Root systems of native shrubs and trees in Hong Kong and their effects on enhancing slope stability

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ABSTRACT

Objectives: Mechanical reinforcement by plant roots is believed to have an important role in stabilizing highly saturated slopes against shallow failure. In this study, the root system of four Hong Kong native shrubs (Rhodomyrtus tomentosa and Melastoma sanguineum) and trees (Shefflera heptaphylla and Reevesia thyrsoida) with height that ranged between 1 and 1.5 m was sampled and their characteristics were studied.

Methods: The distribution of roots and root area ratio (RAR) with depth, relationship between root tensile strength (Tr) and root diameter (dr), and also the variation of root cohesion (cr) with depth of the four species were investigated and statistically compared.

Results: Roots of the studied trees were found to extend deeper into the ground (up to 0.8 m) as compared to the shrubs (up to 0.4 m). RAR lies between 0.03 and 0.14% for the top 0.1 m soil and decreased with depth. The obtained Tr–dr relationship of all the studied species fell into the same order as compared to some commonly reported European species. Besides, conventionally adopted power relationship between Tr and dr was confirmed to be applicable for the studied species. The variation of root cohesion with depth was investigated for each species. Root cohesion of less than 1.5 kPa was evaluated for even the top 0.2 m soil when roots with a diameter that ranged only between 1 and 10 mm were considered. The contribution of roots to slope stability was studied on infinite slopes with and without vegetation under two hydrological scenarios (dry and wet slopes).

Conclusions and implications: It was found that the studied young vegetation can bring an unsafe slope to marginal safety (factor of safety slightly larger than unity). Moreover, the studied tree species did not outperform the shrubs. © 2014 Elsevier B.V. All rights reserved.

1. Introduction

Hong Kong, having a hilly terrain with the natural hillsides composed of residual, colluvial and saprolitic soils, is subjected to the subtropical climate with frequent rainstorms. The mean annual rainfall was recorded as high as 3000 mm in the period 1981 to 2010 (HKO, 2012a). According to the records made by the Hong Kong Observatory, averaged from the period of 2001–2010, Hong Kong was affected by 5 tropical cyclones per year with typhoon warning signals hosted for approximately 200 h annually (HKO, 2012b; HKO, 2012c). Although some cyclones may not hit Hong Kong directly, they often brought to the city long duration of heavy rainfall. Rainfall triggered landslides were commonly observed. Cheung et al. (2006) reported that there are around 350 landslides each year in Hong Kong. Most of the landslides are shallow ones with the failure depth less than 1 m (Au, 1998).

The use of shotcrete cover together with soil nails installing into the slope was the most common slope stabilization measure. The rationale behind shotcrete cover is to reduce rainwater infiltration and surface erosion. However, the use of shotcrete can no longer satisfy the public's urge to have a green and sustainable environment. The shotcrete cover prohibits the growth of plants on slopes and therefore gives very low ecological values. In light of this, the use of live vegetation as slope covers appears to offer an attractive solution. First, live plants induce soil suction by evapotranspiration. The shear strength of soil is thus increased (Indraratna et al., 2006; Pollen, 2007; Preti et al., 2010; Rees and Ali, 2012; Simon and Collison, 2002). Second, plant roots reinforce the soils by transferring the soil's shear stress into root tensile resistance through the soil-root friction (Abdi et al., 2010; Gray and Sotir, 1996; Greenway, 1987; Operstein and Frydman, 2000; Reubens et al., 2007; Schiechtl, 1980; Schmidt et al., 2001; Stokes et al., 2009; Xu et al., 2011). This is often quantified through the introduction of additional cohesion called root cohesion (Abe and Ziemer, 1991; Bischetti et al., 2005; Operstein and Frydman, 2000; Stokes et al., 2008; Waldrion and Dakessian, 1981).

Greening technique has been promoted by the Hong Kong Government for only a few years. Technical guidelines have been recently published with a list of recommended native plant species for landscape treatment based on their growth characteristics, ornamental and ecological values (GEO, 2011). Yet, the performance of these native plant species on enhancing slope stability has not yet been completely investigated. In this study, two Hong Kong native shrubs (Rhodomyrtus tomentosa and Melastoma sanguineum) and trees (Shefflera heptaphylla and Reevesia thyrsoida) with height that ranged between 1 and 1.5 m were investigated. The rationale behind the use of native plants for slope stabilization is their adaptation to local environmental conditions. Such plants have higher chance to establish and grow due to their better fitness and tolerance to adverse conditions. Hence, the results obtained in this study can be applied to other slopes in study areas.

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2. Materials and methods

2.1. Sampling

The root systems of the four selected species were sampled on the hillsides in Tai Lam, Tai Tam, and Lung Fu Shan Country Parks as well as the Kadoorie Institute Shek Kong (KISK) of the University of Hong Kong between 2011 and 2013. The average gradient of the slopes was around 25°. As plant age cannot be accurately determined, plants were chosen by their height. For all species, plants ranged between 1.0 and 1.5 m high were sampled. Living root system of each plant was carefully removed manually by hand-held tools. Dead roots can be distinguished by discoloration, shriveling and tissue deterioration of roots (Harris et al., 2004; Watson, 2009). Attempts have been made to keep the root system intact and to retain the original root structure and distribution as much as possible. Photos of the retrieved plants were taken for records. To preserve live roots for tensile strength tests, the root system was sampled on the plant. Spatial distribution of the root system of a plant was investigated. Roots thicker than 0.5 mm in diameter were neglected as they were neither easy to be identified nor measured precisely. It is worth noting that any broken/loss root segments during the excavation/retrieval process will underestimate the RAR but it turns out to be on the safe side when the information is used to compute the shear strength of the rooted soil. It is assumed that RAR varies exponentially with depth \( z \) as illustrated below

\[
\text{RAR} = h_1 e^{-h_2 z} \tag{2a}
\]

where \( h_1 \) and \( h_2 \) are two positive empirical fitting coefficients to be determined from the data. The two coefficients are species dependent.

2.2. Root distribution and root area ratio (RAR) measurements

Spatial distribution of the root system of a plant was investigated. Roots thicker than 0.5 mm were measured at 50 mm depth interval up to the maximum root depth of the plant. At each level, the roots were divided into diameter classes of 0.5 mm interval and the number of roots in each class was recorded. Furthermore, the root area ratio (RAR) at different depth level was calculated by assuming all roots have a circular cross section. RAR is defined as the fraction of an effective soil cross-section area \( A, \text{m}^2 \) occupied by total root cross-sectional area \( A, \text{m}^2 \) at a certain depth (Gray and Leiser, 1982; Gray and Sotir, 1996). RAR varies with depth and is required when one wants to estimate the root contribution to soil strength.

\[
\text{RAR} = \frac{A}{A} = \frac{\sum_{i=1}^{n} n d_i^2 / 4}{A} \tag{1}
\]

where \( d_i \) indicates the diameter of the \( i \)-th root among a total of \( n \) identified roots. Roots finer than 0.5 mm in diameter were neglected as they were either not easy to be identified nor measured precisely. It is worth noting that any broken/loss root segments during the excavation/retrieval process will underestimate the RAR but it turns out to be on the safe side when the information is used to compute the shear strength of the rooted soil. It is assumed that RAR varies exponentially with depth \( z \) as illustrated below

\[
\log(\text{RAR}) = \log(h_1) - h_2 \log(z) \tag{2b}
\]

2.3. Root tensile strength tests

The fresh roots were cut into segments with standardized length of 150 mm for tensile strength test. The cut segments were then stored in 15% ethanol at 4 °C (De Baets et al., 2008). All roots were tested within a month after collection to minimize root deterioration. The testing set-up was tailor-made. It comprised a 2 kN load cell (TCLA-2kNB), a displacement transducer (TML DP-2000E), an electric motor, two ring clamps, and a data acquisition unit to evaluate the root tensile strength (Fig. 1). Before the test, thick periderm at the two ends of root fibers was removed while the periderm of the root body was retained (Genet et al., 2007). The root was fixed by the machine by two ring clamps. Sand papers and rubber sheets were placed between the clamps and the testing root to prevent it from slipping and to reduce the stress concentration, respectively (De Baets et al., 2008). During the tests, the root tensile force and elongation was recorded continuously. The elongation speed was kept constant at 8 mm/min until the root was ruptured. Tensile strength \( T_r \), MPa, of the root fiber was calculated by dividing the maximum tensile force \( F_{\text{max}} \), kN by the cross-sectional area \( A, \text{m}^2 \) of the root at the rupture location (Mattia et al., 2005).

\[
T_r = \frac{F_{\text{max}}}{A} = \frac{4F_{\text{max}}}{\pi d^2} \tag{3}
\]

where \( d \) (mm) is the root diameter at the rupture location (Nilaweera and Nitalaya, 1999; Pollen and Simon, 2005; Tosi, 2007).

Diameter of the tested roots ranged from 0.4 to 16 mm. Following the discussion in Bischetti et al. (2009), Reubens et al. (2007) and Vergani et al. (2012), root with a diameter greater than 10 mm should not be considered in the root reinforcement model. Furthermore, roots finer than 1 mm were not considered due to the uncertainty in identification (Gan et al., 2010; Stokes et al., 2009; Wu et al., 2011). As a result, in this study only roots with diameter in the range of 1 to 10 mm were considered in the statistical analysis which derived the relationship between \( T_r, \) MPa and the diameter \( d \) (mm) of the root. A power decay relationship between \( T_r \) and \( d \) was adopted; which in turn can be expressed as a linear relationship in a log \( (T_r) \)-log \( (d) \) space, as shown below

\[
T_r = k_1 d^{-k_2} \tag{4a}
\]

\[
\log(T_r) = \log(k_1) - k_2 \log(d) \tag{4b}
\]

where \( k_1 \) and \( k_2 \) are two positive empirical fitting coefficients to be determined from the tests and they are species dependent.

2.4. Estimation of root cohesion

During shear, the developed soil shear stress is transferred to the tensile stress of the embedded roots through interface friction (Gray and Sotir, 1996). The model proposed by Wu et al. (1979) has been widely used to estimate the increase in soil shear strength due to the contribution of roots (e.g. Abdi et al., 2010; Abernethy and Rutherford, 2001; Adhikari et al., 2013; De Baets et al., 2008; Loades et al., 2010; Mattia et al., 2005; Tosi, 2007; Waldron and Dakessian, 1981). Several assumptions were made in the model: (1) perpendicular orientation of root fibers crossing shearing plane with constant thickness of shear zone during shearling (Waldron, 1977; Waldron and Dakessian, 1981), (2) all roots are fully flexible and have linear elastic relationship denoted by the Young’s modulus (Waldron, 1977; Waldron and Dakessian, 1981); (3) soil friction angle is the same in both rooted and unrooted...
soil (Waldron, 1977; Waldron and Dakessian, 1981); (4) root tensile strain is small (Waldron, 1977; Waldron and Dakessian, 1981); and (5) simultaneous mobilization of roots takes place during shearing (Gray and Sotir, 1996). For a rooted soil, its shear strength can be described as follows:

\[ S_r = s + c_r \]  \hspace{1cm} (5)

where \( S_r \) is shear strength of rooted soil (kPa), \( s \) is shear strength of bare soil (kPa), and \( c_r \) (kPa) is the increase in shear strength due to the presence of roots (referred to as root cohesion).

The predicted shear strength increased from a full mobilization of root tensile strength is given by

\[ c_r = t_r (\sin \theta + \cos \theta \tan \phi) \]  \hspace{1cm} (6)

where \( t_r \) is the total mobilized tensile stress of roots per unit area of soil (kPa), \( \theta \) is the angle of shear distortion within the shear zone (°), and \( \phi \) is the soil friction angle (°).

During shearing, root reinforces soil by three main mechanisms, namely breakage, slippage and stretching (De Baets et al., 2008; Tosi, 2007; Waldron and Dakessian, 1981). In different mechanisms, the total mobilized root tensile stress \( (t_r) \) in Eq. (6) is determined by different root parameters. If the soil confining stress acting below the shear plane is high enough to hold the roots firmly in their original position, roots break when the tensile stress of roots reaches its rupture stress during shearing (Docker and Hubble, 2008). In this mode, \( t_r \) is calculated by the root tensile strength Eq. (7); (Waldron and Dakessian, 1981). If the roots are short and the soil confining stress is low, roots tend to slip out during shearing (Gray and Sotir, 1996). Therefore, \( t_r \) is determined by the interface friction stress between the root and the soil (Waldron and Dakessian, 1981). Gray and Sotir (1996) stated that the lack of sufficient root elongation may prevent the mobilization of root tensile strength. In this case the roots are stretched and the root tensile stress is governed by root tensile modulus and the root–soil interface friction (Waldron, 1977; Waldron and Dakessian, 1981).

Breakage mode is often being considered as the most popular model for root cohesion estimation, and is adopted in this study. The total mobilized tensile strength of roots per unit area of soil can be calculated from the product of mean shear strength mobilized in roots \( (T_r, \text{MPa}) \) and root area ratio \( (\text{RAR}) \) (Gray and Sotir, 1996).

\[ t_r = T_r \cdot \text{RAR} \]  \hspace{1cm} (7)

Wu et al. (1979) suggested that the value of \( \sin \theta + \cos \theta \tan \phi \) is relatively insensitive to normal ranges of \( \theta \) and \( \phi \) and most likely falls into the ranges from 1.0 to 1.3. In general an average value of 1.2 can be used. By considering the mean friction angle of common residual soils in Hong Kong (33.4°, Ho and Fredlund (1982)) and the typical ranges of \( \theta \) (48-72°; Wu et al., 1979), the term \( \sin \theta + \cos \theta \tan \phi \) has a range from 1.15 to 1.18 which gives an average of 1.17. This value was used in this study. Combining this with Eqs. (5) and (6), the increase in shear strength due to the presence of roots now becomes:

\[ c_r = 1.17 \text{RAR} \cdot T_r \]  \hspace{1cm} (8)

In Eq. (8), firstly, RAR varies with soil depth. Secondly, \( T_r \) varies with root diameter in which is also a function of depth. Therefore, the variation of \( c_r \) at different soil depths can be calculated. It is further assumed that the relationship between \( c_r \) and depth \( z \) follows an exponential decay. It can be written as

\[ c_r = n_1 z ^ { -n_2 } \]  \hspace{1cm} (9a)

\[ \log(c_r) = \log(n_1) - n_2 \log(z) \]  \hspace{1cm} (9b)

2.5. Slope stability analysis considering different hydrological conditions

Factor of safety (FoS) is a commonly used index to describe the stability of a slope. The factor is expressed by the ratio of the fully mobilized soil shear strength to the mobilized stress. To investigate the effectiveness of the selected plant species on enhancing slope stability, FoS was calculated assuming an infinite unsaturated soil slope reinforced by roots. The effects of soil matric suction and overburden stress due to the plants were considered. Yet, wind load was neglected in the current...
study due to its insignificant effect as suggested in Wu et al. (1979). FoS for a unsaturated root soil slope considering an area unit is given as:

\[
 FoS = \frac{c_i + \left( \gamma h \cos^2 \beta + w_i \cos \beta \right) \tan \phi' - w_u \tan \phi_b}{\left( \gamma h \cos \beta + w_i \right) \sin \beta}
\] (10)

where \(c_i\) is the true soil cohesion, \(c_r\) is the root cohesion, \(\gamma\) is the unit weight of the rooted soil, \(h\) is the thickness of the smooding mass measuring from the ground surface, \(\beta\) is the slope gradient, \(w_i\) is the unit overburden due to the plant (kPa), \(\phi'\) is the effective soil friction angle, \(w_u\) is the soil matric suction value, tan \(\phi_b\) indicates how the shear strength increase with increasing matric suction. It was assumed that the depth of the failure plane located above the water table (i.e., the soil remains unsaturated).

Unsaturated infinite soil slopes with three different gradients (30°, 35° and 40°, respectively) having typical soil properties in Hong Kong were analyzed. Two hydrological scenarios were considered: (i) dry soil in sunny days; and (ii) wet soil in rainy days. The soil was assumed to have a dry unit weight of 17 kN/m³, while (i) dry soil in sunny days; and (ii) wet soil in rainy days. The soil was assumed based on the findings reported by Ho and Fredlund 1982. Failure plane was assumed to locate above the ground water table. Table 1 summarizes the geotechnical and hydrological input parameters. Different soil moisture content \(w\) and pore water pressure \(w_u\) were assumed for the different said scenarios. Note that \(\gamma = \gamma_f(1 + w)\) and \(w_i\) was assumed to be the average weight of each species in this study. The hydrological parameters were adopted based on a series of field measurements conducted at the Kadoorie Institute Shek Kong. Due to transpiration by plants, it is of no surprise to believe that a vegetated slope has higher matric suction and lower soil moisture content than a bare slope.

2.6. Statistical analysis

Power decay law was adopted to fit the variation of root tensile strength \(T_r\) against root diameter \(d\). The fitting coefficients were determined using SPSS (version 17) by regression analysis of \(\log(T_r)\) and \(\log(d)\). Adjusted \(R^2\) values and coefficient of significance (p-value) were calculated to indicate the goodness of fit, considering a level of significance of 0.05. Komogorov–Smirnov’s and Levene’s test, which are suitable for small samples, were used to verify the normality and homogeneity of variance required for later ANCOVA analyses. In both cases, a significance level of 0.05 was adopted. The normality tests were applied to log-transformed values and residuals; while Levene’s test was applied to the log-transformed values. ANCOVA analysis was performed to test the inter-species and intra-species differences in root tensile strength, RAR and root cohesion considering root diameter and depth as covariates, respectively. To compare root tensile strength between species and within the same species taking diameter into consideration as a covariate, ANCOVA was applied to the linear regression of \(\log(T_r)\) against \(\log(d)\), with a significance level of 0.05. In some cases, the root diameter was divided into two classes (greater or smaller than 2 mm) for the ANCOVA analysis. Furthermore, ANCOVA was also applied to the linear regression of \(\log(RAR)\) and \(\log(c_i)\) against \(\log(z)\) to compare RAR and root cohesion among species with the consideration of depth as a covariate. Similarly, a significance level of 0.05 was adopted.

3. Results

3.1. Root distribution and root area ratio (RAR)

The root systems of 3 R. tomentosa, 5 M. sanguineum, 6 S. heptaphylla and 9 R. thyrsoida were carefully retrieved and examined to reveal their root distribution and RAR variation with depth. The ranges of height, basal diameter, canopy size and above-ground dry weight of the plants are listed in Table 2. Fig. 2 shows the distribution of root diameter classes with depth for different species. Generally speaking, the roots of shrubs are finer than that for the trees. Besides, the root system of tree species extends deeper into the ground (up to 0.8 m below ground as compared to the shrubs of 0.4 m only). R. thyrsoida comprises fewer roots and exhibits mainly a tap root system. Fig. 3 shows the variation of RAR with depth having RAR evaluated by considering all roots or roots with diameter ranged between 1 and 10 mm, respectively. It can be seen clearly that RAR reduces noticeably with depth. For all studied species, RAR becomes insignificant at a depth below 0.5 m. Furthermore, roots having diameter ranged between 1 and 10 mm show only one-third of RAR to that when roots of all diameters are considered.

Table 3 summarizes the ANCOVA analysis of RAR with depth as a covariate. It was found that all RAR results satisfied the normality requirement but only some fulfilled the homogeneity of variance requirement. The results show the followings. First, RAR between the two shrubs is significantly different (\(F_{1,38} = 5.76, p = 0.021\)). Second, RAR between the two trees is similar (\(F_{1,135} = 3.92, p = 0.07\)). Third, RAR within a species (R. tomentosa and R. thyrsoida) is significantly different (\(R. tomentosa: F_{2,24} = 3.80, p = 0.016; R. thyrsoida: F_{8,87} = 4.05, p < 0.001\)).

3.2. Root tensile strength

A total of 121 R. tomentosa, 31 M. sanguineum, 86 S. heptaphylla and 112 R. thyrsoida root segments were successfully tested. Tests were considered to be unsuccessful when there was slipping or rupture of root specimens at the clamps. The overall successful rate was about 90%. Table 4 summarizes the range of \(T_r\) and root diameter in each species. The summary was prepared based on two different root diameter classes. The first class contained roots of all diameters while the second class was restrained to roots with diameters ranged between 1 and 10 mm. As can be seen from the number of samples, majority of the roots fell into the range of 1 to 10 mm. Fig. 4 shows the variation of \(\log(T_r)\) with \(\log(d)\) for each species. Table 5 gives the value of the fitting coefficients and the statistical significance of the relationships based on the roots with diameters ranged between 1 and 10 mm. A linear decrease of \(\log(T_r)\) with \(\log(d)\) can be confirmed with the reported small p-value. The \(k_2\)-values of different species are very close to each other (varied between 0.816 and 0.830) except M. sanguineum.

Table 6 summarizes the ANCOVA analysis of root tensile strength with diameter as a covariate. The requirements for normality and homogeneity of variance were always satisfied. The results show that the root tensile strength of shrubs was significantly different from that of the trees (\(F_{1,243} = 21.34, p < 0.001\)). However, there was neither significant difference within the shrubs nor the trees (\(F_{1,103} = 0.03, p = 0.886; F_{1,137} = 1.76, p = 0.187\); respectively). For the root tensile strength of root having diameter smaller than 2 mm, different species

<table>
<thead>
<tr>
<th>Geotechnical parameters</th>
<th>Hydrological parameters</th>
<th>Bare slope</th>
<th>Vegetated slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_i) (kPa)</td>
<td>(\gamma_f) (kN/m²)</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>(\beta_f) (°)</td>
<td>Sunny days</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>(\phi_f) (°)</td>
<td>Rainy days</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>(w_u) (kPa)</td>
<td>Pore water pressure</td>
<td>-2</td>
<td>-10</td>
</tr>
<tr>
<td>(w_u) (%)</td>
<td>Soil moisture content</td>
<td>-70</td>
<td>-80</td>
</tr>
<tr>
<td>(w_u) (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(w_u) (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
show no significant difference ($F_{3,39} = 1.48, p = 0.234$). However, different species exhibit significant differences in the root tensile strength for root thicker than 2 mm diameter ($F_{3,198} = 5.74, p = 0.001$). Comparing roots with diameter smaller than 2 mm to that larger than 2 mm, the root tensile strength of *R. tomentosa* and *R. thyrsoidea* show no significant difference ($F_{1,84} = 3.65, p = 0.059; F_{1,82} = 3.96, p = 0.05$; respectively) while *M. sanguineum* and *S. heptaphylla* was found to have significant difference ($F_{1,16} = 2.61; p = 0.126; F_{1,52} = 0.16; p = 0.694$; respectively).

### 3.3. Root cohesion

Considering the variation of mean root tensile strength ($T_r$) with root diameter and also the variation of diameter with soil depth, root cohesion ($c_r$) can be calculated following Eqs. (1) and (8). Note that only roots with diameter ranged between 1 and 10 mm were considered in the calculation. Fig. 5 shows the variation of root cohesion with depth. The root cohesion is generally small (in an order of 1 kPa only). *S. heptaphylla* appears to give the highest $c_r$ with depth. Due to the low RAR for *R. thyrsoidea*, its root cohesion is small. For all species, the root cohesion becomes negligibly small beyond 0.5 m below ground.

Table 7 summarizes the ANCOVA analysis of root cohesion with depth as a covariate. The requirement of normality and homogeneity

### Table 2

Size and weight ranges of the retrieved plants.

<table>
<thead>
<tr>
<th>Species</th>
<th>No. of samples</th>
<th>Height (m)</th>
<th>Basal diameter (mm)</th>
<th>Canopy (m)</th>
<th>Above-ground dry weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>R. tomentosa</em></td>
<td>3</td>
<td>1.10–1.42</td>
<td>15–31</td>
<td>0.62–0.75</td>
<td>0.73–2.68</td>
</tr>
<tr>
<td><em>M. sanguineum</em></td>
<td>5</td>
<td>1.00–1.47</td>
<td>10–24</td>
<td>0.48–1.12</td>
<td>0.26–2.97</td>
</tr>
<tr>
<td><em>S. heptaphylla</em></td>
<td>6</td>
<td>1.21–1.42</td>
<td>16–29</td>
<td>0.40–1.03</td>
<td>0.31–5.97</td>
</tr>
<tr>
<td><em>R. thyrsoidea</em></td>
<td>9</td>
<td>1.00–1.37</td>
<td>10–33</td>
<td>0.52–1.50</td>
<td>0.24–1.95</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Root distribution with depth for different species: (a) *R. tomentosa* ($N = 3$), (b) *M. sanguineum* ($N = 5$), (c) *S. heptaphylla* ($N = 6$) and (d) *R. thyrsoidea* ($N = 9$).

**Fig. 3.** Distribution of root area ratio RAR with depth for different species: (a) all roots; (b) roots with diameter ranged between 1 and 10 mm.
of variance were always satisfied, except for the cases of (1) comparison between shrub and tree and (2) comparison within \( R. \) thyrsoides in which the variances were not homogeneous. The findings are summarized as follows. First, there was no significant difference in root cohesion among the species \( (F_{3,137} = 2.46, p = 0.065) \). Second, there was no significant difference in root cohesion between the two shrubs \( (F_{1,35} = 1.60, p = 0.215) \) but that between the two trees can be considered as different \( (F_{1,140} = 4.40, p = 0.038) \). Third, there was no significant difference in root cohesion within \( R. \) tomentosa \( (F_{2,31} = 1.94, p = 0.190) \) and \( S. \) heptaphylla \( (F_{3,37} = 1.12, p = 0.369) \). Forth, root cohesion within \( M. \) sanguineum was significantly different \( (F_{4,17} = 5.92, p = 0.004) \).

### 3.4. Factor of safety of vegetated slopes

Fig. 6 shows the influence of plants on the factor of safety (FoS) of the infinite slope considering two hydrological situations: sunny and rainy days. No single species showed distinguishable effect from the others. In other words, different species gave very similar amount of influence of plants on the factor of safety (FoS) of the studied species (except \( M. \) sanguineum) was dominated by roots larger than 2 mm diameter. The result was different from that of the desert shrub species \( (Adhikari et al., 2013) \) in which more than 50% of the roots were smaller than 2 mm in diameter. It is perhaps attributed to species genetics and environmental factors. The Levene’s test showed that the variance of RAR of different species was not homogeneous (i.e., significant differences in the variance). This variability may be also due to genetic variability and/or environmental factors such as soil moisture. RAR of the studied species was similar to that found in Southern Alps (France) \((Burylo et al., 2011)\) but obviously smaller than the Mediterranean species (mostly lied below 0.5% but can be as high as 2% for grasses and shrubs) reported by \( De Baets et al., (2008)\).

In their study, the reference area referred to the area under the crown of a plant. In other studies for various species \( (Bischetti et al., 2005; Mattia et al., 2005; Norris, 2005)\), the concept of cellulose content was often used to explain the observation. The fitted log\((k_1)\) value of the studied species varied in a wide range.

### 4. Discussion

#### 4.1. Root distribution and RAR

Root class distribution as shown in Fig. 2 revealed that root system of the studied species \( (except M. \) sanguineum) was dominated by roots larger than 2 mm diameter. The result was different from that of the desert shrub species \( (Adhikari et al., 2013)\) in which more than 50% of the roots were smaller than 2 mm in diameter. It is perhaps attributed to species genetics and environmental factors. The Levene’s test showed that the variance of RAR of different species was not homogeneous (i.e., significant differences in the variance). This variability may be also due to genetic variability and/or environmental factors such as soil moisture. RAR of the studied species was similar to that found in Southern Alps (France) \((Burylo et al., 2011)\) but obviously smaller than the Mediterranean species (mostly lied below 0.5% but can be as high as 2% for grasses and shrubs) reported by \( De Baets et al., (2008)\).

In their study, the reference area \( A \) \((Eq. (1))\) for the calculation of RAR referred to the area under the crown of a plant.

### 4.2. Root tensile strength

Tensile strength tests confirmed that there exists a power decay relationship between the root tensile strength and root diameter for all the studied species considering root diameter ranged between 1 and 10 mm. The same relationship has been reported in many previous studies for various species \( (Rischetti et al., 2005; Mattia et al., 2005; Norris, 2005)\). The concept of cellulose content was often used to explain the observation. The fitted log\((k_1)\) value of the studied species varied in a wide range.

#### Table 3

<table>
<thead>
<tr>
<th>Species</th>
<th>No. of samples</th>
<th>( d ) (mm)</th>
<th>( T_r ) (MPa)</th>
<th>( k_2 )</th>
<th>Adjusted ( R^2 )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R. ) tomentosa</td>
<td>121</td>
<td>0.9</td>
<td>4.4</td>
<td>87</td>
<td>1.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Max</td>
<td>10.5</td>
<td>74.0</td>
<td>8.4</td>
<td>74.0</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.4</td>
<td>22.2</td>
<td>3.5</td>
<td>22.4</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>1.6</td>
<td>14.1</td>
<td>1.6</td>
<td>12.8</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>11.5</td>
<td>133.4</td>
<td>6.8</td>
<td>42.6</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.02</td>
<td>345.1</td>
<td>3.3</td>
<td>23.8</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>( S. ) heptaphylla</td>
<td>86</td>
<td>1.3</td>
<td>55</td>
<td>1.3</td>
<td>7.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Max</td>
<td>14.0</td>
<td>85.7</td>
<td>9.7</td>
<td>85.7</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.5</td>
<td>18.8</td>
<td>5.2</td>
<td>24.0</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>3.6</td>
<td>15.5</td>
<td>2.4</td>
<td>16.9</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>( R. ) thyrsoides</td>
<td>112</td>
<td>0.6</td>
<td>3.3</td>
<td>85</td>
<td>1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Max</td>
<td>15.8</td>
<td>218.7</td>
<td>9.5</td>
<td>129.4</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.4</td>
<td>32.0</td>
<td>4.1</td>
<td>28.3</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>2.9</td>
<td>32.4</td>
<td>2.2</td>
<td>21.8</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>
a narrow range (1.561 to 1.844), which corresponded to $k_1$ of 36.4 and 69.8, respectively. The decay coefficient $k_2$ varied narrowly from 0.816 to 0.830 among $R$. tomentosa, $S$. heptaphylla and $R$. thyrsoidea; while $M$. sanguineum gave a much smaller $k_2$ equal to 0.513. Generally speaking, the root tensile strength values were in the same order of root tensile strength values reported by Abdi et al. (2010), Burylo et al. (2011), De Baets et al. (2008), Ji et al. (2012) and Vergani et al. (2012) for their shrub and tree species in Mediterranean, Iran, Alps of France, Italian Alps, China respectively.

ANOVA analysis revealed that there was no significant difference on tensile strength within the respective shrub and tree species. However, the root tensile strength between the studied shrubs and trees are statistically different. Roots of the tree species ($S$. heptaphylla and $R$. thyrsoidea) have higher resistance to tension than those of the shrub species ($R$. tomentosa and $M$. sanguineum). On the other hand, comparable tensile strength between shrub and trees was reported by De Baets et al. (2008) and Gray and Barker (2004); while higher tensile strength of French shrub species when compared with trees was observed (Burylo et al., 2011). The inter-species variation of tensile strength is high as it is expected to depend largely on local environment. This shows the importance of local research on native species.

### Table 6

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among all species considering diameter as a covariant</td>
<td>$F_{3,241} = 7.66$</td>
<td>0.001</td>
</tr>
<tr>
<td>Between shrub and tree species considering diameter as a covariant</td>
<td>$F_{3,245} = 21.34$</td>
<td>0.001</td>
</tr>
<tr>
<td>Within shrubs considering diameter as a covariant</td>
<td>$F_{1,103} = 0.03$</td>
<td>0.866</td>
</tr>
<tr>
<td>Within trees considering diameter as a covariant</td>
<td>$F_{1,117} = 1.76$</td>
<td>0.187</td>
</tr>
<tr>
<td>Among all species considering diameter $&lt; 2$ mm</td>
<td>$F_{3,106} = 1.48$</td>
<td>0.234</td>
</tr>
<tr>
<td>Among all species considering diameter $\geq 2$ mm</td>
<td>$F_{3,106} = 5.74$</td>
<td>0.001</td>
</tr>
<tr>
<td>Within $R$. tomentosa considering diameter smaller and larger than 2 mm</td>
<td>$F_{1,84} = 3.65$</td>
<td>0.059</td>
</tr>
<tr>
<td>Within $M$. sanguineum considering diameter smaller and larger than 2 mm</td>
<td>$F_{1,16} = 2.61$</td>
<td>0.126</td>
</tr>
<tr>
<td>Within $S$. heptaphylla considering diameter smaller and larger than 2 mm</td>
<td>$F_{1,52} = 0.03$</td>
<td>0.649</td>
</tr>
<tr>
<td>Within $R$. thyrsoidea considering diameter smaller and larger than 2 mm</td>
<td>$F_{1,82} = 3.96$</td>
<td>0.050</td>
</tr>
</tbody>
</table>

### Table 7

<table>
<thead>
<tr>
<th>Comparisons</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among all species considering depth as a covariant</td>
<td>$F_{3,137} = 2.46$</td>
<td>0.065</td>
</tr>
<tr>
<td>Between shrub and tree species considering depth as a covariant</td>
<td>$F_{3,137} = 2.46$</td>
<td>0.065</td>
</tr>
<tr>
<td>Within shrubs considering depth as a covariant</td>
<td>$F_{1,35} = 1.60$</td>
<td>0.215</td>
</tr>
<tr>
<td>Within trees considering depth as a covariant</td>
<td>$F_{1,101} = 4.40$</td>
<td>0.038</td>
</tr>
<tr>
<td>Within $R$. tomentosa considering depth as a covariant</td>
<td>$F_{1,11} = 1.94$</td>
<td>0.190</td>
</tr>
<tr>
<td>Within $M$. sanguineum considering depth as a covariant</td>
<td>$F_{1,7} = 5.92$</td>
<td>0.040</td>
</tr>
<tr>
<td>Within $S$. heptaphylla considering depth as a covariant</td>
<td>$F_{1,37} = 1.12$</td>
<td>0.369</td>
</tr>
<tr>
<td>Within $R$. thyrsoidea considering depth as a covariant</td>
<td>$F_{1,37} = 1.12$</td>
<td>0.369</td>
</tr>
</tbody>
</table>

***: Requirement of homogeneity of variance was not satisfied.
4.3. Root cohesion

Note that in the current study only roots with diameter ranged between 1 and 10 mm were used to evaluate the root cohesion based on Wu’s model. The root cohesion lied below 1.5 kPa even at shallow depth and decreased with depth (except *R. thyoides* which showed a maximum at 0.4 m below ground). The root cohesion became very small at depth below 0.5 m for both the studied shrubs and trees. The values are generally very small when compared to available literature of herbaceous and shrubby species (De Baets et al., 2008; Mattia et al., 2005) but are in the same order as *P. nigra* (tree species) reported by Burylo et al. (2011).

4.4. Effect of vegetation on factor of safety

Fig. 6 shows that the roots can noticeably improve the safety margin of slopes. Such an increase in FoS should be partially contributed by the mechanical reinforcement (root cohesion of about 1 kPa) and partly due to the hydrological effect (increase in suction of 10 kPa and 8 kPa in sunny and rainy days respectively). Note that an increase of 8 kPa suction in rainy days would give an increase of shear strength by $\mu_c \tan \phi = 8 \tan 15.3^\circ = 2.1$ kPa. Besides, root cohesion in this study should have been underestimated since only the breakage mechanism of the Wu’s model was considered and the contribution was limited to roots having diameter ranged between 1 and 10 mm. Slippage of thicker roots which should also contribute to root cohesion was not taken into account in the current analysis.

It was shown that the plants could turn an unsafe slope marginally safe (factor of safety slightly larger than unity). However, when compared to shrubs, the tree species gave indistinguishably the same reinforcement effect.

5. Conclusion

Mechanical reinforcement by plant roots has been investigated for decades in Northern American and Europe. However, root characteristics of Hong Kong native species and its performance in slope upgrading have been less explored. In this study, the root system of four Hong Kong native shrubs (*Rhodomyrtus tomentosa* and *Melastoma sanguineum*) and trees (*Schefllera lepaptphylla* and *Reevesia thyoides*) with height ranged between 1 and 1.5 m were sampled. The mean distribution of root class with depth of each species was presented. Roots of the studied trees were found to extend deeper into the ground (up to 0.8 m) as compared to the shrubs (up to 0.4 m). Besides, the mean root area ratio (RAR) of each species was evaluated at 0.05 m depth interval. In particular, variations of RAR with depth for (1) all identified and (2) root having diameter ranged between 1 and 10 mm were showed. RAR lies between 0.03 and 0.14% for the top 0.1 m soil and decreased with depth when all roots were considered. However, only if the roots with diameter ranged between 1 and 10 mm were considered, RAR lies below 0.05% even close to the ground. A tailor-made model was considered and the contribution was limited to roots having diameter ranged between 1 and 10 mm. Slippage of thicker roots which should also contribute to root cohesion was not taken into account in the current analysis.

Based on this study, the studied tree species did not outperform the shrubs in terms of root reinforcement.

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References


