Sains Malaysiana 40(6)(2011): 577–585

Pull-Out and Tensile Strength Properties of Two Selected Tropical Trees

(Ciri-Ciri Tarikan-Keluar dan Kekuatan Tegangan Dua Pokok Tropika Terpilih)

NORMANIZA OSMAN*, MOHAMAD NORDIN ABDULLAH
& CHE HASSANDI ABDULLAH

ABSTRACT

A bioengineering technique is gradually being used as an alternative for slope stabilisation design. The effect of vegetation on soil strength, particularly in terms of root reinforcement aspects has therefore become a major interest. 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 two tropical trees namely Leucaena leucocephala *and* Acacia mangium *were investigated on different stem sizes.* L. leucocephala *performs the higher pullout strength than* A. mangium. *The results also show that pullout resistance is much affected by the root than the shoot profiles. In terms of tensile strength, the tensile strength decreases with increasing root diameter, implying the finer root diameter contribute to the higher tensile strength. In both parameters,* L. leucocephala *exhibits the highest value. The study suggests that* L. leucocephala *has an added value as a good potential slope plant for slope stabilization work as it exhibits outstanding root mechanical properties. Interestingly, the results also showed that the pullout force was much affected by the tensile strength. It can be concluded that some root and shoot properties do have a great impact on root mechanical properties such as tensile and pullout strengths.*

Keywords: Lateral roots; pull-out; root morphologies; shoot morphologies; tap roots

ABSTRAK

Penggunaan kaedah bio-kejuruteraan semakin mendapat tempat sebagai alternatif dalam merekabentuk penstabilan cerun. Kesan vegetasi terhadap kekuatan tanah, terutamanya dalam aspek pengukuhan akar telah menjadi tumpuan utama. Walau bagaimanapun, terdapat kekurangan dalam mendokumentasikan ciri-ciri mekanikal akar terutamanya di Malaysia. Di dalam kajian ini, kedua-dua tarikan-keluar dan kekuatan tegangan bagi dua pokok tropika iaitu Leucaena leucocephala *dan* Acacia mangium *dikaji pada saiz batang yang berbeza.* L. leucocephala *menunjukkan kekuatan tarikan-keluar yang lebih tinggi daripada* A. mangium. *Keputusan juga menunjukkan bahawa rintangan tarikan-keluar lebih dipengaruhi profil akar berbanding pucuk. Bagi kekuatan tegangan pula, kekuatan tegangan berkurang dengan peningkatan diameter akar, mengandaikan yang diameter akar yang halus menyumbang kepada kekuatan tegangan yang lebih. Bagi kedua-dua parameter,* L. leucocephala *mempunyai nilai yang paling tinggi. Kajian ini mencadangkan* L. leucocephala *mempunyai nilai tambah sebagai tumbuhan yang berpotensi untuk menstabilkan cerun di mana ia menunjukkan ciri-ciri akar yang menakjubkan. Menariknya, keputusan juga menunjukkan bahawa daya tarikan-keluar turut dipengaruhi oleh kekuatan tegangan. Dapat disimpulkan bahawa beberapa ciri akar dan pucuk mempunyai impak yang besar terhadap ciri mekanikal akar seperti tegangan dan kekuatan tarikan-keluar.*

Kata kunci: Akar-akar lateral; akar-akar tunjang; morfologi akar; morfologi pucuk; tarikan-keluar

INTRODUCTION

Slopes in natural condition are prone to erosion as they are exposed to the erosion agents such as water, wind and others. The consequences of big scale erosion are unpredictable and can cause fatality. In most cases, slope stability is affected by the steepness or slope gradient, soil texture and bedrock underneath and also the rate of rainfall. Areas with high annual rainfall such as tropical humid climate basically face problems in slope stability. High intensity of rainfall leads to saturation of the soil and the saturated slope become unstable as its factor of safety is usually less than 1.0 (Van Beek et al. 2005). Among the factors considered as resistant forces against big scale erosion and landslide on slope are root tensile strength, root shear strength and pull-out strength whereas the compound strength generated by both soil and root (Abe & Iwamoto 1986). The conventional methods in managing and restoring the slope stability such as soil nailing, key stones, masonry wall, netting, and rubble pitching are often used to solve the problems. However, the use of vegetation in restoring the slope stability had gained much interests as many researchers recognize the long term potential and advantages of vegetation in maintaining the slope stability (Mitsch 1998). Moreover, it has been accepted as a low cost solution especially in humid tropical areas (Collison et al. 1995).

Hence, 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, the number and size of roots which cross the slip surface are extremely important (Cammerat et al. 2005; Reubens et al. 2007; Van Beek et al. 2005) and the root architecture, especially the branching pattern has a close relationship with the strength of anchorage (Stokes et al. 1996). Apart from that, the mechanical characteristic of roots is that they are strong in tension and soils. On the other hand, they are strong in compression and weak in tension (De Baets et al. 2008). This combined effect of soil and roots, producing a composite material in which the roots are fibres 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.

Therefore, this research was aimed to study the engineering properties of the root of Malaysian species. Knowing the influence of plant root pullout and tensile strengths towards the reinforcing effect, a series of pull-out and tensile tests have been conducted on the roots of selected trees namely; *L. leucocephala* and *A. mangium*. The relationship between the engineering, the shoot and the root properties was also investigated.

TABLE 1. Soil physical properties

Atterberg limits	
Liquid Limit	26.9 %
Plastic Limit	14.6%
Plasticity Limit	21.3 %
Linear Shrinkage	3.23
Specific Gravity	2.61
Compaction	
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)	7.5 %
Clay (<0.002 mm)	3.0 %

MATERIALS AND METHODS

The assessment of the root strength of the species was conducted by means of field and laboratory tests. The plants for both pull-out and tensile test experiments were obtained from a flat land approximately 1350 m^2 located at the Institute of Mathematical Sciences, University of Malaya (3° 07' 51" N and 101°39'25.9" E). The site was observed to have abundance of the plants studied. Based on the grain size distribution curve, the soil is described as silty sand and its physical properties are tabulated in Table 1. Details on the plant species studied are tabulated (Table 2).

TEST METHODS

Pullout Test The location of the selected plant sample was identified and marked using the stem tagging. Nine samples were chosen for each species, three for each stem diameter treatment (0-20 mm, 20-40 mm and 40-60 mm). Before setting up the equipment, the ground surface around the plant had been cleared. After measuring height of the plant, the stem of the plant was cut approximately at 10 cm above the root crown, to ensure that the barrel could be placed properly and the wedges were able to fully grip the plant stem as tight as possible. Appropriate wedges were chosen depending on the size of the stem and root crown diameter (Figure 1).

FIGURE 1. Root gripping by wedge and barrel

TABLE 2. General descriptions on species studied

	Species	
	Acacia mangium	*Leucaena leucocephala*
Depth of rooting (cm)	26.09 ± 4.54	37.02 ± 3.57
Height of plant (cm)	265.09 ± 53.51	273.22 ± 36.21
Maximum lateral root distance (cm)	45.02 ± 16.32	54.97 ± 17.73
Total root length (cm)	460.53 ± 91.1	1256.62 ± 382.19
Root length density (RLD) (cm m^{-3})	8.33 ± 1.52	13.65 ± 2.78

Prior to the test, the dial gauge for the load ring and the vertical displacement were set to zero. Then, the root pull out was started by applying the pull out force at a constant rate (Figure 2). When the test are in progress, both dial gauges were observed and readings for the load ring were recorded on a Pull out Test form at every increment of 50 divisions' of vertical displacement until the root system failed. The root pull-out resistance of the species studied and the relationship between pull-out resistance and various root morphologies were analyzed.

FIGURE 2. Plant was pull-out from the soil

Root Tensile Test In the laboratory, a total of 36 and 21 root segments of *A. mangium* and *L. leucocephala* root samples were washed and then cut into 200 mm in length and the root was clamped with sand paper each time during the testing. These segments were grouped into ranges of 0.0-2.5 mm, 2.5-5.0 mm and 5.0-8.0 mm. The laboratory root tensile test was conducted by using the Universal Testing Machine (Instron, Model 5582, United Kingdom) 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 were measured. The value of tensile strength was derived as maximum force/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. The maximum tension failure and the relationship between root tensile strength properties and root morphologies were also deduced.

ROOT ARCHITECTURE ANALYSIS AND PROFILES

The root architecture (pattern) was determined through observation and comparison of the root morphologies other than branching patterns by using Yen's description model (1972). All root samples of the selected plants were obtained manually by uprooting those plants in the field. The root diameter was measured by using vernier caliper and the fresh weight of the root sample was obtained by using an electronic balance. The Root Length Density (RLD) is calculated as total root length/soil volume. This parameter reflects the intensity of the root system.

RESULTS AND DISCUSSION

PULL-OUT RESISTANCE OF *ACACIA MANGIUM* AND *LEUCAENA LEUCOCEPHALA*

In *Acacia mangium,* the maximum stem diameter of nine tested samples ranged from 17 to 33 mm, with maximum lateral spread of 49.5 mm from the base of the trunk and maximum depth of 25.56 cm, were chosen. The average of the pull-out resistance force increased drastically at the early stage of the test i.e. at small displacement, less than 20.0 mm (Figure 3). The lateral root of the plants were activated and provided most of the resistance for the plant. Subsequently, the gradient decreased gradually and the pullout resistance began 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.

In *Leucaena leucocephala,* the stem diameters of nine tested samples were used for the test, ranged from 18 mm to 35 mm. The lateral roots spread not more than 58.5 cm from the primary root and the depth was up to 27 mm. The average pull-out resistance was 2.25 ± 0.45 kN. Two distinct peak values were observed in the average of pull-out resistance force as against the displacement. The first peak (P1) value is due the maximum lateral root resistance whereby the second peak (P2) is the maximum mobilized tap root resistance (Figure 4). This is, arguably, one of the special features provided by the VH-type plant (Table 3) which 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 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.

Overall results imply that *A. mangium* only has single peak value. This 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* was 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. Between the two species, *L. leucocephala* exhibit the highest mean pull-out force (Table 4). Understanding 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. The strength of plant roots especially the pull-out strength is important

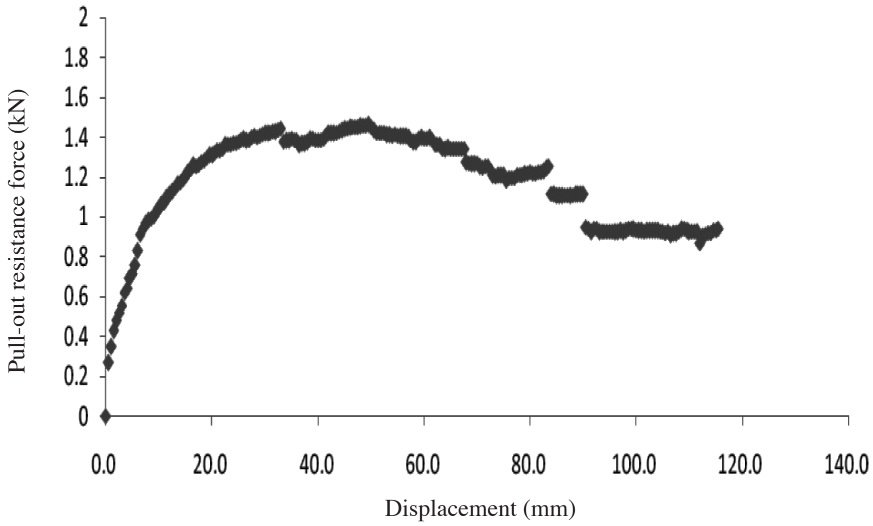


FIGURE 3. Average pull-out resistance force-displacement curve for a pull-out test on five replicates *A. mangium*

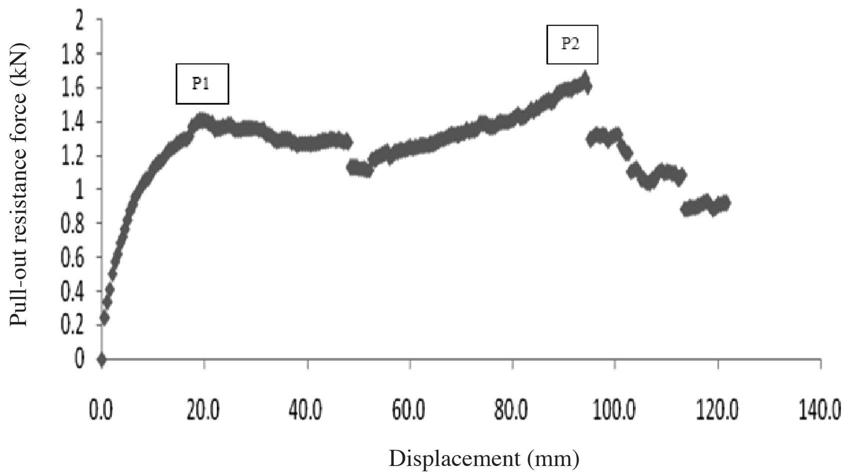


FIGURE 4. Average pull-out resistance force- displacement curve for a pull-out test on five replicates *L. leucocephala*. P1 and P2 contributed by lateral and tap roots, respectively

TABLE 3. Root growth pattern in trees (after Yen 1972)

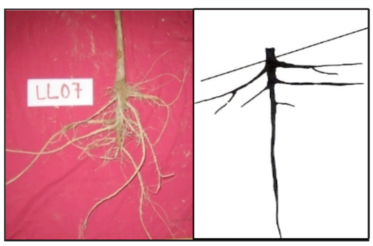
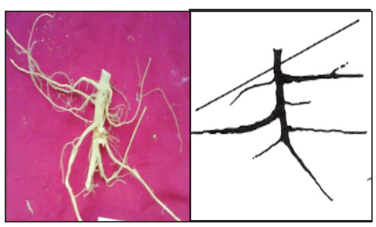
Species	Illustration	Root growth type
L. leucocephala		VH-type
A. mangium		H-type

TABLE 4. Pull-out test and tensile strength of *Acacia mangium* and *Leucaena leucocephala* (data are means ± standard error)

Species	Pull-out Force (kN)	Tensile strength (N/mm^2)
Acacia mangium	1.69 ± 0.34	54.37 ± 10.80
Leucaena leucocephala	2.25 ± 0.45	104.83 ± 18.72

Significant difference between species at $LSD_{p<0.05}$ = 0.73 (pull-out) and 18.9 (tensile strength)

in natural condition i.e to withstand torrential runoff and prevent erosion as exhibited by *Vetiveria zizanioides* (Mickovski et al. 2007). It has also been discovered that most of the reinforcement in *Vetiveria zizanioides* is provided by the upslope lateral root that resists the force and prevent them from uprooting.

A study carried out upon pull-out test with different model of root system by Stokes et al. (1996) discovered that the branching angle of the lateral root system lead to differences of uprooting force. This might explain the trend that has been discovered in this study, different composition of root distribution and branching between *A. mangium* and *L. leucocephala* can be as factors causing the differences in pull-out values. High force of pull-out exhibited by *L. leucocephala* shows the capability of the species to resist the uprooting forces. In tandem with *L. leucocephala*'s ability to establish on slope condition and reinforced the soil (Normaniza et al. 2008), the features to resist the uprooting helps the species anchorage and stability on slope against forces such as wind.

RELATIONSHIP BETWEEN PULL-OUT RESISTANCE AND PLANT MORPHOLOGIES

All plant species were combined to determine the regression analysis. A linear relationship (R^2 = 0.36; Figure 5) is observed between pullout capacity and stem diameter i.e. the pullout capacity increases as the diameter increasing. In addition, the existence of a linear (R^2 = 0.36; Figure 6) relationship between pullout and shoot dry weight also indicates that the maturity and the strength of the roots is depending on the development of the shoot. It is also hypothesized that Root Length Density (RLD) has a positive effect on the pull-out capacity. It is evidently shown in a strong linear relationship between pullout and root length density (R^2 = 0.60; Figure 7) observed in this study.

Overall regression analysis showed 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, which is to be expected given the relatively a 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 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

The root segments tested exhibited variation in value of tensile strength. Result of the tensile force of roots in each ranges of diameter shows that *L. leucocephala* exhibited the highest tensile force (Figure 8), with the average of 104.3 ± 18.72 N/mm^2. Hence, based on the observation of tensile force at failure versus diameter, an increase in diameter increases the force (Figure 9). Similar trend was also observed by Tosi (2007). Final results showed that the average tensile strength (Force/root area) of *L.*

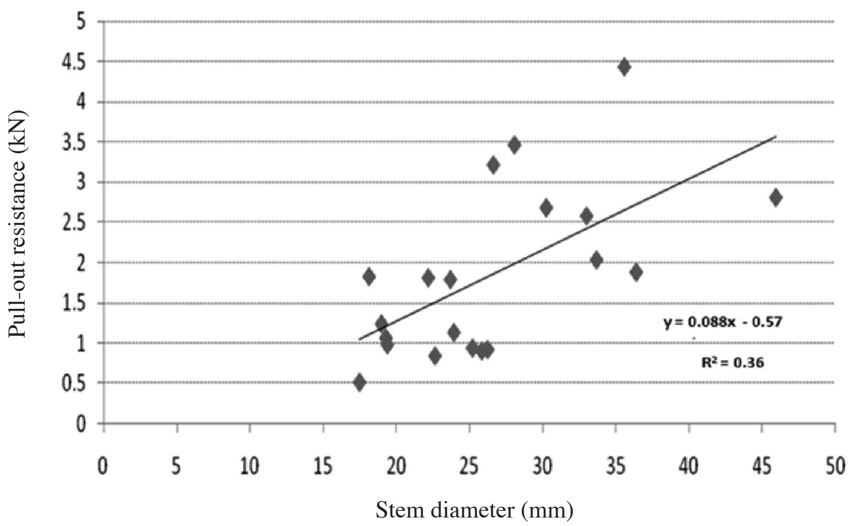


FIGURE 5. Maximum pull-out resistance versus stem diameter

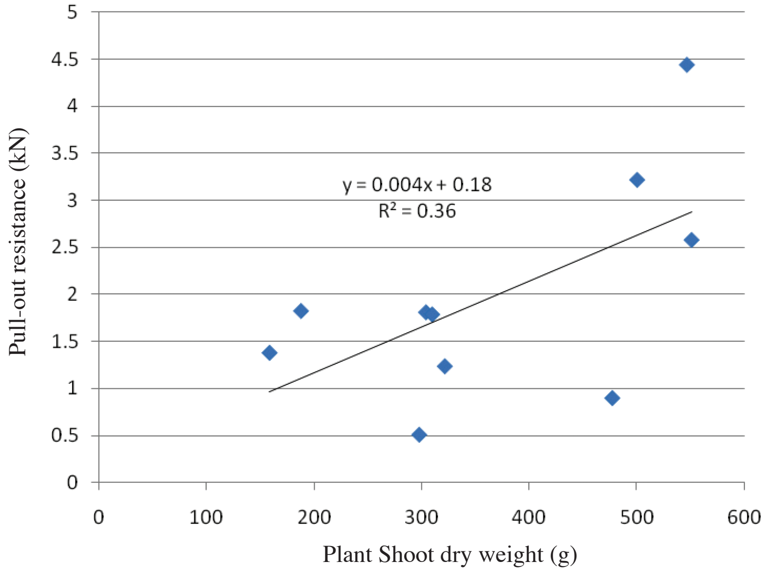


FIGURE 6. The relationship between the maximum pull-out resistance and the plant shoot dry weight

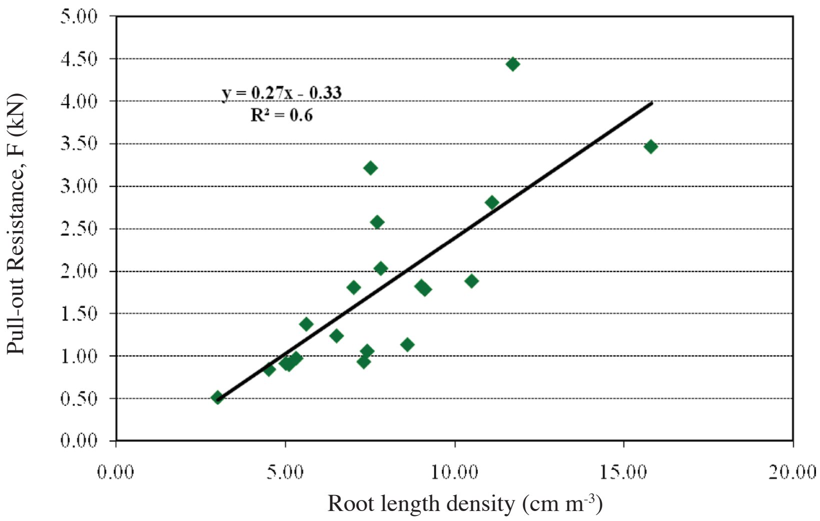


FIGURE 7. Relationship between pullout resistance and root length density

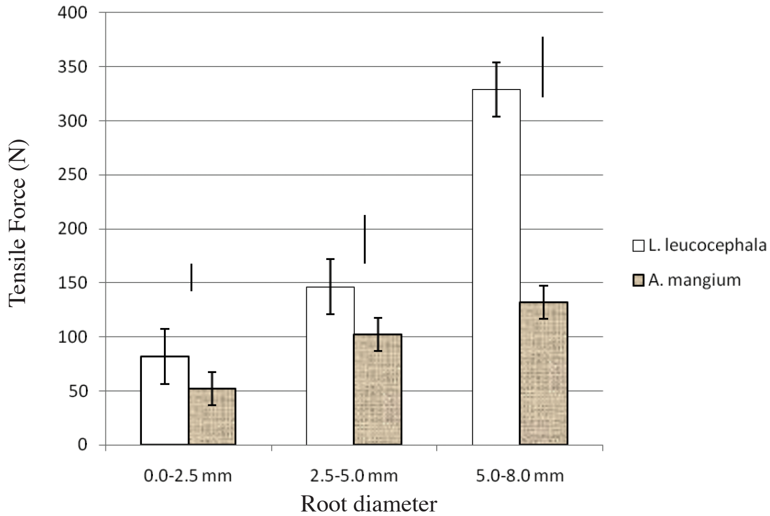


FIGURE 8. Tensile force at failure of roots according to different diameter classes

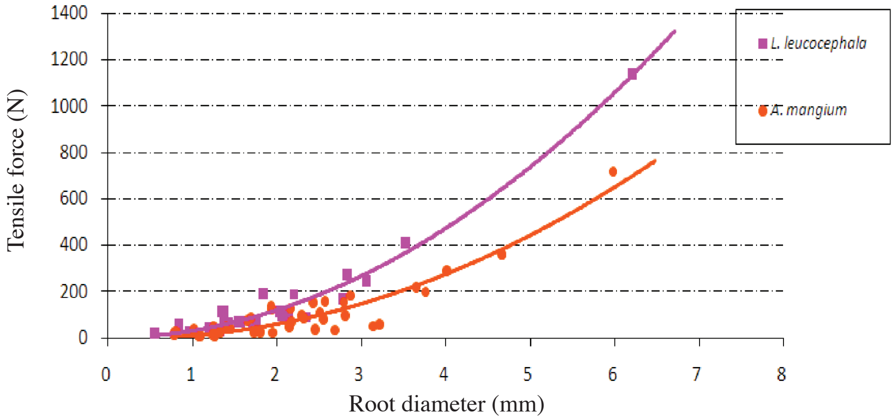


FIGURE 9. Tensile force at failure versus root diameter

leucocephala was the highest, almost double than that of *A. mangium* (Table 4).

RELATIONSHIP BETWEEN TENSILE STRENGTH PROPERTIES AND ROOT MORPHOLOGIES

From the regression analysis between tensile strength and root diameter, it can be observed that the tensile strength decreased with increasing root diameter (Figure 10) which is in line with the previous root studies (Baets et al. 2008; Genet et al. 2008; Tosi, 2007). During soil shearing, the finer and thinner roots that have high tensile strength would slip while the thicker roots with lower tensile strength would break (Mickovski & Van Beek 2009). It is reported by Genet et al. (2005) that this high resistance of the finer roots towards breakage was contributed by the higher cellulose content as been discovered in *Pinus pinaster* and *Castaena sativa*. Thus, this property of higher tensile strength in the finer roots would ultimately yield an increase in shear strength of the root-soil composite in the field or natural condition. Hence, the finer roots will be able to provide better ductility to the root-soil composite with a higher capacity to withstand surface erosion and runoff (Mickovski & Van Beek 2009).

RELATIONSHIP BETWEEN PULLOUT AND TENSILE STRENGTHS

Most research carried out previously did not incorporate the pull-out and tensile strength. They only focused on either one of the test (e.g. Baets et al. 2008; Norris 2007; Tosi, 2007). Nilaweera & Nutalaya (1999) did both pull-out and tensile test, however they did not analyze the relationship between these two parameters. Interestingly, the results in this study showed that the pullout force is much affected by the tensile strength ($R^2 = 0.77$; Figure 11).

ROOT GROWTH PATTERN

The root growth pattern of the species studied had been determined during the studies (Table 2). The results provide important information as how tree anchorage is possibly affected by architecture. We discovered that the root branching pattern of *A. mangium* follows the model of root growth pattern by Yen (1972) as it roots grow horizontally (H-type) and it may have three roles in slope stabilization: soil reinforcement, slope stability and wind resistance. In assessing the root architecture of *L. leucocephala,* its root system seem more prominent in terms of depth of

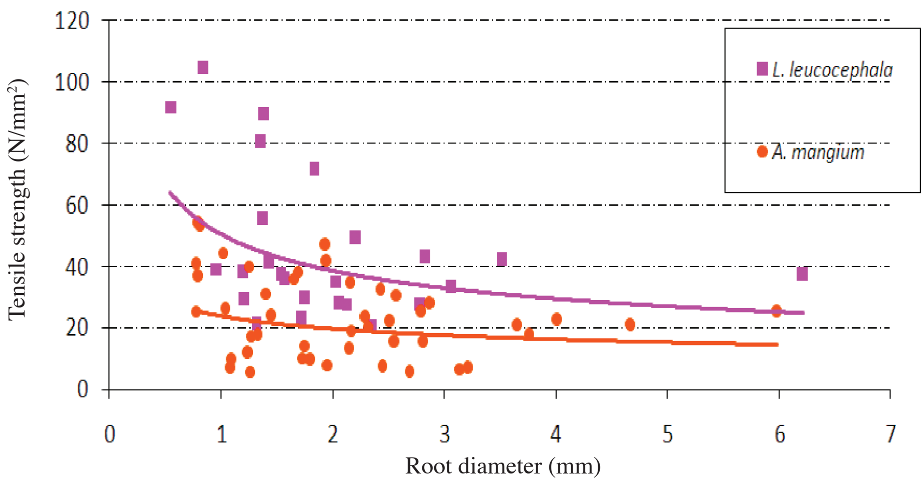


FIGURE 10. Tensile strength versus root diameter

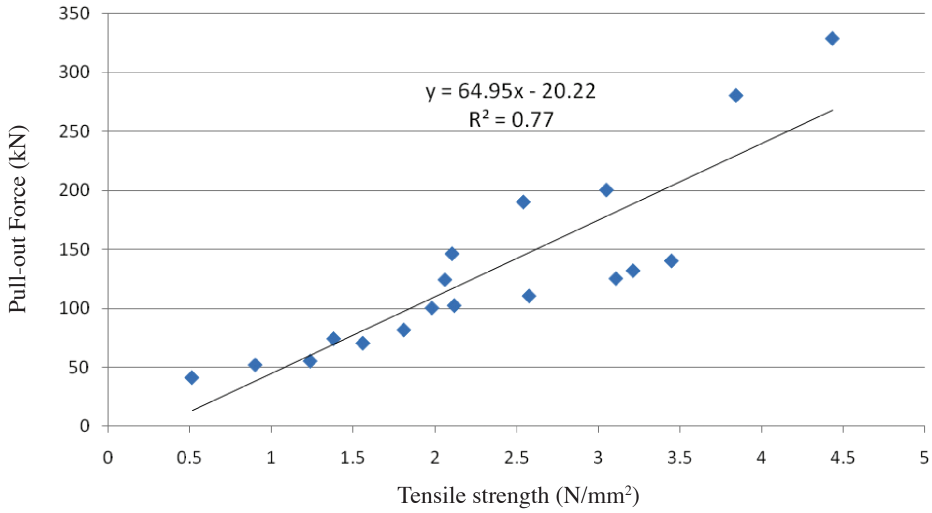


FIGURE 11. Relationship between pull-out forces versus root tensile strength

rooting, total root length, maximum lateral root distance and root length density (Table 2) which establish vertically and horizontally (VH-type), respectively, as compared to *A. mangium*. In comparison, root architecture of *L. leucocephala* is more prominent in the deeper soil depth as it has a combined reinforcement effect of both long tap and extensive lateral roots.

CONCLUSION

The pull-out resistance is observed to be affected by both shoot and root profiles. However the parameter studied was much affected by the root (Root Length Density) rather than the shoot profiles (e.g. shoot dry weight and stem diameter), indicating that root profile gives more attribution to pull-out capacities as compared to shoot. The results also imply that the soil stability will increase with time as the root system grows. As for the tensile strength, the value decreases with increasing root diameter. The results also showed that the pullout force is much affected by the tensile strength. It can be concluded that some root and shoot properties do have a great impact on root mechanical properties such as tensile and pullout strengths. In both parameters, *L. leucocephala* exhibits the highest values. The study also suggests that *L. leucocephala* has an added value as a good potential slope plant for slope stabilization work i.e. high resistance towards torrential runoff and prevent erosion, as it exhibits outstanding root mechanical properties.

ACKNOWLEDGEMENTS

This research was funded by Slope Engineering Branch, Public Works Department, Malaysia and partly sponsored by Ministry of Science, Technology and Innovation (the 9th Malaysian Plan).

REFERENCES

Abe, K. & Iwamoto, M. 1986. Preliminary Experiment on Shear in Soil Layers with a Large Direct-Shear Apparatus. *Journal of the Japanese Forestry Society* 68(2): 61-65.

Baets, S.D., Poesen, J., Wemans, K., Baerdemaeker, J.D. & Muys, B. 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil* 305: 207-226.

Cammeraat, E., Van Beek, R. & Kooijman, A. 2005. Vegetation succession and its consequences for slope stability in SE Spain. *Plant and Soil* 278: 135-147.

Collison. A.J.C., Anderson, G. & Lloyd, D.M. 1995. Impact of vegetation on slope stability in a humid tropical environment: a modelling approach. *Proceedings of the Institute of Civil Engineers: Water and Maritime Engineering* 112: 168-175.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., Baerdemaeker, J.D. & Muys, B. 2008. Root tensile strength and root distribution off typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil* 305: 207-226.

Genet, M., Kokutse, M., Stokes, A., Fourcaud, T., Cai, X., Ji, J. & Mickovski, S. 2008. Root reinforcement in plantations of Cryptomeria japonica D. Don: effect of tree age and stand structure on slope stability. *Forest Ecology and Management* 256: 1517-1526.

Genet, M., Stokes A., Salin, F., Mickovski, S.B., Fourcaud, T., Dumail, J. & van Beek, R. 2005. The influence of cellulose content on tensile strength in tree roots. *Plant and Soil* 278: 1-9.

Mickovski, S.B., van Beek, L.P.H. & Salin, F. 2007. Uprooting resistance of vetiver grass (*Vetiveria zizanioides*). In *Eco- and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability* 53-60, edited by Stokes et al.

Mickovski, S.B. & van Beek, L.P.H. 2009. Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizanioides*) plants grown in semi-arid climate. *Plant Soil* 324: 43-56.

Mitsch, W.J. 1998. Ecological Engineering-the 7-year itch. *Ecological Engineering* 10: 119-138.

Nilaweera, N.S. & Nutalaya, P. 1999. Role of tree roots in slope stabilization. *Bulletin of Engineering Geology and the Environment* 57: 337-342.

Normaniza, O., Faisal, H.A. & Barakbah, S.S. 2008. Engineering properties of *Leucaena leucocephala* for prevention of slope failure. *Ecological Engineering* 32: 215-221.

Norris, J.E. 2007. Root reinforcement by hawthorn and oak roots on a highway cut-slope in southern England. *Plant and Soil* 278: 43-53.

Reubens, B., Poesen, J., Danjon, F., Geudens, G. & Muys, B. 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: A review. *Trees - Structure and Function* 21: 385-402.

Stokes, A., Ball, J., Fitter, A.H., Brain, P. & Coutts, M.P. 1996. An experimental investigation of the resistance of model root systems to uprooting. *Annals of Botany* 78: 415-421.

Tosi, M. 2007. Root tensile strength relationships and their slope stability implications of three shrubs species in the Northern Apennines (Italy). *Geomorphology* 87: 268-283.

Van Beek, L.P.H., Wint, J., Cammeraat, L.H. & Edwards. J.P. 2005. Observation and simulation of root reinforcement on abandoned Mediterranean slopes. *Plant and Soil* 278: 55-74.

Yen, C.P. 1972. Study on the root system form and distribution habit of the ligneous plants for soil conservation in Taiwan. *Journal Chinese Soil and Water Conservation* 3: 179-204.

Normaniza Osman* & Mohamad Nordin Abdullah
Institut Sains Biologi
Fakulti Sains
Universiti Malaya
50603 Kuala Lumpur
Malaysia

Che Hassandi Abdullah
Ketua Unit Penyelidikan dan Perkembangan
Cawangan Kejuruteraan Cerun
Tingkat 12, Blok F, Ibu Pejabat JKR
Jalan Sultan Salahuddin
50582 Kuala Lumpur
Malaysia

*Corresponding author; email: normaniza@um.edu.my

Received: 21 May 2010
Accepted: 3 November 2010