Journal of Tropical Forest Science 34(2): 176–186 (2022)
https://doi.org/10.26525/jtfs2022.34.2.176

EVALUATION OF ROOT PROFILES AND ENGINEERING PROPERTIES OF PLANTS FOR SOIL REINFORCEMENT

Saifuddin M[1, 2, *], Osman N[2] & Khandaker MM[3]

[1]*Computer and Communication Engineering (CCE), Faculty of Science and Engineering, International Islamic University Chittagong, Kumira, Chittagong-4318, Bangladesh*
[2]*Institute of Biological Sciences, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[3]*School of Agricultural Science and Biotechnology, Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Besut Campus, 22200 Besut, Terengganu, Malaysia*

**saifuddin.cu.um@gmail.com*

Submitted March 2021, accepted September 2021

The potential values and application of soil bioengineering techniques are crucial for the slope protection and ecological restoration. Knowledge related to the biological and engineering properties of plants is essential for the implementation of soil bioengineering techniques. Thus, four tropical species namely *Leucaena leucocephala, Acacia mangium, Dillenia suffruticosa* and *Melastoma malabathricum* were evaluated in terms of root profiles and root engineering properties. *Leucaena leucocephala* showed the highest root tensile strength followed by *A. mangium, D. suffruticosa* and *M. malabathricum.* Pull-out resistance was mostly affected by the root than the shoot profiles. Leaf area index (LAI) and root biomass were strongly correlated ($R^2 = 0.79$), implying that the root biomass would be higher if the plant canopy was higher. Tree species, *L. leucocephala* and *A. mangium,* had deep rooting system and recommended for slope protection. Shrub species, *M. malabathricum* and *D. suffruticosa* had shallow root system and suggested for controlling soil erosion. Based on the overall engineering properties, *L. leucocephala* showed excellent performance through its root profiles and can be a potential plant for soil reinforcement. In conclusion, plant pull-out resistance, root tensile strength and type of roots can be used as important tools to identify plant performance for soil reinforcement. The results can be an aid to select potential slope plants for implementing soil bioengineering and slope protection techniques successfully.

Keywords: Root profiles, pull-out resistance, root tensile strength, soil reinforcement

INTRODUCTION

Hillsides and vast areas of forests have been rapidly transformed and made suitable to meet the development need of the country. Such transformed lands are used for constructing highways and other transportation systems. This system has been widely practiced in Malaysia for the last two decades. The changes in land-use have inevitably involved removing of vegetation cover and cutting of hill slopes which resulted in acute problems, affecting physical, chemical and biological properties of soils (Komoo et al. 2011, Mizal-Azzmi et al. 2011). In Malaysia, a significant number of failure on residual slope and natural landslides have been reported during the past decades especially during high intensity rainfall (Tu et al. 2009, Pradhan 2013). Simultaneously, lack of vegetation and potential species on hilly areas have led to natural disasters (Mugagga et al. 2012, Song et al. 2012).

Many new technologies have been introduced and implemented to ensure efficient development without stressing the environment. Bioengineering is a well recognised, preferred and widely practiced technique in stabilising slope and controling soil erosion, and often considered as a practice for vegetation on slopes (Stokes et al. 2008, Stokes et al. 2013, Lee et al. 2020, Masi et al. 2021). Moreover, the technique is environmental friendly and affordable, with high success rate. Furthermore, the use of handy equipment and various plants makes it cost effective and provides long-term soil stability. Plant materials, especially root profiles, are the most important. Generally, plant roots are strong in tension and weak in compression. On the other hand, soil is strong in compression and weak in tension (Stokes et al. 2013). When roots spread deep into the soil, they cover the soil and act as a composite material which can tightly hold the soil particles in place among the root system, enabling soil masses and stability of slopes (Stokes et al. 2009, Masi et al. 2021).

The proper influence of vegetation and stability of slope depends on the types of plant species, their root system and root architecture (Ji et al. 2012, Wang et al. 2013, Saifuddin & Normaniza 2014a). However, root system and architecture vary considerably across plant species and play a significant role in determining the means by which the roots are reinforced and anchored into the soil (Nicoll et al. 2006, Hodge et al. 2009, Fan & Chen 2010). Root biomass tends to increase soil-root interactions and surface roughness by adding organic substances into the soil. Greenwood et al. (2004) stated that root and shoot biomass influence the soil hydrology by removing excess water through plant canopy transpiration, and increase the factor of safety of a slope via above ground biomass known as surcharge. In addition, root biomass removes water from slopes and consequently enhances soil shear strength (Stokes et al. 2009). Likewise, root systems reinforce soil by transferring shear stress in the soil to tensile resistance in the roots (Fan & Chen 2010). The roots with long tap root can penetrate vertically to prevent soil movements (Loades et al. 2010). Moreover, increases in the number of lateral roots, crossing in the shear plane, reduce soil movement and show high pull-out resistance (Danjon et al. 2008, Normaniza et al. 2011). Additionally, it provides immediate shear strength and modifies the soil water regime by changing the mechanical and hydrological properties of the soils (Saifuddin & Normaniza 2014b). Branched roots are difficult to uproot comparing to those without branches due to the existence of lateral roots in the soil-root composites (Stokes et al. 2013). The presence of tap and dichotomous root pattern in soil can enhance pull-out resistance (Khalilnejad 2013). Therefore, potential plants have been recommended by researchers for quicker resolution and better performance in terms of ecological functions on slopes. Thus, selection of suitable plant species is indeed important for soil reinforcement, slope protection and sustenance. As such, in order to improve the bioengineering application in countries such as Malaysia, this study was carried out to understand the root-soil interactions and reinforcement properties of four selected potential plant species.

Leucaena leucocephala is a fast growing, semi ever green and nitrogen fixing tropical legume tree. It can grow on steep slopes in dry seasons, with outstanding capacity to restore forest cover, watersheds and grasslands (Saifuddin et al. 2015, Saifuddin et al. 2020). Whereas, *A. mangium* has high growth rate in bare soils. This plant can facilitate growth and development of other native trees due to it has ability to maintain temperature, reduce radiation, improve nutrition and increase soil organic matters (Yang et al. 2009). Melastoma malabathricum is a shrub species and is usually found in abandoned areas. It has the potential to remove aluminium ion (Al+) from the soil and its flowering feature enhances the flora-fauna interactions on slopes (Idris 2011). *Dillenia suffruticosa* is a woody shrub species and found in secondary forest. It can grow up to 10 m in length in open lands of moist soil. It has phytoremediation property and can be used as live poles for bioengineering practices. Despite the prominent characteristics of these species, they lack scientific investigations on morphological, engineering and root reinforcement properties. Knowledge of root architecture, tensile strength and morphological characteristics is necessary to select the correct species for slope protection. Therefore, the main objective of this study is to investigate the pull-out resistance, tensile strength and root architecture of these four plants for use in implementing soil reinforcement technique on slopes. The relationship between the pull-out resistance and the root properties was also investigated.

MATERIALS AND METHODS

Plant materials and experimental setup

Two year old native plants namely *L. leucocephala, A. mangium, M. malabathricum* and *D. suffruticosa* were selected to analyse their root properties based on their availability in Malaysia, and their potential physiological and morphological characteristics. To examine the root properties of these species, root traits and pull-out resistance, were investigated along the slopes. The experiment site is located at 30 7' N and 101 39' E at University of Malaya. The key characteristics of these mature plants are provided in Table 1. The soil was collected from the experiment site and subjected to ASTM standards testing to characterise its basic physical properties (D422-63 2007 and D7263-09 2009). As per the grain size distribution curve, the soil is observed as silty sand and its physical properties are provided in Table 2.

Table 1 General characteristic of mature plants, classified by soil characteristics

Species (Scientific name)	Genus	Family	Classification	Height (m) at mature stage	Preferred site (soil pH)
Leucaena leucocephala	*Leucaena*	Mimosoideae	Tree	10–12	Moderate acidic, > 4
Acacia mangium	*Acacia*	Fabaceae	Tree	25–35	Moderate acidic, > 4
Dillenia suffruticosa	*Dillenia*	Dilleniaceae	Shrub	5–10	Moderate acidic, > 4
Melastoma malabathricum	*Melastoma*	Melastomataceae	Shrub	1–2	Severe acidic, < 3

Table 2 Physical properties of slope soil

Properties	Unit
Linear shrinkage	3.23
Specific gravity (unit less)	2.61
Optimum moisture content	13.5%
Maximum dry density	1.85 mg m^{-3}
Type	**Size distribution**
Gravel (2 to 60 mm)	10.0%
Sand (0.06 to 2 mm)	79.5%
Silt (0.002 to 0.06 mm)	7.5%
Clay (< 0.002 mm)	3.0%

Measurements of plant height, leaf area index, pull-out test, root biomass and root tensile test

Measurement tape was used to measure the plant height. Leaf area instrument was used to measure the leaf area index (LAI) of the plants in three replications per species. As per the optical method, at first LAI of plant canopy was calculated by measuring the photosynthetically active radiation (PAR) of above (PAR_a) and below (PAR_b) (Eckrich et al. 2013). Then the ratio of PAR_a to PAR_b was used to calculate the actual LAI using a ceptometer.

A customised lab pull-out machine was executed to conduct the pull-out test. The plant sample was cut at approximately 10 cm above the root crown. Appropriate wedges were chosen, depending on the size of the stem diameter, to ensure that the wedge was able to grip the stem tightly. The dial gauge and vertical displacement load ring were set to zero. Then pull-out test of roots was carried out by implementing force at a constant rate of 2 mm min^{-1} (Normaniza et al. 2011). During the testing, the experimental value was recorded from both dial gauge and load ring at every increment of 50 divisions of vertical displacement, until the root system collapsed. The value of pull-out resistance and root morphological characteristics were calculated for regression analysis.

After executing the pulling-out test, root samples were collected and washed carefully so that the soil was removed and no root biomass was broken down. Root system properties, i.e. tap and lateral root positions, branching patterns and root architecture were examined according to Yen (1987) and Fan and Chen (2010) root models. Overall root architecture was determined considering the three factors: tap root, position of lateral roots and length of total root matrix. Root diameter was measured by vernier slide caliper, and the length of the tap root was measured by metric ruler. Universal testing machine was applied to measure root tensile strength according to ASTM standard procedure (D638-03, 2003). Root sample was cut into 15 cm in length. Then both ends of each root sample were clamped with the testing machine to avoid slippage during testing. The tensile strength testing was conducted for all root samples at 0.5 N load with a constant crosshead speed of 5 mm min^{-1} (Genet et al. 2005). The required force to break the root, and extension at failure point, was automatically generated by the universal testing machine. The ratio of the cross-sectional area of root at broken point and the applied force is considered as tensile strength (Abdi et al. 2010). Root sample was dried at 60 °C for 48 hours, and then the biomass was determined by a digital balance.

Statistical analysis

The SPSS software (version 16) was used to carry out statistical analysis. A one way ANOVA was applied to estimate the significant differences among the mean values. The significant difference ($p < 0.05$), among the obtained values, was evaluated using the Fisher's least significant difference (LSD). Regression analysis and graphical presentation of the figures was prepared by Microsoft Excel program.

RESULTS

The results showed that there were differences in plant height, LAI and root biomass among the studied species. Plant height was significantly ($p < 0.05$) higher for *L. leucocephala*, followed by *A. mangium*, *D. suffruticosa* and *M. malabathricum* (Table 3). The results of LAI (the ratio of leaf area per unit area of land) also showed significant ($p < 0.05$) differences among the studied species. At the 24th month of plant growth, *L. leucocephala* showed a higher LAI than *M. malabathricum*, which was due to the high plant height. Biomass production of all the plant species was measured at the 24th month of plant growth. *Leucaena leucocephala* produced the highest root biomass, followed by *A. mangium* and *D. suffruticosa*, while *M. malabathricum* produced the lowest root biomass. This observation may be attributed to the higher LAI of *L. leucocephala* than other species studied. The above statement was qualified by correlation studies where LAI and root biomass were positively ($R^2 = 0.79$) correlated (Figure 1). The high LAI of plants may be attributed to the large amount of belowground biomass, which was in agreement with the findings of other researchers (Normaniza & Barakabah 2011).

The pull-out resistance varied among the four studied species (Figure 2). *Leucaena leucocephala* showed the highest uprooting resistance, followed by *A. mangium*, *M. malabathricum* and *D. suffruticosa*. The correlations among the pull-out resistances and the plant morphological properties are demonstrated in Table 4. It was observed that

Table 3 Morphological characteristics of two-year old species studied

Species	Height (m)	LAI	Root biomass (g)
Leucaena leucocephala	5.1 ± 0.3^{a}	2.8 ± 0.1^{a}	560 ± 15^{a}
Acacia mangium	5 ± 0.1^{ab}	2.1 ± 0.2^{b}	300 ± 11^{b}
Dillenia suffruticosa	3 ± 0.1^{c}	1.9 ± 0.06^{c}	202 ± 8^{c}
Melastoma malabathricum	1.5 ± 0.05^{d}	1.7 ± 0.1^{cd}	150 ± 5^{d}

Means (± standard error) with different letters within the same column were significantly different ($p < 0.05$); LAI = leaf area index

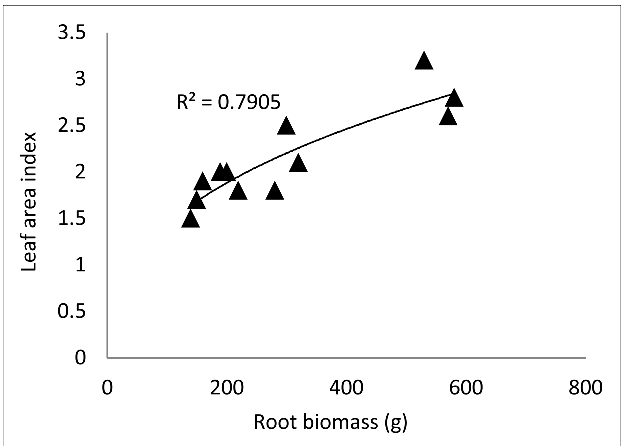


Figure 1 Overall relationship between root biomass and leaf area index (LAI) of four studied species

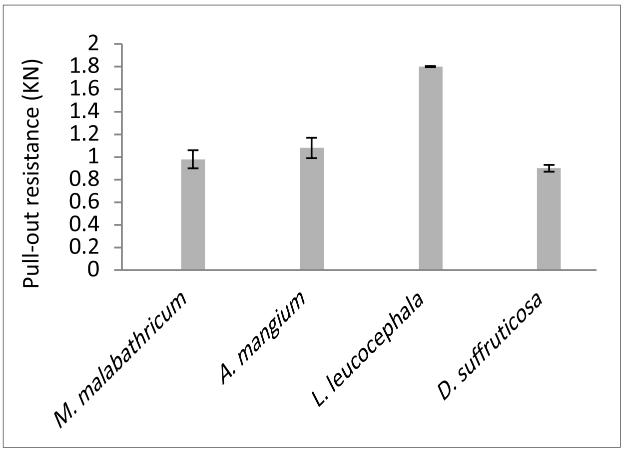


Figure 2 Pull-out resistance (means ± SE) of four studied species

Table 4 Relationship between pull-out resistance and root morphological characteristics

Correlation	Equation	Equation number	R value
Pull-out resistance vs stem diameter (mm)	y = 0.088x - 0.50	1	0.62
Pull-out resistance vs plant height (cm)	y = 0.015x - 0.903	2	0.74
Pull-out resistance vs shoot dry weight (g)	y = 0.004x + 0.566	3	0.50
Pull-out resistance vs number of lateral roots	y = 0.433x - 0.273	4	0.75
Pull-out resistance vs total root length (cm)	y = 77.1x + 107	5	0.83
Pull-out resistance vs root length density (cm m^{-3})	y = 2.65x + 3.7	6	0.77
Pull-out resistance vs deep of rooting (cm)	y = 0.06x + 0.11	7	0.69
Pull-out resistance vs root crown diameter (mm)	y = 0.094x - 0.73	8	0.61

many factors influenced the pull-out resistance (Normaniza & Barakabah 2011). Equation one (1) showed a weak linear relationship (R = 0.62) between pull-out resistance and stem diameter, i.e. the pull-out resistance increased with increasing stem diameter. Likewise, there was a strong linear correlation (R = 0.74) between pull-out resistance and plant height (Equation 2). This was due to the fact that root biomass seemed to depend on plant height. In order to identify the correlation between pull-out resistance and plant shoot dry weight, the test results were plotted, and a weak linear relationship (R = 0.50) was observed in Equation three (3). This weak correlation may be due to the fact that maturity and growth of root were moderately influenced by the development of its shoot (Ali 2010). It has been documented that lateral roots played a very important role in increasing pull-out resistance (Normaniza et al. 2011). In this study, the pull-out resistance strongly correlated (R = 0.75) with the number of lateral roots (Equation 4). In the case of lateral root length, the relationship was strong (R = 0.83) and linear, implying that pull-out resistance is directly depended on root length (Equation 5). Likewise, it was documented that root length density positively influences the pull-out resistance (Ali 2010, Normaniza et al. 2011). Relationship studies showed that there was a strong linear correlation (R = 0.77) between pull-out resistance and root length density (Equation 6). Plant species with well-developed tap rooting system had high pull-out resistance. This is due to the high length of tap rooting system (Ali 2010). Equation seven (7) clarified the variation between pull-out resistance and depth of rooting, and a linear correlation was found where the pull-out resistance increased with increasing depth of rooting. The diameter of root crown was associated with the increment of stem size. Equation eight (8) showed a weak correlation, implying that pull-out resistance increased linearly as the root crown diameter increased.

Root tensile strength was assessed by dividing the applied force on the cross-sectional area of the root near the rupture point (Genet et al. 2005). Root specimens of the four species exhibited variation in tensile strength value. The results showed that *L. leucocephala* exhibited a higher tensile strength than the other three species. Maximum root tensile strength of *L. leucocephala, A. mangium, M. malabathricum* and *D. suffruticosa* were 104.8, 54.3, 29.7 and 47.1 MPa, respectively (Table 5). Additionally, root tensile strength decreased with increasing root diameter, implying that maximum force was influenced by the root diameter (Figure 3). This finding was in line with many previous tensile strength studies (Abdi et al. 2010, Fan & Chen 2010). Thus, the finding implied that *L. leucocephala* has high soil reinforcement potentiality.

Table 5 Tensile strength properties of the studied species

Species	*Leucaena leucocephala*	*Acacia mangium*	*Dillenia suffruticosa*	*Melastoma malabathricum*
No of samples	21 ± 0.2^{a}	36 ± 0.3^{d}	31 ± 0.05^{c}	26 ± 0.15^{b}
Maximum load at failure (N)	1138.04 ± 21^{d}	718.32 ± 10^{c}	670.35 ± 7^{b}	406.05 ± 5^{a}
Maximum tensile strength (N mm^{-2})	104.83 ± 1.5^{d}	54.37 ± 5b^{c}	47.15 ± 2^{b}	29.72 ± 1^{a}
Maximum diameter (mm)	6.21 ± 0.01^{b}	5.98 ± 0.02^{a}	6.64 ± 0.02^{cd}	6.49 ± 0.011^{bc}

Means (± standard error) with different letters within the same column were significantly different ($p < 0.05$)

In this study, the root architecture of the four species was classified according to Yen (1987), as shown in Table 6. A typical distribution of root system provides a general idea on how roots develope, and indicates the localization of lateral and fine roots within the root-soil matrix system (Fu et al. 2010). The majority of root matrix of *L. leucocephala* was found within the first 80 cm of soil depth. There was a strong and deep tap root which was observed at 3 m of soil depth. Few lateral roots were oriented horizontally to the main tap root, and most of the fine roots were surrounded by lateral roots. In the case of *A. mangium*, more than 80% of the root matrix was found within the top 60 cm of soil depth. Most of the roots extended horizontally while lateral roots extented widely. Therefore, according to Yen (1987) root model and Fan & Chen (2010) classification, *L. leucocephala* and *A. mangium* root systems were classified into two different types: vertical horizontal (VH)-type and horizontal (H)-type, respectively. The results related to *L. leucocephala* and *A. mangium* root patterns were in agreement with Normaniza et al. (2011). Whereas, the root systems of *M. malabathricum and D. suffruticosa* exhibited shallow roots, similar to M-type. The 80% of root matrix of *M. malabathricum and D. suffruticosa* was observed within the top 30 cm of soil depth. The main roots grow profusely under the stump or base. Ali (2010) reported that the M-type root is suitable to control surficial erosion of soil. The H-type and VH-type roots are proposed to be beneficial for slope stabilisation and wind resistance (Reubens et al. 2009).

DISCUSSION

In this study, *L. leucocephala* exhibited comparatively higher morphological characteristics than the other three species. A higher plant height and LAI were observed in *L. leucocephala*. A significant increase in root biomass was also observed in *L. leucocephala*, implying that high morphological traits could be involved in production of the root biomass. Nandy et al. (2007) documented that high morphological characteristics may be attributed to the well physiological activities of the leaves, which result in greater competition for light capture and subsequently accelerate the plant growth. Hence the development of root system is influenced by plant growth. Plants which get sufficient nutrients and sunlight will be able to grow and achieve maturity very quickly (Saifuddin & Normaniza 2012). At the same time, they can develop healthy root system to anchor the soil intensely.

It was reported that the morphological characteristics of plants vary significantly among species (Idris 2011). Based on correlation studies, LAI and root biomass were positively correlated, implying that a greater above ground biomass or plant shoots would increase below ground biomass. A high canopy cover may increase the transpiration capacity of plants (Herwitz et al. 2004). Therefore, an increase of root biomass significantly enhances the water uptake from the soil layers and removes them out to the atmosphere via canopy transpiration (Stokes et al. 2009). The major effects of high root biomass and plant canopy, such as LAI, are to enhance

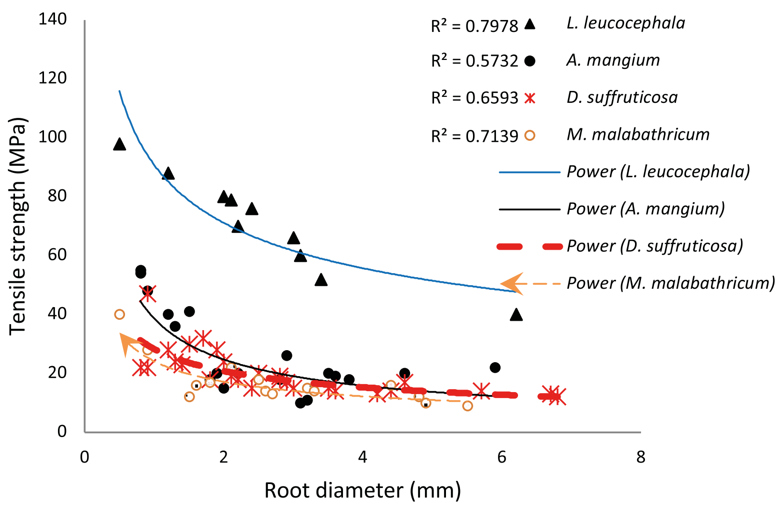
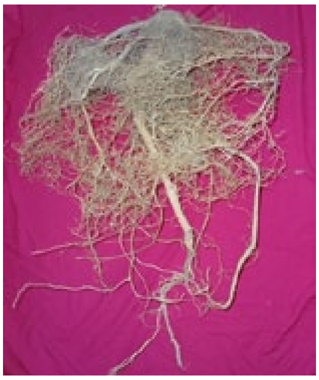
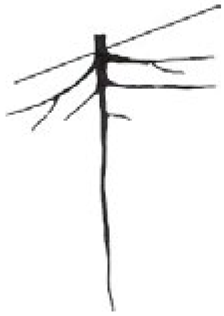
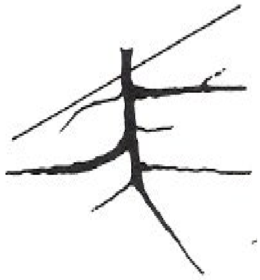
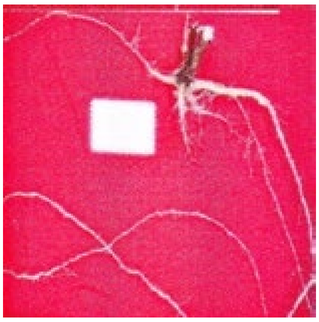
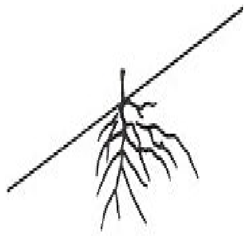
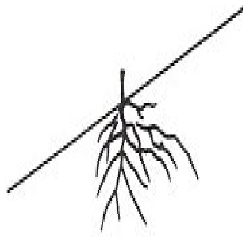


Figure 3 Relationship between root tensile strength and root diameter of four studied species

Table 6 Description of root system and architecture of the studied species

Plant species with root morphology	Root system	Type of root architecture
Leucaena leucocephala • More than 80% of the root matrix found in the top 60 cm • There is a strong tap root but lateral roots grow horizontally and profusely. • Role: slope stabilization and wind resistance		 VH-type
Acacia mangium • 80% of root matrix founds within the top 60 cm • Most of the lateral roots extend horizontally • Role: soil reinforcement, slope stabilization and wind resistance		 H-type
Dillenia suffruticosa • 80% of root matrix founds within the top 30 cm • Lateral root grows profusely • Role: surficial erosion control		 M-type
Melastoma malabathricum • 80% of root matrix founds within the top 30 cm • Main root grows profusely under the stump • Role: surficial erosion control		 M-type

water absorption and reduce soil moisture content through plant canopy (Saifuddin & Normaniza 2014a). Therefore, plant height, LAI and biomass production were likely to exert an influence on soil properties through soil-plant-atmosphere continuum. Moreover, the slope hydrology is affected by vegetation covering; the intensity of rainfall is reduced by the plant canopy or LAI, known as rainfall interception (Joseph et al. 2007). The consequence of these interception processes is prevention of soil displacement and soil erosion. Toriman & Nor (2007) found that in a forest area of Malaysia, interception lost 23.9% of the total rainfall, and rainfall interception varies depending on plant canopy, plant height and types of plants. This study suggested that *L. leucocephala* has potential value for soil reinforcement as it exhibited good plant canopy and root profiles. Root biomass contributed to tree anchorage as well. It was well documented that plants with high root biomass showed more resistance to overturning (Stokes et al. 2009, Normaniza et al. 2011). This characteristic of roots would eventually increase the soil shear strength by producing a composite material which is known as soil-root matrix. Fu et al. (2009) indicated that plant canopy, root biomass and plant growth were important factors to select potential species for soil conservation. Therefore, plant canopy and root biomass are useful tools in selecting potential species for soil reinforcement.

Overall correlations and regression analysis showed that the pull-out resistance of the studied species linearly correlated with its morphological traits. Taller plants resisted uprooting forces better than the shorter ones (Ali 2010). The pull-out resistance of plant was influenced by shoot dry weight; the more development of stem section, the more plant root system is developed (Stokes et al. 2009). The increment of pull-out resistance of plants with extensive lateral roots was due to the fact that strong soil-root interaction increased by the presence of additional lateral roots (Hodge et al. 2009, Khalilnejad 2013). Positive relationship between pull-out resistance and depth of rooting was also observed. Tree species, *L. leucocephala* and *A. mangium* exhibited higher uprooting resistance than shrub species, *M. malabathricum* and *D. suffruticosa.* Overall correlation analysis showed that pull-out resistance depended on several morphological traits such as plant height, stem diameter, lateral root length and root length density. Pull-out resistance strongly correlates with four important traits: plant height, number of lateral roots, lateral root length and root length density (Normaniza et al. 2011, Khalilnejad 2013).

The contribution of root tensile strength in governing slope stabilisation has been well documented, and the root reinforcement capacity is dependent on the degree of root tensile strength (Baets et al. 2008, Abdi et al. 2010). Thus, total anchorage or soil reinforcement by root is related to individual root tensile strength. However, root tensile strength varries with plant species, diameter, age and soil nutrient (Comino & Marengo 2010). Root tensile strength also depends on environment, season, altitude and root orientation (Gray & Sotir 1996). It was well documented that the root tensile strength decreased with the increase of root diameter (Saifuddin & Normaniza 2012, Zhang et al. 2013). This is because smaller diameter roots possess higher cellulose per unit area, than larger diameter roots (Genet et al. 2005). Therefore, the mechanical strength of individual root and their interaction with soil is controlled by individual root tensile strength. Between the shrub species, *M. malabathricum* produced relatively high root biomass and tensile strength. Between the trees, *L. leucocephala* was more prominent to play a major mechanical role on soil, and its high root tensile strength could ultimately enhance soil reinforcement.

Fan & Chen (2010) documented that the reinforcement capacity of plants depends on the root profiles, as their root architecture vary with species. The type of roots and root architecture play a significant role in controlling the way root reinforce and anchor the soil (Greenwood et al. 2004). Roots with multiple branches generally anchore large volume of soil and show maximal resistance to pull-out, than roots with fewer branches (Hodge et al. 2009, Ji et al. 2012). The VH- and H-type roots were found to be suitable for soil reinforcement, slope protection and wind resistance. The M-type root architecture was less effective in reinforcing soil than VH- and H-type roots (Thomas & Pollen-Bankhead 2010). In respect to soil reinforcement, *L. leucocephala* and *A. mangium* had maximum impacts on soil due to deep rooting, followed by *D. suffruticosa and M. malabathricum.* Stokes et al. (2009) reported that shrub species can be planted on newly cut and engineered slopes to control soil erosion. It is also documented that fine roots of all types of plant communities (shrubs and trees) bind the soil in place strongly, than thick roots. As a result, fine roots contribute mostly in reducing soil erosion and increase topsoil stability (Pierret et al. 2007). The average root depth of *M. malabathricum and D. suffruticosa* is located mostly in the surface (< 30 cm depth). The development of their roots and association with soil-root matrix will help to tie the ground soil particles together and reduce surficial erosion (Stokes et al. 2013). Thus, based on the extensive root characteristics and type of roots, *L. leucocephala* and *A. mangium* were recommended to be the most appropriate for soil reinforcement, and *M. malabathricum and D. suffruticosa* were suggested to be the most suitable to prevent surficial erosion.

CONCLUSIONS

The current study assessed potential plants with impact to implement soil bioengineering and reinforcement techniques. Pull-out resistance, tensile strength and root architecture were assessed in order to quantify the soil mechanical reinforcement. The pull-out resistance was observed to be affected by the roots rather than the shoot profiles. It was discovered that root architecture of *L. leucocephala* and *A. mangium* was VH- and H-type, respectively and recommended for soil reinforcement. *Dillenia suffruticosa and M. Malabathricum* showed M type roots, suggested for controlling soil erosion. It was found that *L. leucocephala* produced relatively high root biomass, tensile strength and pull-out resistance. Thus, this study suggests that *L. leucocephala* has an added value as a good potential slope plant for soil reinforcement, as it exhibited VH-type rooting with outstanding root profiles.

ACKNOWLEDGEMENTS

This study was funded by the University of Malaya Research Grant (UMRG-PV052-2011A).

REFERENCES

Abdi E, Majnounian B, Genet M. et al. 2010. Quantifying the effects of root reinforcement of Persian Ironwood (*Parrotia persica*) on slope stability; a case study: Hill slope of Hyrcanian forests, northern Iran. *Ecological Engineering* 36: 1409–1416. https://doi.org/10.1016/j.ecoleng.2010.06.020.

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

ASTM (American Society of Testing and Materials) D638-03. 2003. *Standard Test Method for Tensile Properties of Plastics*. ASTM International, West Conshohocken, PA. https://www.astm.org/Standards/D638.

ASTM (American Society of testing and Materials) D422-63. 2007. *Standard Test Method for Particle-Size Analysis of Soils*. ASTM International, West Conshohocken, PA. https://www.astm.org/Standards/D422.

ASTM (American Society of testing and Materials) D7263-09. 2009. *Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens*. ASTM International, West Conshohocken, PA. https://www.astm.org/Standards/D7263.

Baets DS, Poesen J, Reubens B, Wemans K, De-Baerdemaeker J & MUYS B. 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant Soil* 305: 207–226. https://doi.org/10.1007/s11104-008-9553-0.

Comino E & Marengo P. 2010. Root tensile strength of three shrub species, *Rosa canina, Cotoneaster dammeri* and *Juniperus horizontalis*: soil reinforcement estimation by laboratory tests. *Catena* 82: 227–235. https://doi.org/10.1016/j.catena.2010.06.010.

Danjon F, Barker DH, Drexhage M & Stokes A. 2008. Using three-dimensional plant root architecture in models of shallow-slope stability. *Annals of Botany* 101: 1281–1293. https://doi.org/10.1093/aob/mcm199.

Eckrich CA, Flaherty EA & Ben-David M. 2013. Estimating leaf area index in southeast Alaska: a comparison of two techniques. *PloS one* 8: e77642. https://doi.org/10.1371/journal.pone.0077642.

Fan CC & Chen YW. 2010. The effect of root architecture on the shearing resistance of root-permeated soils. *Ecological Engineering* 36: 813–826. https://doi.org/10.1016/j.ecoleng.2010.03.003.

Fu D, Duan C, Hou X, Xia T & Gao K. 2009. Patterns and relationships of plant traits, community structural attributes, and eco-hydrological functions during a subtropical secondary succession in central Yunnan (southwest China). *Archives of Biological Science Belgrade* 61: 741–749. https://doi.org/10.2298/ABS0904741F.

Genet M, Stokes A, Salin F, Mickovski SB, Fourcaud T, Dumail JF & Van-Beek R. 2005. The influence of cellulose content on tensile strength in tree roots. *Plant Soil* 278: 1–9. https://doi.org/10.1007/s11104-005-8768-6.

Gray DH & Sotir RB. 1996. *Biotechnical and Soil Bioengineering Slope Stabilization*. John Wiley and Sons Incorporation. New York.

Greenwood J, Norris J & Wint J. 2004. Assessing the contribution of vegetation to slope stability. *Proceedings of the Institution of Civil Engineers* 157: 199–207.

Herwitz SR, Levia DF & Ewe SML. 2004. Transpiration rates of the understory annual *Impatiens capensis* (Balsaminaceae) in response to the autumnal changes in canopy leaf area. Flora-Morphology, Distribution. *Functional Ecology of Plants* 199: 524–530. https://doi.org/10.1078/0367-2530-00181.

Hodge A, Berta G, Doussan C, Merchan F & Crespi M. 2009. Plant root growth, architecture and function. *Plant Soil* 321: 153–187. https://doi.org/10.1007/s11104-009-9929-9.

Idris RM. 2011. Rehabilitation of acidic soil using potential slope plants. MSc thesis, University of Malaya, Kuala Lumpur.

Ji J, Kokutse N, Genet M, Fourcaud T & Zhang Z. 2012. Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (*Robinia pseudoacacia*) and Arborvitae (*Platycladus orientalis*) stands on the Loess Plateau, China. *Catena* 92: 139–154. https://doi.org/10.1016/j.catena.2011.12.008.

Joseph AK, Ahuja RL, Green RT & Ma L. 2007. Modelling crop canopy and residue rainfall interception effects on soil hydrological components for semi-arid agriculture. *Hydrological Processes* 21: 229–241. https://doi.org/10.1002/hyp.6235.

Khalilnejad A. 2013. Numerical simulation and experimental study of root anchorage. PhD thesis. Department of

Civil Engineering, University of Malaya, Kuala Lumpur. http://studentsrepo.um.edu.my/id/eprint/8796.

Komoo I, Aziz S & Sian LC. 2011. Incorporating the Hyogo Framework for Action into landslide disaster risk reduction in Malaysia. *Bulletin of the Geological Society of Malaysia* 57: 7–11. https://doi.org/10.7186/bgsm57201102.

Lee JT, Chu MY, Lin YS, Kung KN, Lin WC & Lee MJ. 2020. Root traits and biomechanical properties of three tropical pioneer tree species for forest restoration in landslide areas. *Forests* 11: 179. https://doi.org/10.3390/f11020179.

Loades KW, Bengough AG, Bransby MF & Hallett PD. 2010. Planting density influence on fibrous root reinforcement of soils. *Ecological Engineering* 36: 276–284. https://doi.org/10.1016/j.ecoleng.2009.02.005.

Masi Eb, Segoni S & Tofani V. 2021. Root reinforcement in slope stability models: a review. Geosciences 11: 212. https://doi.org/10.3390/geosciences11050212.

Mizal-Azzmi N, Mohd-Noor N & Jamaludin N. 2011. Geotechnical approaches for slope stabilization in residential area. *Procedia Engineering* 20: 474–482. https://doi.org/10.1016/j.proeng.2011.11.190.

Mugagga F, Kakembo V & Buyinza M. 2012. A characterisation of the physical properties of soil and the implications for landslide occurrence on the slopes of Mount Elgon, Eastern Uganda. *Natural Hazards* 60: 1113–1131. https://doi.org/10.1007/s11069-011-9896-3.

Nandy P, Das S, Ghose M & Spooner-Hart R. 2007. Effects of salinity on photosynthesis, leaf anatomy, ion accumulation and photosynthetic nitrogen use efficiency in five Indian mangroves. *Wetlands Ecology and Management* 15: 347–357. https://doi.org/10.1007/s11273-007-9036-8.

Nicoll B, Berthier S, Achim A, Gouskou K, Danjon F & Van-Beek L. 2006. The architecture of *Picea sitchensis* structural root systems on horizontal and sloping terrain. *Trees-Structure and Function* 20: 701–712. mhttps://doi.org/10.1007/s00468-006-0085-z.

Normaniza O & Barakabah SS. 2011. The effect of plant succession on slope stability. *Ecological Engineering* 37: 139–147. https://doi.org/10.1016/j.ecoleng.2010.08.002.

Normaniza O, Abdullah Mn & Abdullah CH. 2011. Pull-out and tensile strength properties of two selected tropical trees. *Sains Malaysiana* 40: 577–585. http://eprints.um.edu.my/id/eprint/6268.

Pierret A, Latchackak K, Chathanvongsa P, Sengtah-Euanghoung O & Valentin C. 2007. Interactions between root growth, slope and soil detachment depending on land use: a case study in a small mountain catchment of Northern Laos. *Plant Soil* 301: 51–64. https://doi.org/10.1007/s11104-007-9413-3.

Pradhan B. 2013. A comparative study on the predictive ability of the decision tree, support vector machine and neuro-fuzzy models in landslide susceptibility mapping using GIS. *Computers and Geosciences* 51: 350–365. https://doi.org/10.1016/j.cageo.2012.08.023.

Reubens B. et al. 2009. The effect of mechanical stimulation on root and shoot development of young containerised *Quercus robur* and *Robinia pseudoacacia* trees. *Trees-Structure and Function* 23: 1213–1228. https://doi.org/10.1007/s00468-009-0360-x.

Saifuddin M, Normaniza O & Khandaker MM. 2020. Carbon sink and bio-chemical potentiality of two legume tree species. *Journal of Tropical Forest Science* 32: 217–226. https://www.jstor.org/stable/26921869.

Saifuddin M, Normaniza O, Rahman MM & Amru NB. 2015. Soil reinforcement capability of two legume species from plant morphological traits and mechanical properties. *Current Science* 108: 1340–1347. https://www.jstor.org/stable/24905497.

Saifuddin M & Normaniza O. 2014a. Evaluation of hydro-mechanical properties and root architecture of plants for soil reinforcement. *Current Science* 107: 845–852. https://www.jstor.org/stable/2410558.

Saifuddin M & Normaniza O. 2014b. Hydrological and mechanical properties of plants to predict suitable legume species for reinforcing soil. *Chinese Science Bulletin* 59: 5123–5128. https://doi.org/10.1007/s11434-014-0391-6.

Saifuddin M & Normaniza O. 2012. Physiological and root profile studies of four legume tree species. *Life Science Journal* 9: 1509–1518. http://www.lifesciencesite.com/lsj/life0904/229_11970life0904_1509_1518.pdf.

Song YS, Hong WP & Woo KS. 2012. Behavior and analysis of stabilizing piles installed in a cut slope during heavy rainfall. *Engineering Geology* 129–130: 56–67. https://doi.org/10.1016/j.enggeo.2012.01.012.

Stokes A, Atger C, Bengough A, Fourcaud T & Sidle R. 2009. Desirable plant root traits for protecting natural and engineered slopes against landslides. *Plant Soil* 324: 1–30. https://doi.org/10.1007/s11104-009-0159-y.

Stokes A, Norris JE, Beek LPH et al. 2008. How vegetation reinforces soil on slopes. Pp 65–118 in Norris JE (ed) *Slope Stability and Erosion Control: Ecotechnological Solutions*. Springer, The Netherlands. https://doi.org/DOI: 10.1007/978-1-4020-6676-4_4.

Stokes A, Raymond P, Polster D & Mitchell SJ. 2013. Engineering the ecological mitigation of hillslope stability research into the scientific literature. *Ecological Engineering* 61P: 615–620. https://doi.org/10.1016/j.ecoleng.2013.07.065.

Thomas RE & Pollen-Bankhead N. 2010. Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation. *Ecological Engineering* 36: 47–61. https://doi.org/10.1016/j.ecoleng.2009.09.008.

Toriman ME & Nor SM. 2007. An analysis of rainfall interception on the selected experimental plot of Pangkor Hill Reserved Forest. *Journal Wildlife and Parks* 22: 169–178.

Tu XB, Kwong AKL, Dai FC, Tham LG & Min H. 2009. Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. *Engineering Geology* 105: 134–150. https://doi.org/10.1016/j.enggeo.2008.11.011.

Wang N, Jiao JY, Du HD, Wang DL, Jia YF & Chen Y. 2013. The role of local species pool, soil seed bank and seedling pool in natural vegetation restoration on abandoned slope land. *Ecological Engineering* 52: 28–36. https://doi.org/10.1016/j.ecoleng.2012.12.055.

Yang L, Liu N, Ren H & Wang J. 2009. Facilitation by two exotic *Acacia*: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. *Forest Ecology & Management* 257: 1786–1793. https://doi.org/10.1016/j.foreco.2009.01.033.

Yen CP. 1987. Tree root patterns and erosion control. Pp 92–111 in Jantawat S (ed) *Proceedings of The International Workshop on Soil Erosion and Its Countermeasures*. Soil and Water Conservation Society of Thailand, Bangkok.

Zhang SY, Fei BH, Yu Y, Cheng HT & Wang CG. 2013. Effect of the amount of lignin on tensile properties of single wood fibers. *Forest Science and Practice* 15: 56–60. https://doi.org/10.1007/s11632-013-0106-0.