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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 (*Schefflera heptaphylla* and *Reevesia thyrsoidea*) 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 (T_r) and root diameter (d), and also the variation of root cohesion (c_r) 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 T_r–d 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 T_r and d 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.

1. Introduction

Hong Kong, having a hilly terrain with the natural hillsides composing residual, colluvial and saprolitic soils, is subjected to the subtropical climate with frequent rainstorms. The mean annual rainfall was reported 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; Waldron 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*

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tomentosa and *Melastoma sanguineum*) and two tree species (*Schefflera heptaphylla* and *Reevesia thyrsoidea*) were selected among the aforementioned plant list. Young plants with height less than 1.5 m were chosen for sampling. The variation of root distribution and root area ratio (RAR) with depth and the relationship between root tensile strength and root diameter were investigated for each species. Additional soil cohesion due to the presence of roots (root cohesion) was evaluated by the Wu's root model (Wu et al., 1979). The results were statistically compared among the species. Root cohesion was then considered in infinite slope models. The aim was to investigate the contribution of roots in young plants to enhance the slope safety. Two different hydrological scenarios were considered: (a) dry soil in sunny days and (b) wet soil in rainy days. It was hypothesized that the plants would give a promising increase in the safety margin for wet soil slopes and the tree species would give a more pronounced reinforcement effect.

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 retrieved manually by hand-held tools. Dead roots can be distinguished by discolouration, 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 perverse live roots for tensile strength test, the roots were sealed in plastic bags after excavation, before being transported to laboratory for testing in the following weeks.

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 also calculated by assuming all roots have a circular cross section. RAR is defined as the fraction of an effective soil cross-section area (A, m^2) occupied by total root cross-sectional area (A_r, 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

$$\mathrm{RAR} = \frac{A_\mathrm{r}}{A} = \frac{\sum_{\mathrm{i}=1}^{n} \pi d_\mathrm{i}^2/4}{A} \tag{1}$$

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 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

$$\mathrm{RAR} = h_1 z^{-h_2} \tag{2a}$$

$$\log(\mathrm{RAR}) = \log(h_1) - h_2 \log(z) \tag{2b}$$

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

2.3. 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 to 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_max, kN) by the cross-sectional area (A_r, m^2) of the root at the rupture location (Mattia et al., 2005).

$$T_r = \frac{F_\mathrm{max}}{A_r} = \frac{4F_\mathrm{max}}{\pi d^2} \tag{3}$$

where d (mm) is the root diameter at the rupture location (Nilaweera and Nutalaya, 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 and d. The 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

$$T_\mathrm{r} = k_1 d^{-k_2} \tag{4a}$$

$$\log(T_\mathrm{r}) = \log(k_1) - k_2 \log(d) \tag{4b}$$

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 Rutherfurd, 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 shearing (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