ROOTING CHARACTERISTICS OF SOME TROPICAL PLANTS FOR SLOPE PROTECTION

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SAIFUDDIN M & NORMANIZA O. 2016. Rooting characteristics of some tropical plants for slope protection. The examination of root architecture and mechanical properties of tropical plants are limited. Thus, this study was aimed at investigating root architectural and mechanical properties of seven tropical plants. Based on root growth pattern, it was observed that *Leucaena leucocephala* and *Pterocar pusindicus* had taproots and their lateral roots grew horizontally and profusely. Therefore, the root systems of *L. leucocephala* and *P. indicus* were categorised as VH-type and the trees were recommended for planting in the middle of the slope. *Peltophorum pterocarpum* and *Acacia mangium* exhibited R- and H-types root systems respectively and were also recommended for planting in the middle of the slope. *Melastoma malabathricum*, *Dillenia suffruticosa* and *Lantana camara* possessed shallow roots. Their root systems were more similar to the M-type and these plants were suggested for planting at the top or toe of the slope. Leaf area index and root biomass of the species were positively correlated ($r^2 = 0.90$). Tensile strength decreased with increasing root diameter, implying that lower root diameter contributed to the higher tensile strength. Different plants have different types of root architecture and tensile strength. These rooting characteristics can be used as important factors in selecting potential plants for slope stability.

Keywords Root architecture, root tensile strength, root biomass, leaf area index, slope stability

INTRODUCTION

In Malaysia, in the last two decades, hillsides and vast areas of forest have been rapidly transformed into development land including for highways and other transport systems (Komoo et al. 2011). Changes in landuse have inevitably involved removing of vegetation cover and cutting of hill slopes which affect soil properties and environment. High intensity and more frequent rainstorms, lack of suitable species on hilly areas and conventional planting technique such as monoculture hydroseeded grasses have been acknowledged as causes for frequent landslides (Mafian et al. 2009, Huat et al. 2011, Song et al. 2012). Reinforcement of soil using ecofriendly approach is highly promising to decrease superficial landslide risk and erosion (Evette et al. 2009, Huat et al. 2011). Thus, vegetation on slope is recommended to reinforce soil of the slope (Mafian et al. 2009, Huat et al. 2011, Aradottir & Hagen 2013). Vegetation and slope stability are interrelated and determined by the ability of the plants to grow on slopes and the interaction of their roots with the soil. Vegetation stabilises the slope by increasing the cohesion factor of soil and removing water on the soil through canopy transpiration which result in low pore water pressure and reduce weight of soil mass (Normaniza & Barakbah 2006, Normaniza et al. 2014).

Root systems mechanically reinforce soil by improving soil shear strength and residual strength (Reubens et al. 2007). Root distribution, density and patterns have close relationships with soil shear strength. Plant roots provide anchorage, fix soil on slopes and retard runoff velocity along the slope surface. Total anchorage or soil reinforcement by root is related to individual root tensile strength which varies with plant species, diameter, age, soil nutrient, soil moisture and cellulose content in roots (De Baets et al. 2008, Comino & Marengo 2010). Proper use of vegetation in stabilising slope shows numerous advantages such as low cost in maintenance, environment-friendly and high biodiversity (Mulia & Prasetyorini 2013).

Plant communities are divided into four categories, namely, grass, herbs, shrub and tree. Their functions and contribution on slope are different as they have different types of rooting systems. The most well-documented and accepted root systems were proposed by Yen (1987) based on the tap, lateral and horizontal roots. According to the author, root systems are categorised into five types, namely, H, R, V, VH and M. Soil reinforcement capacity of plants depends on root profiles as root architecture vary with species (Thomas & Pollen-Bankhead 2010). The type of root, root length and root branching patterns play significant roles in controlling the way root reinforce and anchor soil (Greenwood et al. 2004). Roots with multiple branches generally anchor large volumes of soil and show maximal resistance to pullout from the ground than roots which have no or less branches. Types of soil also influence the resistance of uprooting while distribution of roots varies with nutrient level of soil. In addition, different plant species can perform different functional roles on slope but certain types of plants are better than others in terms of soil reinforcement and surface protection (Coppin & Richards 1990). The H- and VH-root types have been found to be suitable for soil reinforcement, slope protection and wind resistance. The M-type is beneficial in controlling soil erosion and the V-type is suitable for wind resistant (Reubens et al. 2007). R-type root architecture is favourable in protecting slope from failure. The V-type root architecture is less effective in improving soil shear strength compared with R-type root (Fan & Chen 2010). Therefore, selection of root architecture and suitable plant species are indeed important for soil reinforcement, slope protection and sustainability (Zuazo & Pleguezuelo 2009). However, there is lack of documentation on native plants which can meet the potential slope plant characteristics to reinforce soil. To determine the plant species, we assessed root architectural and mechanical traits of plants growing along a degraded slope at Universiti Malaya, Kuala Lumpur, Malaysia. The main objective of this study was to investigate the root architecture and tensile strength of selected plants for slope protection and rehabilitation. We investigated how plants can be used as ecological engineers through better understanding of architectural and mechanical traits of their root systems. Knowledge of root architecture and root morphological characteristics is necessary in selecting the appropriate species for slope protection.

MATERIALS AND METHODS

Study sites and species

This survey was carried out at Universiti Malaya (3° 7' N, 101° 39' E). The species (stem diameter, 25–30 mm) selected in the present study were *Leucaena leucocephala, Peltophorum pterocarpum, Pterocarpus indicus, Acacia mangium, Melastoma malabathricum, Dillenia suffruticosa* and *Lantana camara*. These four trees and three shrubs species were chosen based on their potential physiological and morphological characteristics. They were about 2 years old at the time of the study. These species are abundant in the tropics and have good growing capacity on slopes. The general characteristics of these mature plants are summarised in Table 1 (Normaniza et al. 2014).

Leucaena leucocephala (local name *ipil-ipil*) is one of the most productive fast-growing, semi-evergreen and nitrogen-fixing tropical legume tree. It thrives on steep slopes and in marginal areas with extended dry seasons, making it a prime candidate for restoring forest cover, watersheds and grasslands (Normaniza & Barakbah 2006, Normaniza et al. 2014). *Peltophorum pterocarpum* is a woody ornamental plant and has extensive root system (Saifuddin & Normaniza 2014). This tree is usually planted on roadsides and in gardens and parks and is normally found in well-drained and sandy to clay loams soil (Saifuddin & Normaniza 2012). It has high atmospheric nitrogen-fixing potential (Lok 2011). Due to its high wood quality, this species is an excellent source of timber and wood material. *Acacia mangium* has high tolerance and growth rates on bare soils. This plant can facilitate growth and development of native trees due to its great ability to buffer temperature, reduce radiation, improve nutrition and increase soil organic matter (Yang et al. 2009). *Melastoma malabathricum* is a shrub species found in abandoned area. It has potential to remove aluminium ion from soil and its flowering feature

Table 1 General characteristics of plants studied

Species	Family	Classification	Height at mature stage (m)	Soil pH
Leucaena leucocephala	Mimosoideae	Tree	10–12	> 4, moderately acidic
Peltophorum pterocarpum	Fabaceae	Tree	15–25	5–8, moderately acidic to moderately alkaline
Pterocarpus indicus	Fabaceae	Tree	30–40	4.0–7.4, acidic to neutral
Acacia mangium	Fabaceae	Tree	25–35	> 4, moderately acidic
Dillenia suffruticosa	Dilleniaceae	Shrub	5–10	> 4, moderately acidic
Melastoma malabathricum	Melastomataceae	Shrub	1–2	< 3, severely acidic
Lantana camara	Verbenaceae	Shrub	0.5–2	< 6.5, slightly acidic soil

can help to enhance the flora–fauna interaction of slopes (Idris 2011). *Dillenia suffruticosa*, native to East Asia, is a woody shrub and generally found in secondary forest. It can grow up to 10 m tall in open lands on moist soil. It has phytoremediation properties (Rahim et al. 2011) and can be used as live poles for bioengineering practices (Mafian et al. 2009). *Lantana camara* is an ornamental shrub native to the American tropics. It is very invasive and has profound effects on biodiversity (Bhagwat et al. 2012). Despite the prominent characteristics of these species, there was lack of scientific reports on their root architecture and tensile strength properties that could be used to enhance soil reinforcement.

Soil physical properties

Soil was collected from the investigated site and subjected to standard tests to determine its basic physical properties (ASTM 2007, 2009). Based on the grain size distribution curve, the soil is described as silty sand and its physical properties are shown in Table 2.

Measurement of plant height, root biomass and leaf area index

Plant height was measured using measuring tape. Roots were oven dried at 80 °C for 48 hours and weighed. Leaf area index was determined using leaf area instrument with three replications. Based on the optical method, leaf area index was calculated by measuring photosynthetically active radiation (PAR) of above (PAR_a) and below (PAR_b) plant canopy (Eckrich et al. 2013). The ratio of PAR_a to PAR_b was used to calculate leaf area index by inverting the equation for predicting scattered and transmitted PAR using a set of ceptometers.

Assessment of root architecture and profiles

After pulling out the plant, root samples were washed manually in the laboratory to remove adhering soil and dirt. Root architecture and root order of the tap and lateral roots were examined and root growth pattern was determined based on root branching pattern or architecture of

Table 2 Physical properties of slope soil

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

the species (Yen 1987). Fine roots of the species studied were determined using WinRHIZO Pro program (version 2008a). Four replications were used for these measurements.

Assessment of root diameter and tensile strength

Root diameter was measured using vernier slide callipers. Root tensile strength was determined using universal testing machine (ASTM 2003). Roots were cut into 15 cm in length and each end of the root was clamped with sand paper to avoid slippage during testing. Tensile tests were performed on all specimens within initial load of 0.5 N and constant crosshead speed of 5 mm min^{-1}. Data on force and extension at failure were automatically generated by the software connected to the universal testing machine. The applied force required to break the root was taken as the measure of root strength. Tensile strength was calculated by dividing the applied force by the cross-sectional area of the root at its rupture point (Abdi et al. 2010).

Statistical analysis

Statistical analysis was carried out using SPSS software (version 16). One-way ANOVA was applied to evaluate significant difference between means. Significant ($p < 0.05$) difference between means was compared using Fisher's least significant difference. Microsoft Excel was used for regression analysis and graphical presentation.

RESULTS AND DISCUSSION

Morphological roles

There was significant difference in morphological parameters between the species studied (Table 3). *Pterocarpus indicus* had the greatest plant height and root biomass while *L. camara*, being a shrub, was the lowest. High root biomass increases soil–root interaction and absorbs huge amount of water which ultimately reduces soil water content (Saifuddin & Normaniza 2014). At two years old**,** leaf area indices of trees were higher than that of shrubs. There was strong positive correlation ($r^2 = 0.90$) between leaf area index and root biomass (Figure 1). A promising leaf area index reflects good photosynthesis of carbon source (e.g. leaf) and also carbon supply to different compartments of a plant including root system (carbon sink), hence root biomass is increased. Biosysthesis of the root component (mainly cellulose) which depends largely on carbon supply will enhance root mechanical resistance, i.e. a positive shoot–root interaction (Genet et al. 2005).

From hydrological aspect, high root biomass and leaf area index can reduce soil water content through water absorption and canopy transpiration respectively (Herwitz et al. 2004). Soil hydrology and rainfall intensity of slopes are affected by plant morphology such as plant height, root biomass and canopy size (Stokes et al. 2009). Plants intercept a proportion of incoming rainfall and part of it is returned to the atmosphere by evaporation and flow down via leaves, stem and bark (Guevara-Escobar et al. 2007, Joseph et al. 2007). This interception prevents soil displacement and reduces soil erosion. In Malaysia, 23.9% of total rainfall in the forest is lost via interception (Toriman & Nor 2007). Therefore, plant canopy and biomass production influence soil hydrology through soil–plant–atmosphere continuum (Manzoni et al. 2013). Canopy size, plant biomass and plant height are important factors for selecting species to enhance soil reinforcement (Fu et al. 2009). Root with higher biomass provides greater anchorage to plants because it entangles and holds more soil volume (Stokes et al. 2009). In addition, tree anchorage strength can be predicted by identifying root architecture and tensile strength (Reubens et al. 2007, Comino & Marengo 2010). Thus, besides root biomass, knowledge related to root architecture and tensile strength will assist in selection of suitable plant species for reinforcing soil.

Root architecture and distribution

In this study, root architecture of the seven species are shown in Figure 2. The typical distribution of root system provided a general idea of how roots developed and indicated the localisation of lateral and fine roots within the root system. The majority of root matrix of *L. leucocephala* was found within the first 80 cm of soil depth. There

Table 3 Morphological characteristics of the seven species studied

Species	Height (m)	Leaf area index	Root biomass (g)
Leucaena leucocephala	5.1 ± 0.3 ab	2.8 ± 0.1 abc	560 ± 15 b
Peltophorum pterocarpum	4.4 ± 0.2 d	3.0 ± 0.1 a	576 ± 12 bc
Pterocarpus indicus	5.5 ± 0.1 a	2.8 ± 0.1 ab	606 ± 7 a
Acacia mangium	5.0 ± 0.1 abc	2.1 ± 0.2 d	300 ± 11 d
Dillenia suffruticosa	3.0 ± 0.1 e	1.9 ± 0.1 e	202 ± 8 e
Melastoma malabathricum	1.5± 0.1 f	1.7 ± 0.1 f	150 ± 5 f
Lantana camara	0.5 ± 0.08 g	0.9 ± 0.1 g	45 ± 4 g

Values with similar alphabets in the same column are not significantly different

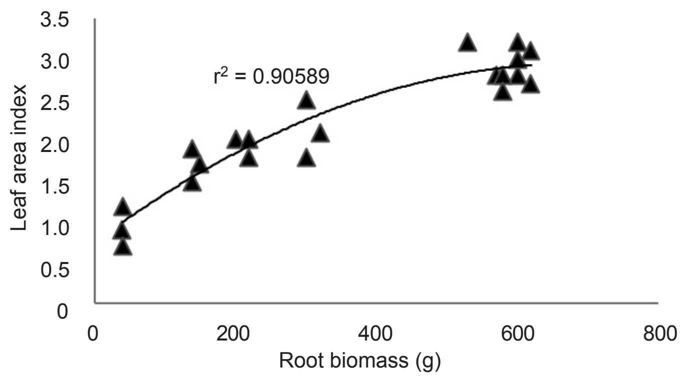

Figure 1 Correlation between root biomass and leaf area index

was strong and deep taproot at 3 m of soil depth. Few lateral roots were oriented horizontally to the main taproot and most of the fine roots were surrounded by lateral roots. On the other hand, lateral roots in *P. pterocarpum* dominated its total root structure. Most of the lateral roots were initiated and extended obliquely from the main vertical roots. The lateral roots were also widely spread in various orientations and were longer than those of *L. leucocephala*. This root system is considered to be an effective branching pattern in providing shear strength to the soil (Fan & Chen 2010). Root branching pattern of *P. indicus* exhibited strong tap root and its lateral roots grew horizontally and profusely. About 80% of its root matrix was found within the top 60 cm of soil depth. This type of root has three roles in slope stabilisation, namely, soil reinforcement, slope stability and wind resistance (Yen 1987).

More than 80% of the root matrix of *A. mangium* was found within the top 60 cm of soil depth. Most of the roots extended horizontally and lateral root extended widely. Therefore, following the classification by Yen (1987), *L. leucocephala*, *P. pterocarpum*, *P. indicus* and *A. mangium* root systems were classified into three different types: VH-, R-, VH - and H-types respectively. These root patterns are in agreement with findings by Nordin et al. (2011). However, Fan and Chen (2010) observed R-type root system in *L. leucocephala*, perhaps due to different soil type. Being shrubby trees, root systems of *M. malabathricum*, *D. suffruticosa* and *L. camara* exhibited shallow roots more similar to M-type. About 80% of the root matrices of *M. malabathricum* and *D. suffruticosa* were observed within the top 30 cm soil depth, while *L. camara*, within 20 cm. Their main roots grew profusely massive under the stump or base. M-type root is suitable for controlling surficial erosion (Ali 2010) whereas, H- and VH-types root are beneficial for slope stabilisation and wind resistance (Reubens et al. 2007). R-type root is considered to be the most effective root system against shear failure (Fan & Chen 2010).

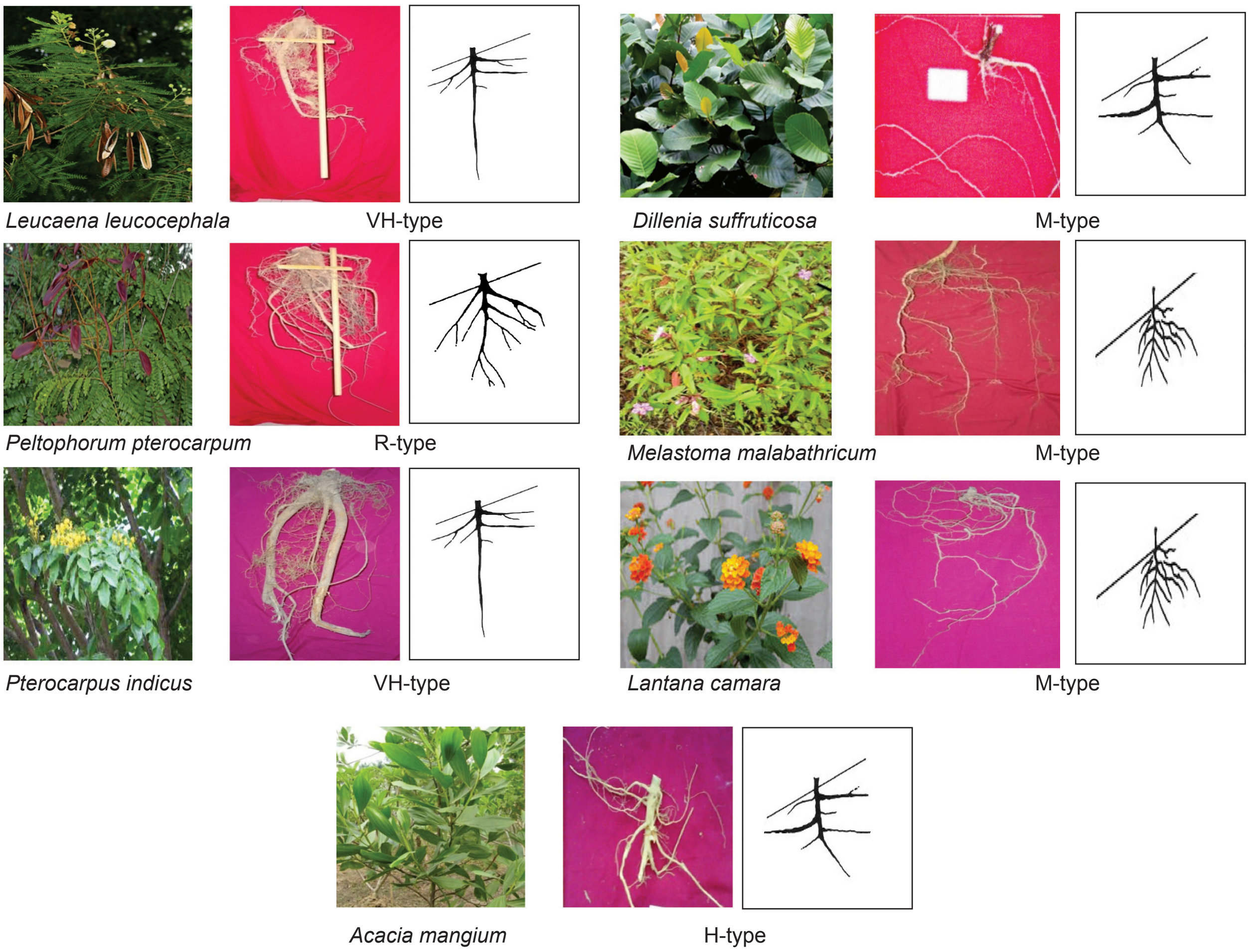

Figure 2 Plant species studied and their root systems and architecture

Root tensile strength

Mechanical contribution of plants depends on root tensile strength. In this study, root tensile strength increased with decreasing root diameter in all species studied and roots with smaller diameters were the most resistant to tension (Figure 3). *Leucaena leucocephala* had the highest root tensile strength followed by *P. pterocarpum*, *P. indicus*, *A. mangium*, *D. suffruticosa*, *M. malabathricum* and *L. camara*. The thin roots of *L. leucocephala* increase soil–root interaction and soil shear strength in a natural slope (Ali 2010, Nordin et al. 2011). Root tensile strength also contributed to tree anchorage. Trees that possess high root tensile strength will be more resistant to overturning (Comino & Marengo 2010). Thus, *L. leucocephala* roots have higher capacity to serve as soil–root composite material and will be able to exhibit better resistance to slope failure during tension compared with the rest of the species studied.

Root reinforcement properties and the most effective position on slope

Generally, plant roots are strong in tension and weak in compression while soil is strong in compression and weak in tension. When, plant roots penetrate into soil, the soil will act as composite material and tightly hold its particles between roots (Stokes et al. 2009, Saifuddin et al. 2013). To strengthen slope against landslides, plant roots need to intercept the potential shear failure zone so that roots can tie ground or soil surface and failure plane together (Ghestem et al. 2014). Potential shear plane of natural slope can be circular or parallel to the soil surface

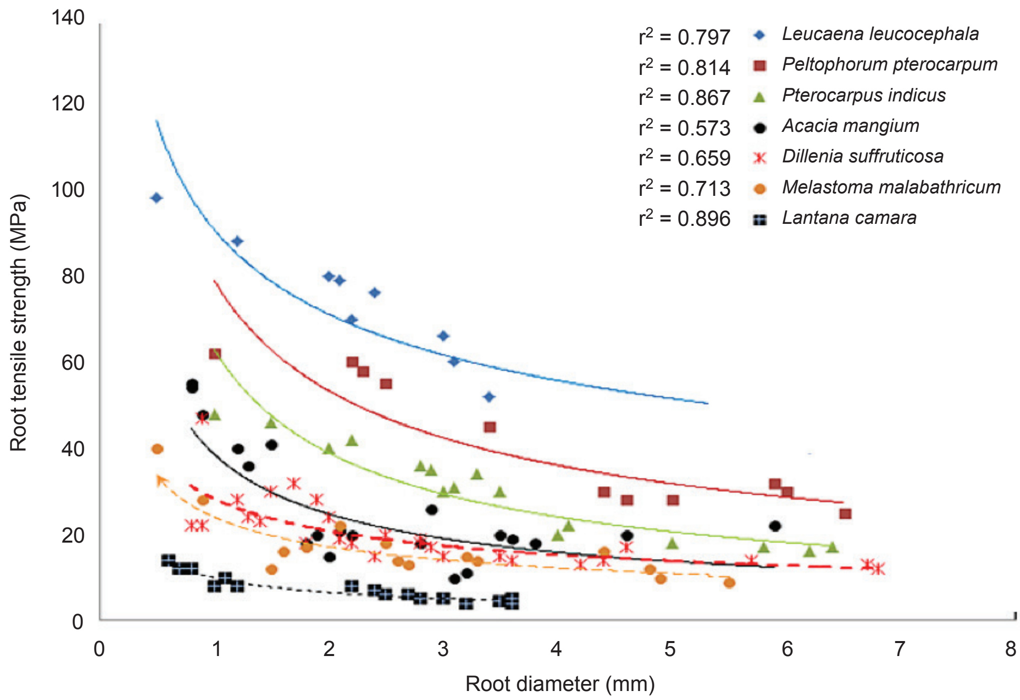

Figure 3 Relationship between root tensile strength and root diameter

(Figure 4). In the cut slope, potential shear failure line is most likely to be circular at a soil depth of 2 m (Perry 1989, Danjon et al. 2008). Different plant species process different types of root systems. For effective reinforcement, different species having different root systems and architecture can be planted at different positions along a slope. Plants with many horizontal and long tap roots will reinforce soil better in the middle of the slope (Danjon et al. 2008). Plants with many oblique, dense and shallow roots will strengthen the top and toe slopes effectively (Ghestem et al. 2014). In this study, both *L. leucocephala* and *P. indicus* had strong tap roots and many horizontal roots. Thus, these two species are recommended for planting in the middle of slope. *Peltophorum pterocarpum* and *A. mangium* are also recommended for reinforcing soil in the middle of the slope due to their oblique and deep roots which can intersect shear plane and reduce the probability of movement and failure. *Dillenia suffruticosa* and *M. malabathricum* had shallow roots and occupied high soil volume near the soil surface. Therefore, these two species would be more suitable at the top and toe of slope rather than in the middle. The root system of *L. camara* occupied larger soil volume near the soil surface, but its root tensile strength was lower than *D. suffruticosa* and *M. malabathricum*. So, this species may be more suitable for growing at the toe of the slope rather than the top. Overall database on rooting characteristics of tropical plants, particularly architectural types, will be helpful in identifying the plants useful for slope stability.

CONCLUSIONS

Findings of this study provided important information on how root growth patterns varied between species. Root of trees were classified as VH-, R- and H-types. Root architecture of the three shrub species exhibited only M-type growth pattern. Root tensile strength varied between the species. Results confirmed tensile strength of roots decreased with increasing root diameter. *Leucaena leucocephala* showed the highest root tensile strength while *L. camara* had the lowest value. For root anchoring, *L. leucocephala* and *P. indicus* were most efficient compared with the rest of the species because their tap and lateral roots (both VH-type) had high reinforcement capacities. *Dillenia suffruticosa*

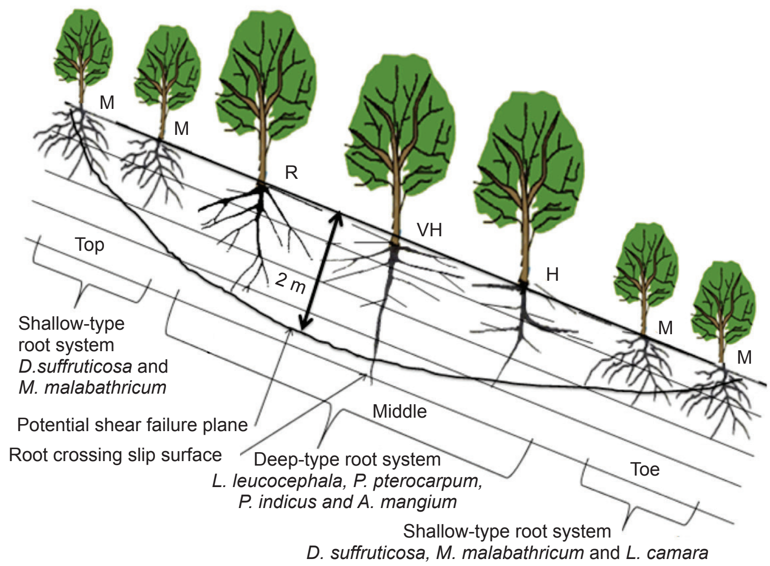

Figure 4 Suggested position of slope plants based on their rooting characteristics and shear failure plane at 2-m soil depth

and *M. malabathricum*, with M-type root growth, showed outstanding potential as erosion control plants. In the case of *L. camara*, neither its tensile strength properties nor its morphological parameters indicated it could assist in slope stabilisation. This study showed that tree species exhibited better soil–root interactions than shrub species. When trees grow in the middle of slope, its extensive morphological and mechanical properties would ultimately result in a more reinforced and stable soil. Root architecture and magnitude of root tensile strength can be used as indicators of individual plant performance for soil reinforcement, especially in selecting potential slope plants. Species selection and planting at appropriate positions on slope will prominently improve slope stability. The obtained results can be useful in improving soil bioengineering techniques, in order to prevent shallow mass movement.

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