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Full Length Research Paper

Use of vegetation for slope protection: Root mechanical properties of some tropical plants

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It is well documented that a bioengineering approach has recently regained a global recognition in preventing and controlling surface run-off, erosion and landslides. However, there is a lack of documentation on the root mechanical properties available especially in Malaysia. In this study, both pull-out and tensile strength of some tropical plants namely *Leucaena leucocephala*, *Acacia mangium* and *Melastoma malabathricum* is investigated on different stem sizes. Plots of pull-out capacity against displacement in *L. leucocephala* exhibit the presence of two peak values. Closer examination concludes that the first peak indicates the failure of the lateral roots and the second peaks is achieved when the tap roots failed. As for the tensile strength tests, results showed that the tensile strength decreases with increasing root diameter. The results also indicate that there is no correlation observed between the tensile strength, root length and root moisture content. Amongst the species, the highest root tensile strength was observed in *L. leucocephala*, followed by *A. mangium* and *M. malabathricum*. Thus, the study suggests that *L. leucocephala* is the best choice for slope stabilization work as it exhibits outstanding root mechanical properties.

Key words: Pull-out, tensile strength, root morphologies, shoot morphologies, lateral and tap roots.

INTRODUCTION

The role of root strength is important in stabilizing steep hill slopes. The slopes are generally stable if they are covered by shrubs whose roots anchor into the soil. It appears that root systems mechanically reinforce soil by transferring shear stress in the soil to tensile resistance in the roots. In addition to root distribution and quantity (Fitter, 1993), it is asserted that the root architecture, especially the branching pattern has a close relationship with the strength of anchorage (Stokes et al., 1996). Thus, increasing cohesion of the soil through vegetation growth can offset long-term decrease in soil strength which brings about weathering, fissuring and progressive softening of soils. Apart from that, the mechanical characteristic of roots is that they are strong in tension (De Baets et al., 2008). Soils, on the other hand, are strong in compression and weak in tension. A combined effect of soil and roots, producing a composite material in which the roots are fibers of relatively high tensile strength and adhesion embedded in a matrix of lower tensile strength soil mass, resulting in a reinforced soil. Therefore, it is the tensile of the roots which contribute to the overall strength of the soil-root composite. Despite several studies and recommendations on the effects of roots, the bioengineering application of deep-rooted shrubs and trees has not been sufficiently carried out in Malaysia. Hence, a project aimed at studying the effect of deep-rooted vegetation of Malaysian's plant species on soil strength has been initiated. Factors which influence the reinforcing effect of the root are its pullout and tensile strengths. Therefore series of pull-out and tensile tests have been conducted on the roots of selected plant species namely; *Leucaena leucocephala* (Normaniza et al., 2008; Ali and Osman, 2008), *Acacia mangium* and *Melastoma malabathricum*. Possible correlations

Table 1. Physical properties of the soil.

Atterberg limits	Percentage (%)
Liqiud limit	26.9
Plastic limit	14.59
Plasticity index	21.31
Linear shrinkage	3.23
Specific gravity	2.61
Compaction	
Optimum moisture content	13.5%
Maximum dry density	1.8515 Mg/m^3

Table 2. Grain size distribution.

Type (mm)	Size distribution (%)
Gravel (2 to 60)	10.0
Sand (0.06 to 2)	79.5
Silt (0.002 to 0.06)	7.5
Clay (< 0.002)	3.0

Figure 1. Pull-out test apparatus was fabricated for 0-60 mm of stem diameter.

between the engineering properties and the plant morphologies are also presented.

MATERIALS AND METHODS

Site description and plant materials

The assessment of the root strength of the species was done by means of field and laboratories tests. For each series of test, approximately 30 root specimens in 3 ranges of stem diameter; 00 - 20, 20 - 40 and 40 - 60 mm, were chosen. In *in situ* root pull-out test, root pull-out resistance of the species studied and the correlations of the pull-out resistance with various plant morphologies were analyzed. This pull-out test series was carried out at Institute of Mathematical Sciences, University of Malaya, located at 3°07' 51" N and 101°39' 25.9" E. The soil at that location is a typical tropical residual soil (Huat et al., 2008; Ali and Lee, 2003; Ali, 1993; Ali et al., 1992; Anderson et al., 1987) and its properties are given in Tables 1 and 2.

However, in the laboratory root tensile test, the maximum tension failure and the correlation of root tensile strength properties with root morphologies were also deduced.

Test methods

Pullout test

The apparatus was specially designed and fabricated for this project (Figure 1). The main features of the apparatus are:

1. It is portable and motorized: Pull out test can be carried out at different locations both on flat surface as well as sloping ground.
2. It can measure to a maximum stem size of 60 mm: The stem of the plants which are suitable for protection against shallow slope failures varies from 10 to 60 mm.
3. It can accommodate relatively large pull-out force: Because of this relatively large capacity; the maximum capacity of 5 tons, the apparatus has to be driven by motor-gear system, with sufficient capacity.
4. It can produce a pull-out force at a constant rate: Since the pulling rate can influence the pull out capacity, the apparatus is designed with a gear system that can produce constant rate of displacement.

To ensure that no slippage occurs during each pull-out test, the root crown was gripped using a specially design wedge and barrel system (Figure 1).

Plants to be tested were identified at least one day before the test. Firstly, the test apparatus was mobilized to the site and the machine was then assembled. The plant shoot was cut to approximately 15 cm above the ground. Next, the bark was removed to prevent slippage of the clamp. By using a vernier caliper, the diameters at clamp were measured. Ground surface around the stem was flattened and cleared of any undergrowth before placing the wedge and barrel. The machine was then moved so that the centre of the machine was in line with the cut stem. The lower part of rods was connected to the barrel while the load ring was attached to the upper part. A displacement gauge was installed on the frame main plate to measure the vertical displacement of the long rods. The two gauges (load and displacement) were set to zero. Motor was switched on to generate force to pull out the root from the ground at an approximate rate of 2 mm/min. At the same time, the centre shaft was pushed upward slowly by the motor which induced reading on load ring gauge. Each division of the load ring gauge is equal to 0.0462 kN of pull-out force. The readings were recorded for every 0.5 mm of displacement. Test was continued until the readings of load ring gauge showed a substantial drop. Photograph of the pulled out root was taken.

Root tensile test

The laboratory root tensile test was conducted by using Universal Testing Machine to determine the root tensile strength. The roots were pulled up vertically at 500 mm/min in the testing equipment. During the test, measurement of Force and Extension at failure had been obtained and automatically generated by the software that

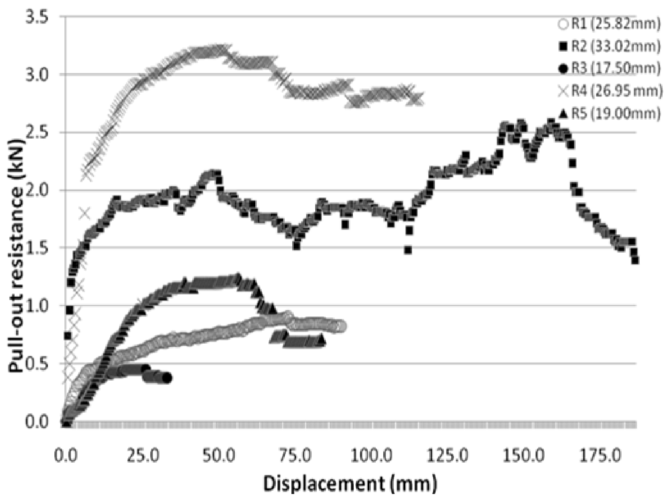


Figure 2. Plots of pull-out resistance versus displacement for *A. mangium.*

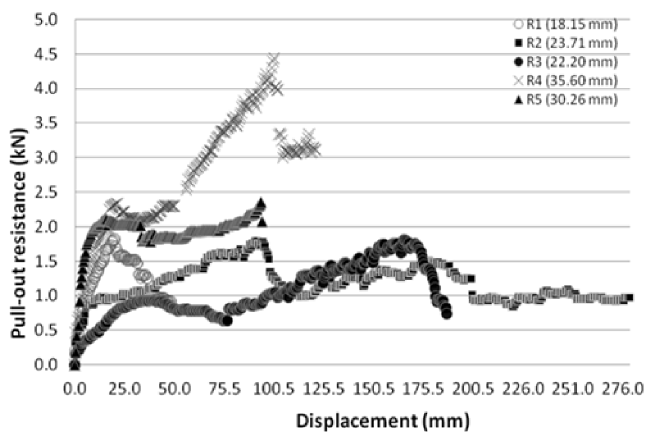


Figure 3. Plots of pull-out resistance versus vertical displacement for *L. leucocephala.*

connected to the Universal Testing Machine. The graph load (kN) versus extension (mm) were obtained. The value of tensile strength was derived as Maximum Force per sectional area of the root (N/mm^2). Different parts of the root along its length, which correspond to different root sizes, were sampled and tested.

Root architecture analysis and profiles

The root architecture (pattern) was determined by using the description of Yen (1972). All root samples of the selected plant were obtained manually by uprooting those plants in the field. The root samples were washed and then were cut into 200 mm in length and the root was clamped with sand paper each time during the testing. The root diameter was measured by using vernier caliper and the fresh weight of the root sample was obtained by using an electronic balance. Then, root moisture content was calculated as follow:

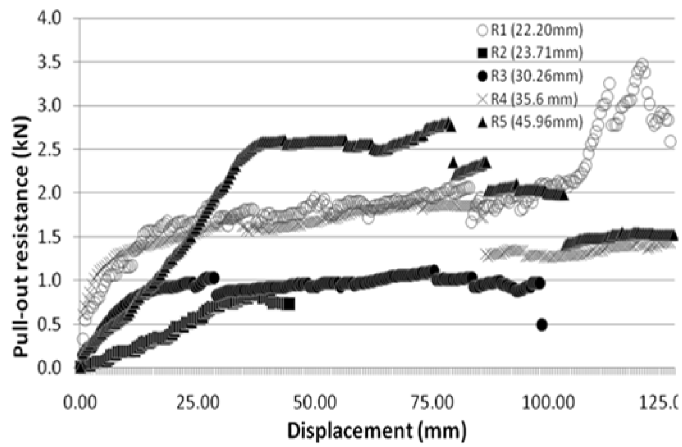


Figure 4. Plots of pull-out resistance versus displacement for *M. malabathricum.*

$$\frac{\text{Root fresh weight} - \text{root dry weight}}{\text{Root fresh weight}} \times 100\%$$

RESULTS AND DISCUSSION

Pull-out tests

Pull-out resistance versus vertical displacement

i. *A. mangium*: The maximum stem diameter ranged between 17 and 33 mm, were chosen (Figure 2). None of the roots of the test plants had lateral spread larger than 25.56 mm from the primary root, nor did the depth of the plant reach more than 49.5 cm. The average of the pull-out resistance force increases drastically at the early stage of the test that is, at a small displacement, less than 20.0 mm (Figure 5). The lateral roots of the plants were activated and provide most of the resistance for the plant. Subsequently, the gradient decreases gradually and the pull-out resistance begins to drop after reaching the maximum value, at about 1.5 kN. At the final stage, the irregular sounds of the root snapping were heard just before the plant was uprooted from the soil.

ii. *L. leucocephala*: The stem diameters of the tested samples ranged from 18 to 35 mm (Figure 3). The lateral roots spread not more than 27 mm from the primary root and the depth was up to 58.5 cm. Two distinct peak values are observed in the average of pull-out resistance force as against the displacement (Figure 6). The first peak (P1) value is due the maximum lateral root resistance whereby the second peak (P2) is the maximum mobilized tap root resistance. This is, arguably, one of the special features provided by the VH-type plant (Table 2) which was generated by both lateral and tap roots. In general, the second peak value which is presumably due to the tap root seems to be higher than

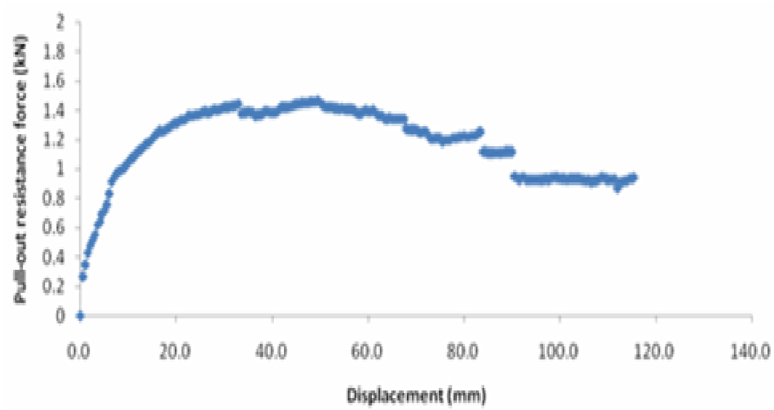


Figure 5. Average pull-out resistance force-displacement curve for a pull-out test on five replicates *A. mangium.*

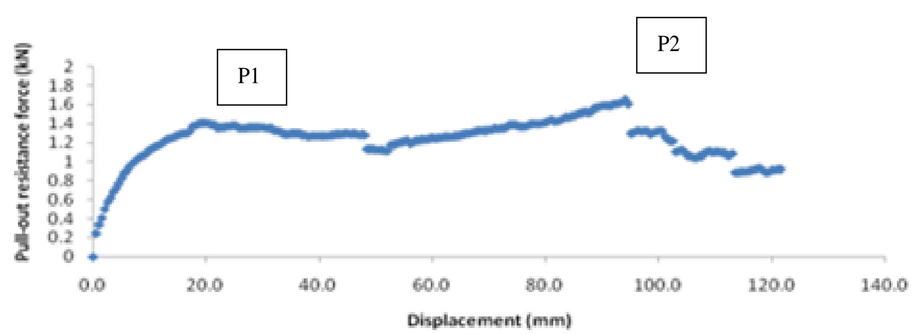


Figure 6. Average pull-out resistance force-displacement curve for a pull-out test on five replicates *L. leucocephala.* PI and P2 contributed by lateral and tap roots, respectively.

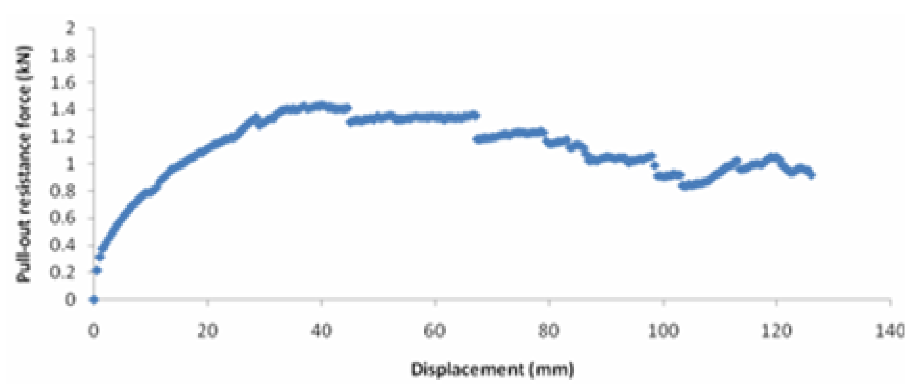


Figure 7. Average pull-out resistance force-displacement curve for a pull-out test on five replicates *M. malabathricum.*

the first peak value. This observation indicates that the tap root plays a major role in providing the maximum pull-out resistance to this type of plant.

iii. *M. malabathricum*: The stem diameter ranged between 22 and 45 mm (Figure 4). The roots spread not more than 28.7 mm from the primary root. Similar to the previous species, *M. malabathricum* exhibits gradual increase in the pull-out resistance as against displacement (Figure 7). However, the initial gradient for each sample seems to be less than those of plants tested in

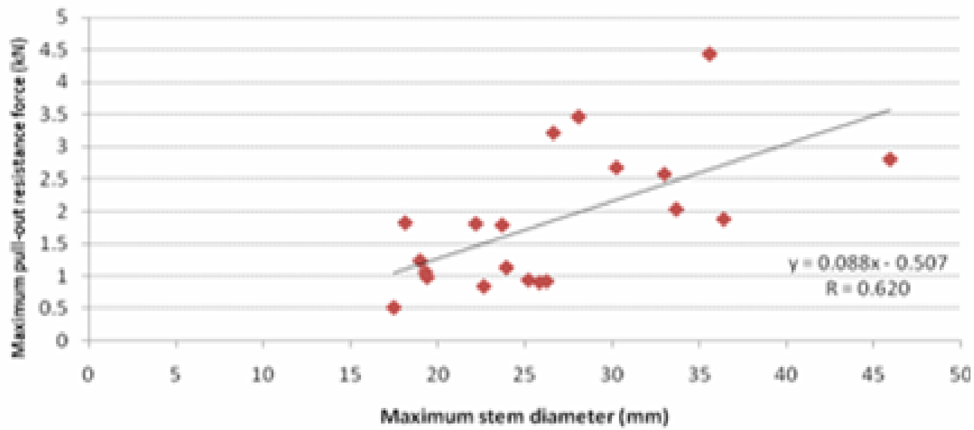


Figure 8. The relationship between the maximum pull-out resistance and the maximum stem diameter for all species.

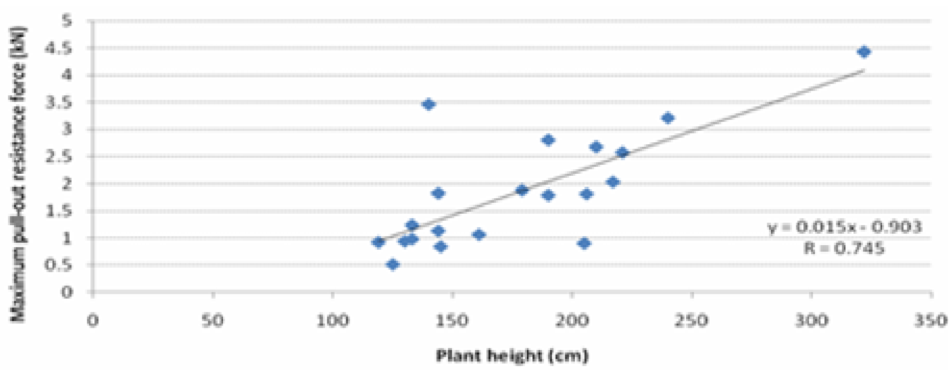


Figure 9. The relationship between the maximum pull-out resistance force and the plant height for all species.

both *A. mangium* and *L. leucocephala*. The average pull-out resistance force-displacement curve of *M. malabathricum* shows a similar trend to those in *A. mangium*. The lateral and fibrous roots of the plant contribute most of the pull-out resistance force to the plant. The value of the maximum pull-out resistance for *M. malabathricum* ranged from 0.84 to 3.47 kN, with an average of 2.02 kN. The displacement increases as the resistance increases and drops drastically at a certain point due to breaking or dislodging of most of the lateral roots that is, when the plant was completely uprooted.

Understanding of the pull-out resistance of a plant is useful in our assessment of the ability of a plant to sustain environmental stress and forces such as wind, landslide, mass movement and soil creeping. Overall results imply that *A. mangium* and *M. malabathricum* show similar trend in which only single peak value can be seen. These species acquire the maximum strength of pull-out resistance from mainly the lateral roots. On the other hand, the pull-out resistance-displacement curve of *L. leucocephala* is slightly different whereby the two distinct peak values become visible; indicating the higher pull-out resistance can vary depending on the conditions and development of both lateral and tap roots.

Correlations between pull-out resistance and shoot morphologies

As mentioned earlier, there are many factors that influence the pull-out resistance- displacement relationship which include the development and conditions of the root system. In order to have a better understanding of these influences, some properties of the root system are correlated to the pull-out resistance.

In this study, pull-out tests have been conducted on plants of different stem sizes. The correlation between the pull-out capacity against the maximum stem size is illustrated (Figure 8). A strong linear relationship is observed between pull-out capacity and maximum diameter that is, the pull-out capacity increases as the diameter increases. In addition, plant height is also recorded to have a strong relationship with pull-out capacity (r = 0.75, Figure 9).

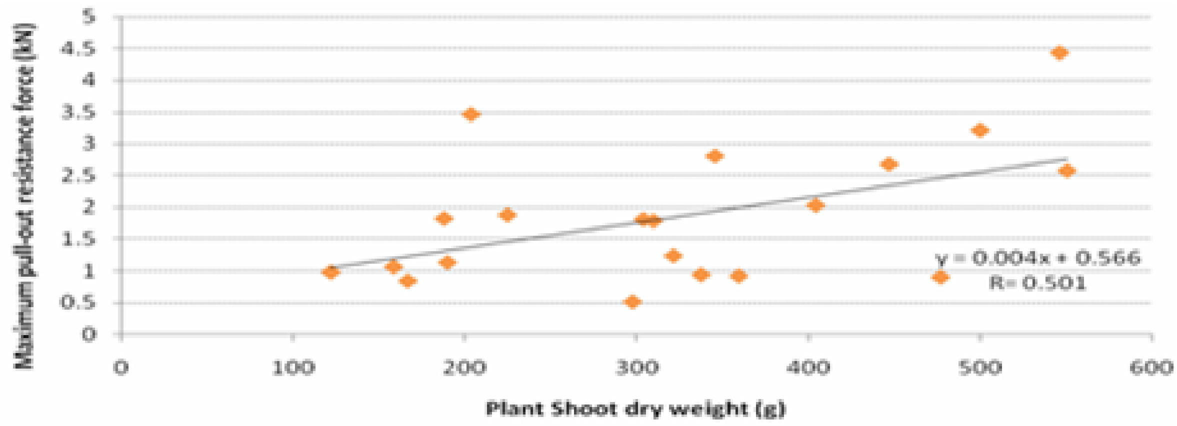


Figure 10. The relationship between the maximum pull-out resistance and the plant shoot dry weight for all species.

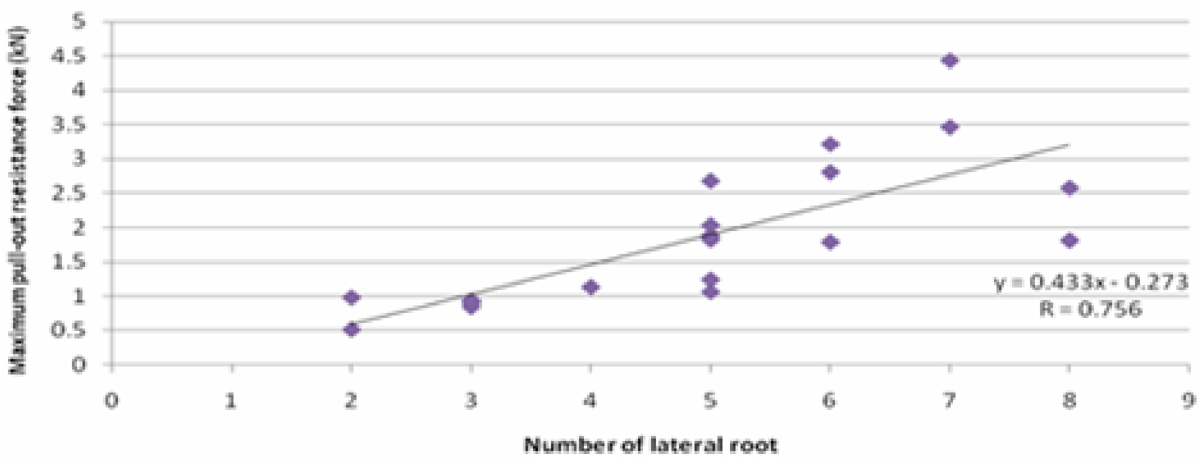


Figure 11. The relationship between the maximum pull-out resistance and the number of lateral root for all species.

The result is anticipated as the length and the root density seem to be correlated to the plant age which can be estimated from the plant height. The results also, arguably, imply that the higher the plant age, the higher the plant diameter and height, thus the higher pull-out resistance.

As part of the test procedure, the shoot for each tested sample was dried and weighed to determine the dry weight or shoot biomass. The existence of a weak linear (Figure 10, r = 0.50) relationship indicates that the maturity and the growth of the roots is depending on the development of the shoot.

Pull-out resistance force versus root morphologies

It was observed that during the test, the lateral roots play a very important role in providing the pull-out resistance especially during the early stage of the test. After the end of each test, number of lateral roots was recorded and results clearly show that the pull-out capacity varies linearly with number of lateral root (Figure 11). After each pull-out test, the plant (together with the root) was completely taken out of the soil and the total length of all roots was then measured. The Root Length Density (RLD) is calculated as total root length / soil volume. This parameter reflects the intensity of the root system and hypothesized to have a positive effect on the pull-out capacity. It is evidently shown that the relationship is linear where the pull-out resistance directly depends on the root length density (Figure 12).

Overall correlation and regression analysis show that the pull-out resistances of all species have a positive, either weak or strong, linear relationships with all the morphological properties of the plants. Bigger plants can resist pull-out force better than the smaller plants. The increase in plant size will normally generate high pull-out resistance. Taller plants will resist uprooting better than

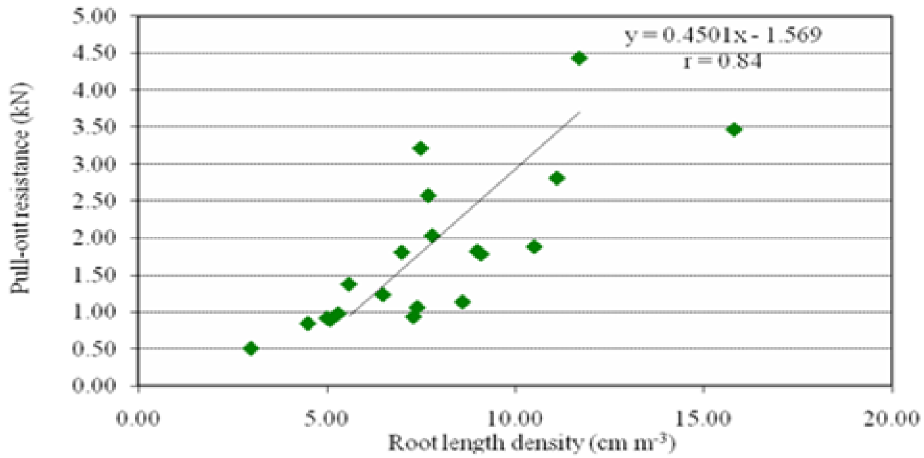


Figure 12. Relationship between pullout resistance and root length density for all species.

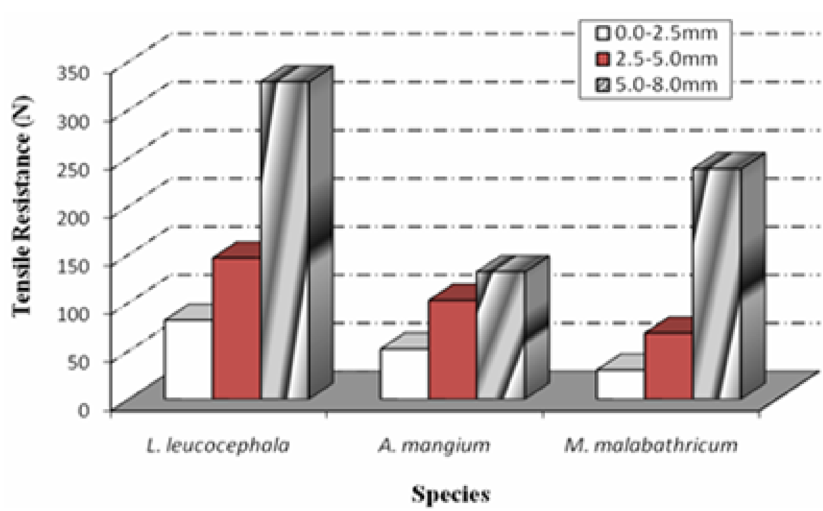


Figure 13. Tensile resistance at certain root diameter.

the shorter ones, which is to be expected given the relative constant root to shoot ratio. Plants that invest more in their above ground parts would also invest more in the proliferation of their root systems. The pull-out resistance of plant is dependent on the plant shoot dry weight, which means that as more development happens on the stem section, the more developed the plant root system. The increase in pull-out resistance of plants that have root systems with extensive number of lateral root is due to the fact that the stronger soil-anchorage is developed by the lateral roots.

Tensile strength tests

In general, most of the root segment tested follows a typical pattern of tensile load versus extension curve. The first failure point becomes an indication of the subsequent failure until the root segment examined is broken into two pieces. In some root segments, the ability to accommodate the load after the first failure is higher than other segments. However, the root ability depends on the strength of the root core which may be observed after failure.

Comparing the test results of all species, *L. leucocephala* shows the highest tensile resistance in all diameters (Figure 13) followed by *A. mangium* and *M. malabathricum* but only for the root diameter < 0.5 mm. For the root diameter > 0.5 mm, *M. malabathricum* exhibits an outstanding value after *L. leucocephala*. This reason may be due to the high root length density (data not shown) of *M. malabathricum* as the root diameter is increasing. The results also indicate that the tensile resistance increases with increasing root diameter in all

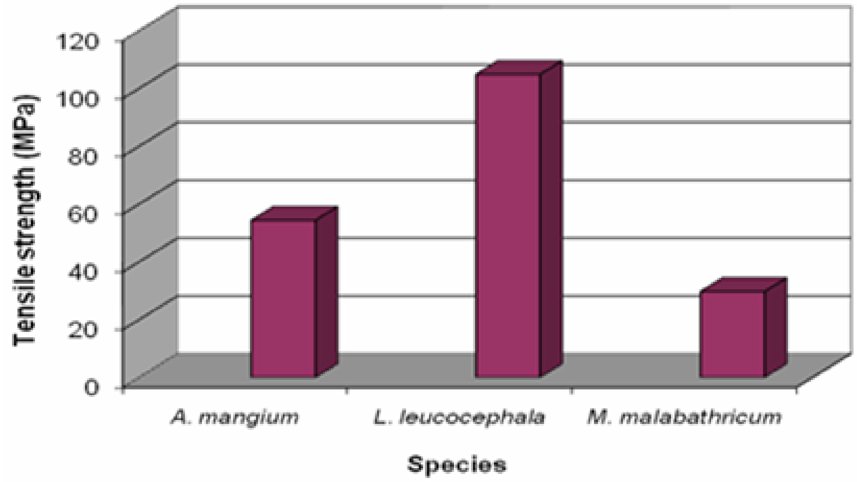


Figure 14. Tensile strength of all species.

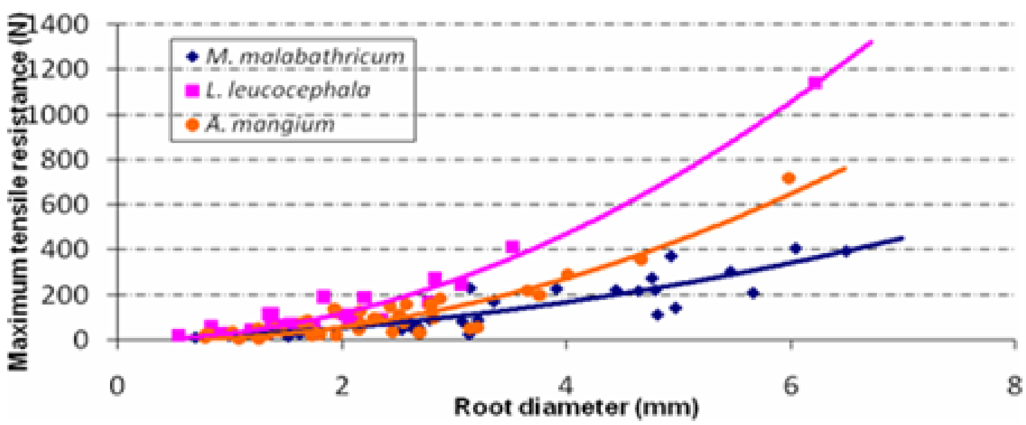


Figure 15. Relationship between maximum tensile resistance and root diameter.

species studied, implying the total maximum force is influenced by root diameter. The significant tensile resistance is observed at higher diameters, except in *A. mangium* (> 5 mm).

Similarly, the average tensile strength (Force / root area) of *L. leucocephala* is the highest which is almost double than that of *A. mangium* and triple than that of *M. malabathricum* (Figure 14). The results also imply the prominent reinforcement characteristic of *L. leucocephala*.

Correlation between tensile strength properties and plant morphologies

The maximum tensile resistance increases with increasing root diameter following a second order polynomial regression curve (Figure 15). The effect of increase is negligible for root diameter less than 3 mm for all species but remarkable increment is observed for root diameter beyond 3 mm. *L. leucocephala* gives the highest resistance (1200 N), followed by *A. mangium* (700 N) and *M. malabathricum* (400 N).

Opposite trend is observed between tensile strength and root diameter (Figure 16). The tensile strength is inversely related to root diameter up to 3 mm, but generally remains constant beyond that value. This is in line with the findings of Stokes and Guitard (1997) in which tensile strength reduces with increasing root circumferences (girth) or diameters.

There is no well correlated relationship observed between tensile strength and root length (Figure 17). This is expected because the maximum tensile load normally depend on the cross sectional area of the root. Similarly, the root-moisture content does not influence the tensile strength (Figure 18). However, the data appears to be

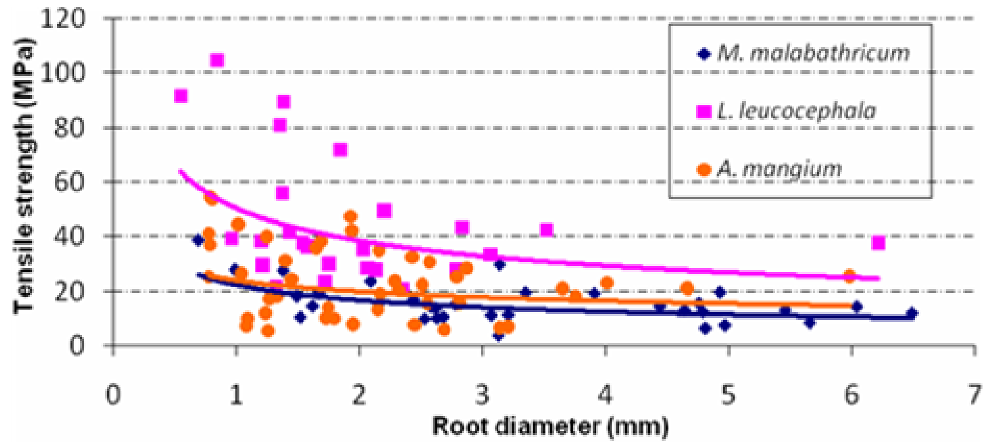


Figure 16. Relationship between tensile strength and root diameter.

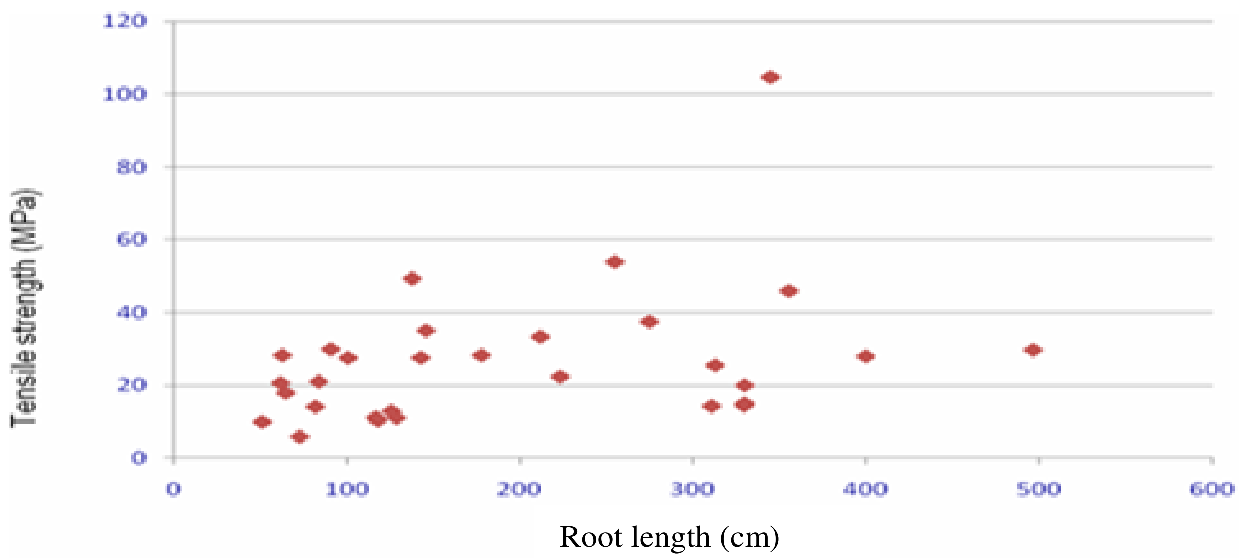


Figure 17. There is no well correlated relationship observed between tensile strength and root length.

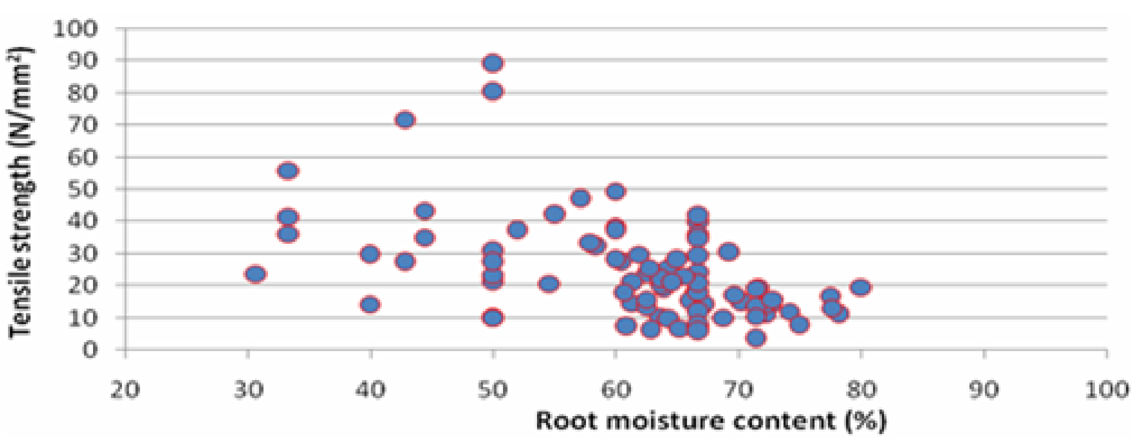


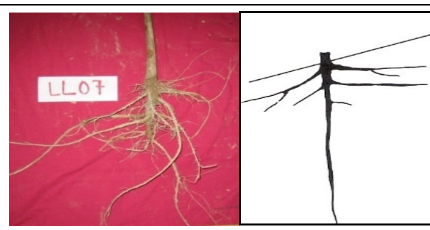
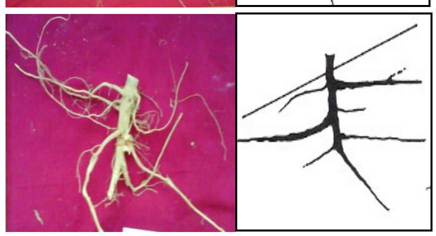
Figure 18. Relationship between tensile strength and root moisture content.

Table 3. Comparison with other shrubs and trees.

Type	Species	Tensile strength (MPa)
Shrubs	*Spartium* j. (Genet et al., 2007)	29.93
Shrubs	*Inula viscosa* (Genet et al., 2007)	18.72
Shrubs	*Rosa canina* (Genet et al., 2007)	22.95
Shrubs	*Melastoma malabathricum**	29.72
Trees	*Leucaena leucocephala**	104.83
Trees	*Acacia mangium**	54.37
Trees	*Pinus densiflora* (Genet et al., 2007)	32.00
Trees	*Salix hastata*(Genet et al., 2007)	13.00

*Plant species tested in the current study.

Table 4. Root growth pattern in trees (after Yen, 1972).

Species	Pattern	Root growth type
L. leucocephala		VH-type
A. mangium		H-type
M. malabathricum		M-type

slight reducing trend on tensile strength with respect to root moisture content (~60-80%). Other root content e.g. cellulose content may contribute to the root strength properties Genet et al. (2007), which was not determined in this study.

Overall results show that *L. Leucocephala* has the highest value in tensile strength followed by *A. mangium* and *M. malabathricum*. The tensile strengths of root for the selected plants decrease with increasing root diameter. Some correlations are observed between tensile strength and root diameter of all species studied. It has also been discovered that root moisture content does not significantly influence the tensile strength properties.

In perspective to other potential slope plants, the mean of root tensile strength does differ significantly with respect to vegetation type (Table 3). The database shows that the shrubs species have slightly lower tensile strength than the current species studied. Interestingly, *L. leucocephala* shows the highest tensile strength amongst the species, indicating an outstanding potential of slope plant.

Root growth pattern

The root growth pattern of the species studied has been determined during the studies (Table 4). The results provide important information as how tree anchorage is affected by architecture. *A. mangium* is found to have three roles in slope stabilization: soil reinforcement, slope stability and wind resistance, as most of its roots grow horizontally (H-type). *L. leucocephala* can play a major role in the latter two (VH-type). In comparison, the root architecture of *L. leucocephala* is more prominent because it has a combined reinforcement effect of both tap and lateral roots which establish vertically and horizontally, respectively (refer 3.1.1b). Although, M. *malabathricum* has shallow root, its root system is dense (M-type), an outstanding potential as erosion control plant. In comparison, root architecture of *L. leucocephala* is more prominent in deep-seated stabilization as it has a combined reinforcement effect of both long tap and extensive lateral roots.

Conclusions

The fabricated equipment has served its intended function and pull-out test had been performed successfully. *A. mangium* and *M. malabathricum* give similar trend in the pull-out resistance and displacement relationship, where only one peak value is observed. While *L. leucocpehala* shows two peaks in which pull-out resistance is mainly contributed by the lateral root (first peak) and tap roots (second peak). A weak relationship is observed between maximum pull-out resistance and plant shoot dry weight but strong linear relationship with the root profiles, implying that root gives more attribution to pull-out capacities as compared to shoot. As for the tensile strength test, the root of *L. leucocephala* has the highest tensile strength followed by *A. mangium* and *M. malabathricum*. Interestingly, the current tropical plants studied exhibit higher tensile strength amongst the previous plants studied. In addition, the tensile strength of root for the selected plant decreases with increasing root diameter. Some correlations are observed between tensile strength properties; maximum tensile resistance, tensile strength and root diameter of all species studied. It has also been discovered that the root moisture content does not influence the tensile strength properties. Hence, the results strongly imply that *L. leucocephala* has a prominent root mechanical properties and it is anticipated that this particular plant has the necessary features to be an outstanding slope plant.

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