F., Cai Y. 2007. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. Geotextiles and Geomembranes 25(3): 194–202.

Tengbeh G.T. 1989. The Effect of Grass Cover on Bank Erosion. PhD thesis, Cranfield Institute of Technology, Silsoe College. 223 p. Alailable at: file:///D:/Downloads/Tengbeh_Thesis_1989.pdf

Tengbeh G.T. 1993. The Effect of Grass Roots on Shear Strength Variations with Moisture Content. Soil Technology 6(3): 287–295.

Veylon G., Ghestem M., Stokes A., Bernard A. 2015. Quantification of mechanical and hydric components of soil reinforcement by plant roots. Canadian Geotechnical Journal 52(11): 1839–1849.

Yen C.P. 1987. Tree root patterns and erosion control. In: International workshop on soil erosion and its countermeasures. Soil and Water Conservation Society of Thailand, Bangkok: 92–111.

Zakaria R., Fadzly N., Rosely N., Mansor M., Zakaria M.Y. 2008. The distribution of macaranga, Genus (Family Euphorbiaceae) in Penang Island, Peninsular Malaysia. Journal of Bioscience 19(2): 91–99.

Zhang C.B., Chen L.H., Liu Y.P., Ji X.D., Liu X.P. 2010. Triaxial compression test of soil-root composites to evaluate influence of roots on soil shear strength. Ecological Engineering 36(1): 19–26.