https://doi.org/10.26525/jtfs2018.30.1.2538

MECHANICAL PULL-OUT CAPACITY AND ROOT REINFORCEMENT OF FOUR NATIVE TREE AND SHRUB SPECIES ON ECOLOGICAL REHABILITATION OF ROADSIDE SLOPES IN HONG KONG

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Submitted January 2017; accepted June 2017

Ecological rehabilitation using woody plants on roadside slopes has been gaining momentum in promoting urban biodiversity since 21st century. Many native tree and shrub species have been used for planting on roadside slopes. Yet, there is limited information in the local forestry and engineering literature on the mechanical properties and their relationship with above-ground characteristics, and the establishment method of native woody plants for shallow slope stabilisation. In this study, field pull-out tests were conducted to investigate the anchorage ability of two shrub (*Rhodomyrtus tomentosa* and *Melastoma sanguineum*) and two trees (*Schefflera heptaphylla* and *Reevesia thyrsoidea*) species. They have been commonly used in roadside slope rehabilitation in recent years. Samples were taken from planted and wild individuals. The plant pull-out resistance quantifies the degree of root reinforcement. The results showed that around 1 to 6 kN was required to uproot a 2 m plant. Trees exhibited better pull-out performance than shrubs. The planted trees had significantly stronger anchorage than natural ones. All the potential native plant species for slope rehabilitation should be screened by field pull-out test, to ensure their achievement of both urban biodiversity enhancement and slope stabilisation purposes.

Keywords: Above-ground characteristics, basal diameter, dry weight, plant height, root anchorage ability, slope stabilisation

INTRODUCTION

Hong Kong is a congested metropolis built on a hilly topography with a mean annual total rainfall (1971–2000) of 2383 mm (Hong Kong Observatory 2016). Only about 24% of the 1108 km^2 of land has been developed. The rest is either designated as country parks (40%) where development is prohibited or remains rural (36%) (Chan et al. 2016). The hilly topography at the fringe of secondary forests with weak residual, colluvial and saprolitic soils for rooting causes slope instability, posing a major geotechnical hazard and risk to livelihood (Ho et al. 2002). Traditionally, slope stabilisation work relies on the application of hard concrete slope coverings for infiltration and erosion control, but criticised as visually intrusive and unpleasant. Since the 1990s, in cities of Europe and North America, and progressively in Hong Kong, native species were planted for slope stabilisation which also enhanced urban landscape (Gray & Leiser 1982, (Coppin & Richards 1990, Barker 1995, Morgan & Rickson 1995, Schiechtl & Stern 1996, Hau & Corlett 2002, Zhang et al. 2013). Reinforcement of slopes by incorporating natural vegetation has been gradually recognised as an effective ecological rehabilitation approach for stabilising slopes at the periphery of highways, and without sacrificing the environment (Geotechnical Engineering Office 2011b).

Contribution of live vegetation to slope stability is provided by both hydrological and mechanical mechanisms. Studies on hydraulic performance of vegetation cover are the focus of slope safety investigations, since soil infiltration and saturation are key elements in triggering shallow slope failure (Geotechnical

Engineering Office 2011a). With substantial uplift in using vegetation on slope surface for engineering and landscape purposes, most researches focused on investigation on improving unsaturated soil hydraulic properties. Recent studies also elaborated on evapotranspiration and transpiration induced soil suction by reducing hydraulic conductivity, thus increasing shear strength and reducing the risk of slope failure (Garg et al. 2015, Gadi et al. 2016, Hazra et al. 2017). Research effort on studying impacts to soil mechanical properties with intervention of root systems, under basis of field trial experiments, are limited in tropical regions. Literature review on previous studies conducted in temperate regions has highlighted the importance of vegetation in reducing soil erosion rate, while improving slope stability with enhancement on soil shear strength from the mechanical and hydrological perspectives (Reubens et al. 2007, Abdi et al. 2010, Preti et al. 2010, Rees & Ali 2012, Leung et al. 2015, Ng et al. 2016).

Intrinsic stability of plants is a key factor for species selection on roadside slopes. In landslide events, shear stress along slopes is converted into pull-out force of trees, which is resisted by root anchorage (Khalilnejad et al. 2012). In previous studies, field pull-out tests of roots (Norris 2005, Docker & Hubble 2008) and plants (Nilaweera & Nutalaya 1999) were conducted to investigate the extent to which roots reinforce the ground stability. Some laboratory experiments of pull-out test with real plant roots (Ennos 1990) and analogue roots (Stokes et al. 1996, Hamza et al. 2007) were also carried out to study the load distribution and deformation behaviour of a root system. The pull-out resistance of a plant depends on the morphology and strength of the roots, and the interface friction between the root and the soils (Stokes et al. 2009). A root can either break or slip out when subjected to uprooting (Norris 2005).

Axial pull-out force of a plant is considered as an important indicator of slope stabilisation function as it reduces the shear stress built up on slope (Mickovski et al. 2009, Khalilnejad et al. 2012). It is considered as an indirect but quantitative measurement of the degree of root reinforcement and shear strength of the rooted soil (Leung 2014). In addition, when investigating the effect of wind on trees or massive soil movement passed to the roots, uprooting occurs if the anchorage of the root system is weak (Hamza et al. 2007). It is believed that an axial pull-out test gives a simple-yet-robust way to evaluate the contribution of roots to slope stability and plant stabilisation to external loadings, and is potentially considered as one of the key parameters in evaluating the efficacy of eco-engineering studies on slope stability (Tardío & Mickovski 2016). Modelling on axial pull-out test data has further supported the mechanical contribution of roots for slope stability (Yan et al. 2016).

Yet, there are limited studies on mechanical contribution on slope stability of plants in South East Asia. Effect of plant establishment methods, i.e. naturally established or planted, on root anchorage has yet been investigated through field trials. The holistic analysis of the relationship between pull-out resistance and co-existing above- and below-ground parameters may support implications for more accurate estimation on mechanical contribution, in terms of different plant types and individual species to slope integrity. The objectives of this study were to evaluate the effects of plant growth forms and establishment methods on uprooting, and to investigate the uprooting performance of the four native species in Hong Kong. It would also formulate a necessary parameter in screening plant species candidates for slope reinforcement.

MATERIALS AND METHODS

Hypothesis and study species

In this study, it was hypothesised that above-ground portions of plants are positively correlated with the extent of root anchorage on the soil substratum, reflected by the pull-out resistance. It was also hypothesised that trees are more resistant to uprooting than shrubs, given that the root architecture of trees is putatively adapted for supporting larger above-ground biomass. The hypothesis was tested by investigating the axial pull-out resistance of four native plant species that are commonly used on slope rehabilitation in Hong Kong: two shrubs *Rhodomyrtus tomentosa* and *Melastoma sanguineum*, and two trees *Schefflera heptaphylla* and *Reevesia thyrsoidea*. These four species are recommended for ecological slope rehabilitation in Hong Kong (Geotechnical Engineering Office 2011b). They are common and widespread in the natural environment in Hong Kong. They exhibited high survival and growth rates as well as high ornamental and ecological values when planted on roadside slopes (Or et al. 2011). In addition, they are highly tolerant to sunlight and drought which are typical environments of roadside slopes (Geotechnical Engineering Office 2011b). Their general characteristics are tabulated in Table 1.

Individuals with varied height, basal diameter and above-ground dry weight were sampled for the test. Plant height was measured from ground level to the terminal bud of the tallest stem, while basal diameter was the stem diameter at ground level. For shrub samples with multiple stems, the basal diameter of the most robust stems was identified and measured. Plant specimens from the wild and those planted on slopes were also tested, as it was speculated that different seedling establishment types would influence the root system development. The study would provide a quantitative basis for assessing slope stabilisation abilities of both trees and shrubs for roadside slopes in Hong Kong and southern China.

Field pull-out test

Plant samples, established differently (i.e. container-grown and naturally established) were investigated by field pull-out test. The container-grown samples were planted on man-made slopes with average dry density of 1.54 g cm^{-3} at Kadoorie Center, The University of Hong Kong (HKUKC). The wild individuals grew naturally on natural slopes with average dry density of 1.30 g cm^{-3} in Tai Tam, Lung Fu Shan and Tai Lam Country Parks. The soil at all sites are completely decomposed granite, which is the typical soil type in Hong Kong (Dudgeon & Corlett 2011).

Prior to each pull-out test, plant characteristics including height (H) and basal diameter (BD) were measured. The soil moisture content at ground surface and suction measured at 30 cm below ground near uprooted plants, measured by soil moisture probes and jet-filled tensiometers respectively, were also recorded. The plant was cut at about 0.15 m above ground, chopped to manageable size and sealed in bags. They were then brought to the laboratory on the same day to determine the above-ground dry weight (W) after oven-drying overnight at 105 °C. The tests were carried out in both dry and wet seasons from 2011 to 2013.

Pull-out apparatus were developed to determine the pull-out resistance of a plant. The plant pull-out equipment comprised of a reaction frame, a 10 kN load cell, a displacement transducer and a winch system (Figure 1). The sensors were connected to an automated data acquisition system. The stem was tied to the winch by a connecting wire to uproot the plant steadily, having the pull-out resistance (P) and uprooting displacement (s) continuously monitored. Sand papers were placed between the stem and the wire to maximise the interface friction and to reduce the occurrence of stem failure.

Table 1 General characteristic of the studied species (Halcrow China Ltd 2011)

Scientific name	Common name	Family	Growth habit	Normal height (m)	Environmental tolerance	Soil conditions tolerance	Slope characteristics
Rhodomyrtus tomentosa	Rose Myrtle	Myrtaceae	Shrub	1–2	Wind, salt, fire, drought, pollution and light tolerant	Infertile, loose/ compacted soil, slightly acidic	Gentle - steep slopes; exposed; coastal and roadside locations
Melastoma sanguineum	Blood-red Melastoma	Melastomaceae	Shrub	1–2	Wind, drought, pollution, light	Infertile, slightly acidic	Gentle - steep slopes; exposed; coastal and roadside locations
Schefflera heptaphylla	Ivy tree	Araliaceae	Tree	> 10	Wind, salt, drought, pollution, light and shade tolerant	Slightly acidic	Gentle slopes; exposed/shaded; roadside
Reevesia thyrsoidea	Reevesia	Sterculiaceae	Tree	5–10	Wind, fire, drought, pollution, light tolerant	Infertile, slightly acidic	Gentle slopes; exposed; roadside

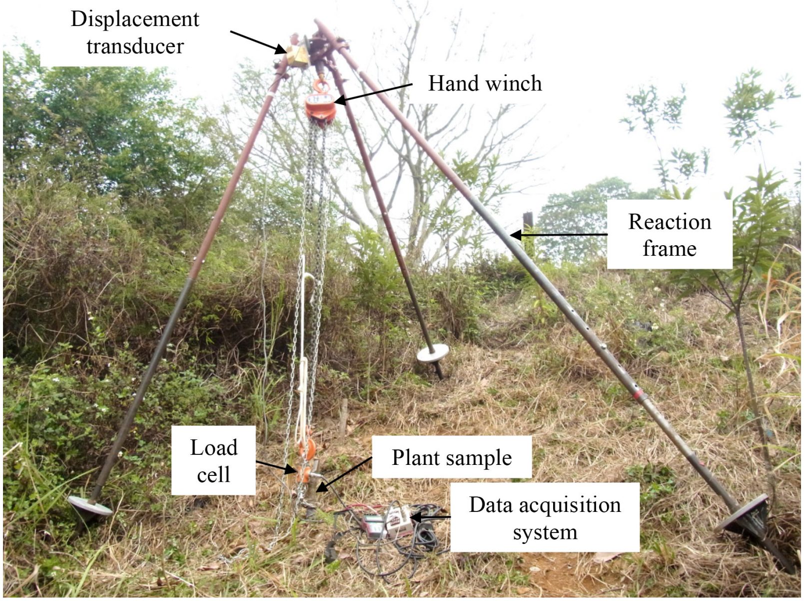


Figure 1 The field pull-out apparatus assembled for the study (Yan et al. 2016)

Data analysis

Correlation between the peak pull-out resistance (P_{max}) and the aforementioned above-ground parameters (H, BD and W) were investigated by Pearson correlation test. Predicting P_{max} with more parameters other than those determined by stepwise analysis, may reduce the statistical significance of fitting. The most significant parameters, identified by linear regression with stepwise mode, were considered as the best parameters for the prediction of P_{max}. To check the normality and homogeneity of variance, Komogorov-Smirnov's and Levene's test were conducted on log-transformed P_{max}. One-way analysis of variance (ANOVA) was used to test the difference of log-transformed P_{max}, between different species and establishment types. Fisher's least significant difference (LSD) test was finally used to identify the species with significant differences. All statistical analyses were conducted by using SPSS 17.0.

RESULTS

General pull-out response

A total of 208 plant samples of the four species were successfully uprooted, and the peak pull-out resistance and displacement were recorded (Table 2). The soil moisture content and suction near the uprooted plants ranged between 11 and 35% and 28 and 35 kPa, respectively, just prior to the pull-out tests.

In general, the pull-out resistance gradually increased to a peak value P_{max} at uprooting displacement, s_p. Fluctuation of the pull-out resistance during the uprooting process can be readily seen, especially in *S. heptaphylla* (Figure 2). On the other hand, the resistance-displacement curve of *R. thyrsoidea* was generally smoother and showed a distinct peak prior to the gradual drop. The pull-out resistance of the shrub *R. tomentosa* sample was rather steady without obvious sharp peak because of the low tensile force of its abundant fine and flexible roots (Leung 2014, Leung et al. 2015) (Figure 3a). Its pull-out resistance may also have been contributed by the soil shear strength as the networks of fine roots were uprooted with an assemblage of soil matrix (Figure 4a). If the soil was compacted, soil matrix was pulled out with the root systems (Figure 4b). Almost all plants were uprooted by tensile failure of the roots at various depths. It could be seen that uprooting ranged from brittle (small, s_p) to very ductile responses (very large, s_p). One *R. tomentosa* sample even exhibited a s_p at 530 mm (Figure 2).

The uprooted samples in Figure 3 echoed the pull-out performance shown in Figure 2. The number of significant peaks in resistance-displacement curve was consistent with the occurrence of major root-soil failure. When a tensile breakage of a major load carrying root

Table 2 Summary of the field pull-out tests of 208 individuals of the four plant species

Establishment types	N	Above-ground characteristics			Pull-out response	
		H (m)	BD (mm)	W (g)	P_{max} (kN)	s_p (mm)
Rhodomyrtus tomentosa						
Natural	27	1.21 ± 0.45	13.51 ± 5.43	189.70 ± 244.14	0.64 ± 0.50	138.41 ± 60.65
Planted	28	0.99 ± 0.37	15.39 ± 5.90	127.84 ± 156.7	0.77 ± 0.59	101.48 ± 105.35
Melastoma sanguineum						
Natural	19	1.26 ± 0.49	17.43 ± 11.76	212.69 ± 337.22	0.84 ± 0.74	75.14 ± 58.06
Planted	15	1.21 ± 0.43	31.50 ± 20.17	251.99 ± 293.46	1.06 ± 0.99	124.33 ± 89.11
Schefflera heptaphylla						
Natural	27	1.35 ± 0.58	28.14 ± 15.02	168.43 ± 166.56	1.92 ± 1.50	103.99 ± 67.99
Planted	31	1.70 ± 0.75	47.53 ± 19.23	1260.47 ± 1029.88	5.48 ± 3.89	197.87 ± 109.80
Reevesia thyrsoidea						
Natural	29	1.70 ± 0.76	19.22 ± 6.90	143.32 ± 142.11	1.94 ± 1.40	75.22 ± 49.06
Planted	32	2.08 ± 0.91	33.91 ± 14.78	666.05 ± 797.65	4.78 ± 3.44	217.48 ± 155.65

H = height (m), BD = basal diameter (mm), W = above-ground dry weight (g) of the native species, P_{max} = peak pull-out resistance (kN), s_p = uprooting displacement

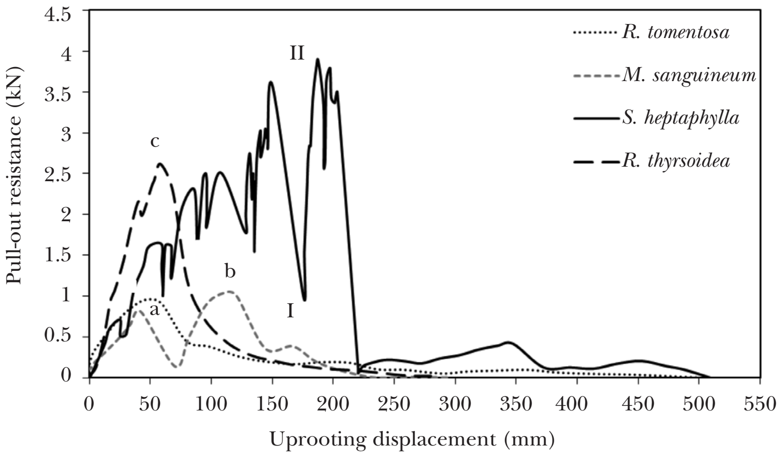
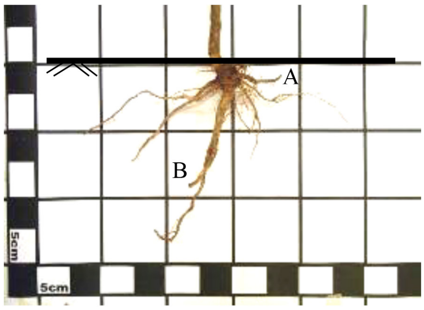


Figure 2 General pull-out responses of the four species; *S. heptaphylla*: peaks show multiple root breakages during vertical pull-out; I = drastic drop in P_{max} showing major root breakage, II = sharp rise in P_{max} afterwards showing that another major root is carrying the load; *M. sanguineum*: peaks a and b indicate two sequential root breakages which correspond to Figure 3 (A and B); *R. thyrsoidea*: peak c indicates one root breakage which fits in with its tap root system, as shown in Figure 3d

occured, an abrupt drop of the pull-out resistance was observed, eg. *M. sanguineum* and *S. heptaphylla* (Figure 2). On the other hand, a gradual decrease in the resistance was exhibited when the load carrying root slipped out from the soil, eg. *R. thyrsoidea* (Figure 2). The decreasing resistance increased again when another root was stretched and carried the load. In other words, the strength of other root branches was mobilised, which subsequently lead to the increase in resistance, eg. *S. heptaphylla,* (Figure 2, I–II). Therefore, the multiple local peaks seen in *S. heptaphylla* can be explained from the perspective of progressive failure of the root system until the entire plant was uprooted. The *S. heptaphylla* (Figure 3c) clearly showed many thick broken roots, whereas two main broken roots was seen in *M. sanguineum,* (Figure 3b, A and B). The two broken roots in *M. sanguineum* correspond with the number of peaks on $P_{max,}$ (Figure 2, a and b). The *R. thyrsoidea*

(a) *R. tomentosa*



(b) *M. sanguineum*

(c) *S. heptaphylla*

(d) *R. thyrsoidea*

Figure 3 Root systems of uprooted plants: a = *R. tomentosa,* b = *M. sanguineum,* c = *S. heptaphylla and* d = *R. thyrsoidea;* grids = 5 cm × 5 cm, thick black line = root collar (ground level)

(a) *R. tomentosa*

(b) *R. thyrsoidea*

Figure 4 Uprooted root samples with assemblages of soil matrix, a = *R. tomentosa* sample with many fine roots and b = *R. thyrsoidea* sample in compacted soil

essentially had one tap root which broke at about 83 cm below the ground level (Figure 3d, C). This root morphology perfectly fits the pull-out performance of the plant in which one single peak resulted from root rupture can be identified (label c on Figure 2) and the peak is followed by a gradual drop in the pull-out resistance (root slipping out).

Correlation between P_{max} and above-ground characteristics

Positive correlation was seen between P_{max} and each of the above-ground characteristics (Table 3). The P_{max} of all the tree samples and *M. sanguineum* had significant correlation with all of the four above-ground plant parameters ($p < 0.001$). However, P_{max} of *R. tomentosa* was only significantly correlated to all above-ground parameters among the planted samples ($p < 0.001$) instead of the natural ones. All of the measured above-ground characteristics of natural *R. tomentosa* had no relationship with P_{max} (Table 3).

With the consideration of all three parameters by stepwise regression analysis, the best above-ground indicator(s) for P_{max} were determined (Table 4). Generally, the best indicators for the prediction of P_{max} were basal diameter and above-ground dry weight. Solely above-ground dry weight, or with height as well, were the best indicators to predict the P_{max} of planted shrubs ($R^2 = 0.817$, $p < 0.001$). Yet, basal diameter of

Table 3 Pearson correlation coefficient (r) between P_{max} and the above-ground parameters including height (H), basal diameter (BD) and above-ground dry weight (W) of the native species

Species	Establishment methods	N	H	BD	W
Rhodomyrtus tomentosa	Natural	27	0.351	0.315	0.316
	Planted	28	0.733***	0.723***	0.817***
Melastoma sanguineum	Natural	19	0.728***	0.935***	0.886***
	Planted	15	0.793***	0.920***	0.939***
Schefflera heptaphylla	Natural	27	0.437*	0.735***	0.843***
	Planted	31	0.763***	0.868***	0.891***
Reevesia thyrsoidea	Natural	29	0.703***	0.751***	0.696***
	Planted	32	0.759***	0.841***	0.741***
Shrubs	Natural	46	0.545***	0.740***	0.633***
	Planted	43	0.760***	0.791***	0.893***
Trees	Natural	56	0.558***	0.653***	0.774***
	Planted	63	0.706***	0.825***	0.812***

*** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$

Table 4 Significant prediction of P_{max} determined by stepwise regression analysis with selected plant parameters

Species	Establishment method	N	Peak pull-out resistance P_{max} (kN)	R^2
Rhodomyrtus tomentosa	Natural	27	N/A	N/A
	Planted	28	0.003 W + 0.378	0.668***
			0.002 W + 0.576 H – 0.082	0.746***
Melastoma sanguineum	Natural	19	0.059 BD – 0.183	0.862***
	Planted	15	0.003 W + 0.256	0.882***
Schefflera heptaphylla	Natural	27	0.008 W + 0.644	0.710***
	Planted	31	0.003 W + 1.229	0.891***
Reevesia thyrsoidea	Natural	29	0.149 BD – 0.894	0.557***
	Planted	32	0.196 BD – 1.858	0.708***
Shrubs	Natural	56	0.051 BD – 0.047	0.528***
	Planted	43	0.003 W + 0.344	0.798***
			0.003 W + 0.393 H + 0.017	0.817***
Trees	Natural	56	0.007 W + 0.835	0.599***
	Planted	63	0.165 BD – 1.567	0.680***
			0.128 BD + 1.162 H – 2.274	0.720***

H = height (m), BD = basal diameter (mm), W = above-ground dry weight (g) of the native species; *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; N/A = P_{max} cannot be predicted by any tested plant parameters the natural shrubs was the most important for prediction of P_{max} (R^2 = 0.528, $p < 0.001$). The P_{max} of both natural and planted tree samples of *S. heptaphylla* and *R. thyrsoidea* could be significantly estimated by above-ground dry weight and basal diameter respectively ($p < 0.001$).

Comparison between species and establishment methods

Similar P_{max} was exhibited among shrub and tree species. However, there was significant difference in P_{max} between the native shrubs and trees (ANOVA: F = 13.085, $p < 0.001$; LSD: $p < 0.002$). Both shrub species had similar P_{max} in planted and natural samples (Figure 5a and b). Yet, tree species showed significant higher P_{max} in planted samples, than natural samples; *S. heptaphylla*: F = 14.405, $p < 0.001$; *R. thyrsoidea:* F = 13.085, $p < 0.001$ (Figure 5c and d).

DISCUSSION

Mechanism of root anchorage

A root system usually comprises of many rooting branches with different diameters (various tensile strengths and material modulus of elasticity) and lengths. The tensile strength and material modulus of elasticity of the studied species was investigated by Leung (2014) and Leung et al. (2015). Power decay relationship was found between root diameter and the two mechanical properties. The growth of root systems implies degree of root anchorage, and are found to be reflected by the above-ground portions of plants (Sundström & Keane 1999, Leung 2014).

Soil-root interfacial shear strength and root tensile strength are the governing factors of uprooting preceding soil condition (Yan et al. 2016). The dominated uprooting mechanism is root breakage, which takes place if root-soil frictional force is larger than root tensile force, in case the roots extend deep into the ground with high soil confining stress to roots. Generally, breakage occurs at weak points, such as nodes or branches (Norris 2005). Only roots close to the stem are stressed during uprooting (Ennos 1990, Hamza et al. 2007) as long as the soil density is high enough to fix the roots in deep ground without root slippage. The distal portion of roots, far from trunk flare, are slightly or not-at-all stressed, mechanically. Plants with more branches on main roots, closer to ground surface, have stronger anchorage.

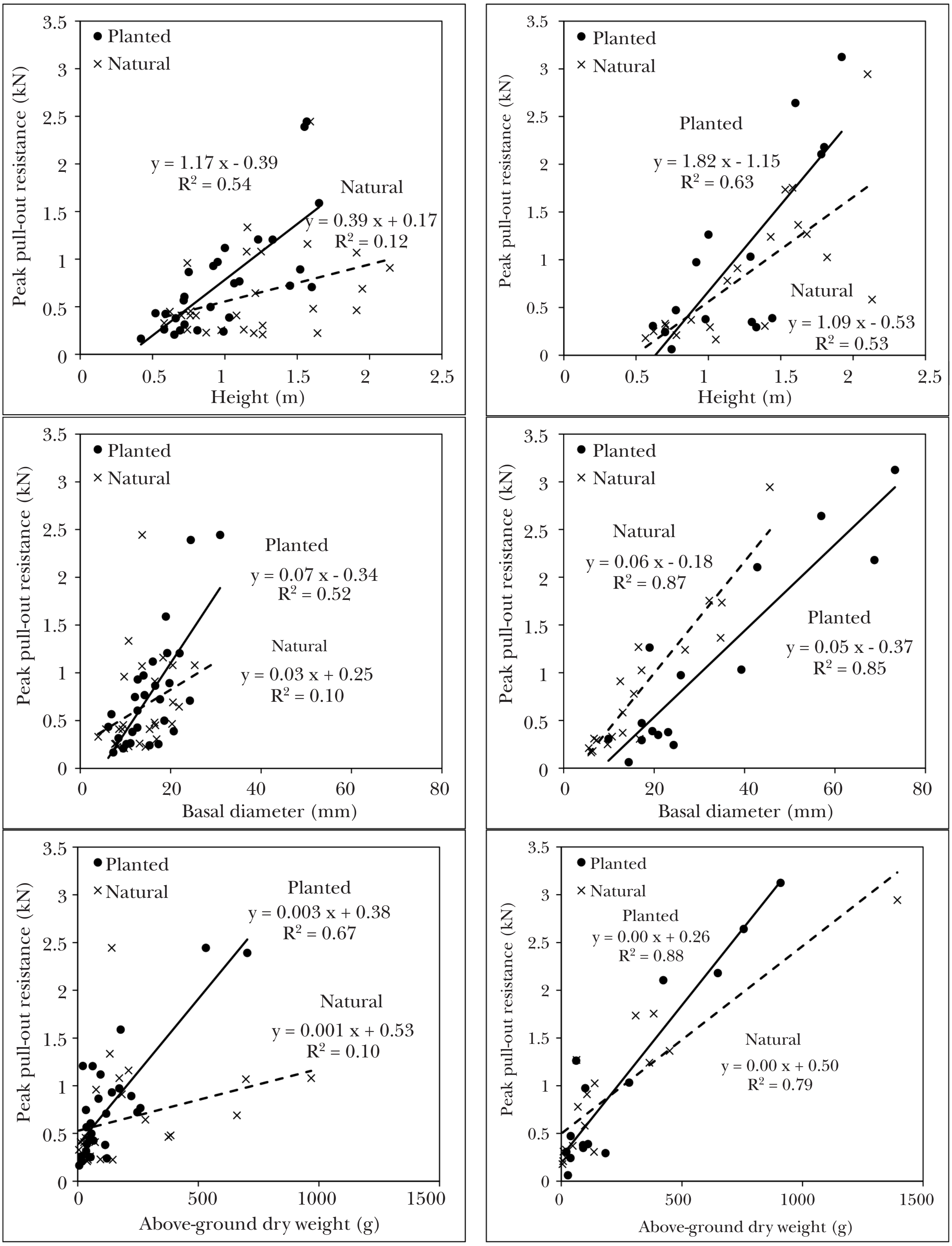
Exhibiting fluctuated pull-out resistance against uprooting displacement, the failure of a plant subjected to axial uprooting was resulted from the progressive failure (rupture and slipping) of individual roots. Multiple-branched root samples produced stepped peak resistance, corresponding to sequentially broken roots (Norris 2005). This was proved by the creepy sound initiated from the breakage of root segment during the field test. Therefore, the root morphology of a plant sample is the key factor influencing its overall shape of the resistance-displacement curve (Docker & Hubble 2008).

In this study, both shrub species were found to have thinner and smaller root mass, while the two tree species had bigger and larger root mass. The *S. heptaphylla* showed a plate root system, but *R. thyrsoidea* appeared to have a taproot system which grew deep into the ground (Figure 3). Due to the increasing soil density and confining stress to roots in depth, high root-soil friction is mobilised during uprooting. Both, increase in root tortuosity and branching numbers, contributed to additional root-soil interface friction (Schwarz et al. 2010). Field observations showed that, complete root system could be uprooted if it consisted of a single vertical taproot without any branches, and limited root-soil friction was mobilised. This situation was found in some immature *R. thyrsoidea* samples.

Compaction is a typical process in slope formation and thus results in soil denser than in-situ one. Soil aggregates are compressed to form larger clumps during the process of compaction. During uprooting, if the bonding between soil clumps is weaker than root-soil bonding, soil clumps enclosing the root systems will be pulled out in addition to high density of fine roots (Leung 2014).

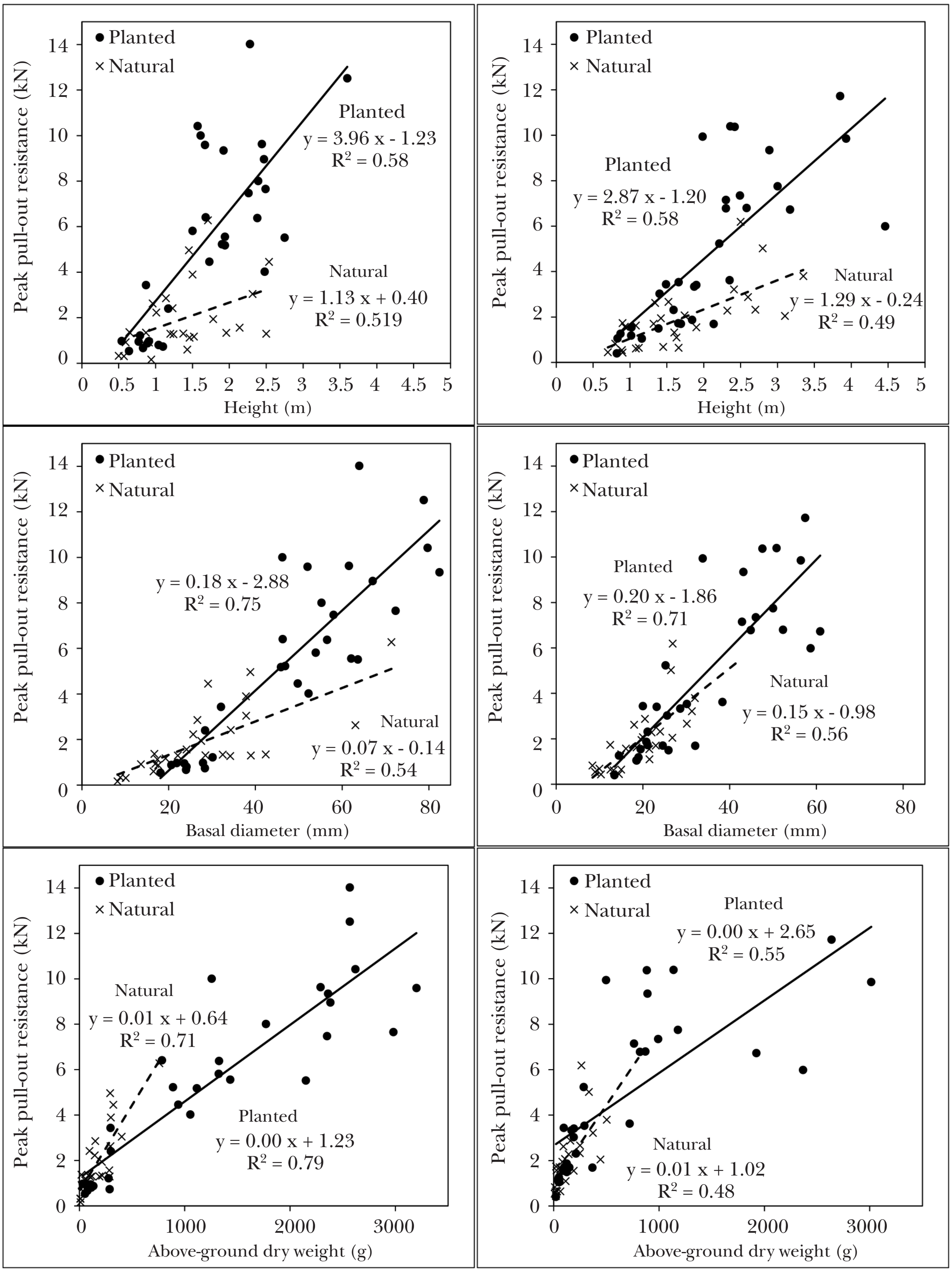
Effects of root characteristics on plant pull-out resistance

Plant pull-out resistance greatly depends on root morphological features (root distribution with depth and different root diameter classes), root mechanical properties (tensile strength and elastic modulus) and root-soil interface friction (Greenway 1987, Abe & Ziemer 1991, Leung et al. 2015). More robust root systems, with large root biomass, have higher pull-out resistance (Ennos



(a) *R. tomentosa* (b) *M. sanguineum*

Figure 5 (Continued)



(c) *S. heptaphylla* (d) *R. thyrsoidea*

Figure 5 Correlation between the peak pull-out resistance P_{max} of the planted seedlings and natural samples with plant height, basal diameter and above-ground dry weight, a = *R. tomentosa*, b = *M. sanguineum*, c = *S. heptaphylla* and d = *R. thyrsoidea*

2000, Leung 2014). This was demonstrated in this study where two tree species with longer and thicker roots and larger root biomass had significantly higher P_{max} (by 77%), than the shrub species (Table 1).

Compared with wild individuals of similar above-ground size, the planted samples had larger root systems with higher abundance of roots in general (Leung 2014). This contributed to higher P_{max} (by 62%) in planted samples, than natural tree samples. Denser root architecture in planted samples was mainly attributed to initial seedling establishment and soil quality of the planting site (Leung 2014). The container-grown seedlings were planted in polystyrene bags in the nursery before being transplanted. High root concentration at the center might be due to the restriction of bags. This facilitated the development of heart root systems in planted seedlings. This implies the feasibility of using live vegetation as slope stability measure. Secondly, although natural soil condition is less compacted and much fertile, which is more favorable for overall plant growth, soil with poor quality on man-made slopes, instead, may trigger the growth of roots for obtaining more soil resources, and thus having more extensive root systems. (Bongarten & Teskey 1987, Becker et al. 1999, Markesteijin & Poorter 2009, Leung 2014). However, the major premise is the establishment of seedlings. Once the plants could establish in poor soil, they could grow well generally and have strong root anchorage (Leung 2014).

Relationship between pull-out resistance and above-ground characteristics of plants

Above-ground structures of plants reflect the growth of root systems, and thus the root anchorage. Sundström and Keane (1999) have found a close relationship of above- (trunk diameter and shoot fresh weight) and below-ground (root fresh weight and cross-sectional area) growth of Douglas fir in Ireland. Potentially, the mechanical stability of plant species grown on man-made slopes could be estimated by certain above-ground characteristics. In our stepwise regression analysis, plant height was found to be the least reliable predictors of P_{max} of the studied species (Table 4). The dry weight ratio of root to shoot (R:S) of certain species with the same ages and establishment methods is expected to be in the same range under identical environmental conditions (Bongarten & Teskey 1987, de Vries & Lam 1997, Becker et al. 1999, Toukura et al. 2006, Markesteijin & Poorter 2009, Tsakaldimi et al. 2009). Therefore, the root biomass is expected to be positively proportional to that of the shoot. In this study, root systems with higher biomass had higher resistance against uprooting (Table 3).

Unlike above-ground dry weight, plant basal diameter can be measured without killing a tree. Basal diameter was also the best P_{max} predictor for *R. thyrsoidea* (Table 4). Over 70% of the individuals had obvious vertical taproots without many thick lateral roots. Larger stem basal diameter does not only imply thicker taproot but also deeper rooting depth, if the taproot grows vertically. With high soil density and confining stress, roots penetrating deeply in soil undergo very high friction when uprooting.

With more standardised shoot growth form, the above-ground characteristics of trees affect the root growth and anchorage, to a higher extent than shrubs. Tree is defined as having a single erected stem branching at some distance from ground level whereas shrub is woody plant with multiple stems growing from ground (Thomas 2014). The P_{max} of the two native tree species was found to be significantly correlated with all above-ground plant parameters (H, BD and W) (Table 3). Comparable pull-out resistance of some Thailand tree species of similar height was also recorded in a previous study (Nilaweera & Nutalaya 1999). Among the shrub species, the growth of *M. sanguineum* is relatively predictable, which explains the more significant correlation between its P_{max} and plant parameters, than that of *R. tomentosa* (Table 3). The planted *R. tomentosa* had more predicted anchorage ability by the above-ground characteristics than the naturally established ones, due to the more standardised growth form of the container grown seedlings (Table 3).

The pull-out test demonstrated that trees were more resistant to uprooting than shrubs even though they are of similar size. The results suggested that pull-out resistance can probably be explained by the life form of a plant. Root architecture of shrubs and trees has been shown to differ from each other (Becker & Castillo 1990, Paz 2003, Saifuddin & Normaniza 2016). Deeper tap root in trees is developed in saplings as a drought avoidance mechanism, as trees experience a larger transpiration stress than shrubs (Robichaux et al. 1984). Furthermore, species established in later successional stages, such as *S. heptaphylla*, are often more shade-tolerant than those in early stage as they have to compete with vegetation which exist prior to their recruitment. Higher allocation of biomass to roots in late-successional species was suggested to be an adaptation to extend seedling survival in the shade (Kitajima 1996). Another plausible explanation for the greater anchorage by trees is that it serves as a requirement for physical support of their above-ground biomass, which is larger than shrubs (Becker & Castillo 1990). It was consistently observed that shrubs have relatively shallow root systems but greater root surface area, where tap root is often lacking (Becker & Castillo 1990, Paz 2003).

CONCLUSIONS

Multiple peaks in resistance-displacement curve corresponded to progressive root failure during uprooting. With deep root extension and high soil density of deep ground, root breakage was the dominant failure mechanism. With investigation of plant pull-out resistance, positive correlation was found between the above-ground portions of plants and their root anchorage magnitude on soil substratum. Basal diameter and above-ground dry weight were found to be the most reliable predictors of plant pull-out resistance, in general. The investigated trees had stronger anchorage against uprooting than the shrubs. Planted trees mobilised higher P_{max} than natural ones, although the difference in mechanical performance between the planted and natural shrubs was insignificant. Similar anchorage magnitude was found between the species, in similar growth form. This can be further proven by evaluating pull-out anchorage magnitude on wider spectrum of plants, being utilised on eco-engineering. Findings in this investigation contributed crucial numerical dataset for evaluating the application of commonly used woody species for roadside slopes stabilisation in Hong Kong and southern China, with similar climatic and pedological parameters.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the research grant HKUST9/CRF/09 and HKUST6/CRF/12R, provided by Research Grants Council of the Hong Kong Special Administrative Region (HKSAR).

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