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Prediction of the root anchorage of native young plants using Bayesian inference

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ABSTRACT

The maximum vertical uproot resistance (P_{max}) of a plant can be used to indicate its stability. Attempts were made to predict the P_{max} of a plant empirically from some of its size parameters. In practice, an infinite number of empirical models with different complexities can be formulated. This study presents a Bayesian model class selection method to evaluate the plausibility of each empirical model among a list of model candidates. The models were ranked to identify the most plausible one. A database of vertical uproot resistance of four shrubs and trees native to Hong Kong was first compiled by performing field uproot tests. The plant size parameters including height, basal diameter, canopy size, and above-ground dry weight, were measured before the uprooting. Second, the mathematical formulation of the Bayesian model class selection method was presented. Using this method the most plausible model for each studied species or plant type was identified. The uncertainty of the model coefficients and therefore the credibility of the predictions were quantified. The selected models were used to predict the P_{max} of the studied plants in some additional tests. It was found that the P_{max} of the studied species could be reliably predicted from the established simple empirical formulas containing only the height and/or basal diameter of the plant as the dependent variables. The study paves the way for nondestructive and reliable prediction of plant anchorage.

1. Introduction

Plants are an important part of the green urban infrastructures (Yang et al., 2012) and form essential components of urban landscaping in modern cities. To make Hong Kong a green model city in Asia, the Hong Kong SAR Government initiated a massive planting program called the Greening Master Plan (GMP) in 1999. The aim of GMP is to maximize greening areas in the urban realm and to connect them to rural areas by green links. The plan formulated the greening framework of an area according to its specific characteristics and needs. From 2004 to 2014, 13.7 million trees, 75.9 million shrubs, and 10.2 million annuals were planted (DEVB, 2015).

The diverse contribution of urban vegetation has been widely studied. Urban vegetation can be used to reduce global temperatures by reducing radiation flux due to shading (Park et al., 2012; Shahidan et al., 2012). By improving microclimatic conditions, plants provide fresh air and mitigate the urban heat-island effect (Dimoudi and Nikolopoulou, 2003; Oliveira et al., 2011; Ng et al., 2012). Urban vegetation can also improve air quality (Jim and Chen, 2008) and reduce noise levels (Van Renterghem et al., 2012). Moreover, as reported by Donovan and Butry (2010), urban trees can increase the market value of nearby properties. In addition to the environmental and economical benefits, it is anticipated that greening in urban areas will improve residents' quality of life (Aoki et al., 1985; Sheets and Manzer, 1991) because a green environment has been shown to help relieve stress (Gidlöf-Gunnarsson and Öhrström, 2007; Grahn and Stigsdotter, 2010). Ng et al. (2015) conducted a survey in Hong Kong and reported that 94% of respondents supported roadside tree planting, which clearly demonstrated the importance of urban greening to society.

Following successful implementation in Europe and North America (Coppin and Richards, 1990; Abe and Ziemer, 1991; Barker, 1995 Morgan and Rickson, 1995; Gray and Sotir, 1996; Schiechtl and Stern, 1996), the use of plants to upgrade urban slopes has received much attention in Hong Kong in recent years. With its hilly terrain, Hong Kong has many man-made (cut and fill) and natural slopes. Vegetation helps to enhance the aesthetic value of roadside slopes and restore degraded ecosystems (Coppin and

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Richards, 1990; Bayfield, 1995; Morgan and Rickson, 1995; Norris and Greenwood, 2006; GEO, 2011; Zhang et al., 2013). Well-vegetated slopes can also reduce soil erosion and increase soil shear strength, which improves soil slopes' resistance to shallow failures (Gray and Sotir, 1996). In recent decades, some laboratory-scale pull-out experiments of real plant roots (Ennos, 1990) and analogue roots (Hamza et al., 2007) had been carried out to investigate the load distribution and deformation behaviour of a root system. Moreover, field pull-out tests of roots (Norris, 2005; Docker and Hubble, 2008) and plants (Nilaweera and Nutalaya, 1999; Normaniza et al., 2011) were also conducted to study the extent to which roots could reinforce the ground and to study the plant stability. In addition, there were studies stimulating tree overturning under wind loading by numerical modeling (Dupuy et al., 2007; Lundström et al., 2008). However, most of the previous research investigated tree stability by uprooting experiments were done in foreign countries such as the UK (Ennos, 1989, 2000; Norris, 2005), Italy (Tosi, 2007), Austria (Docker and Hubble, 2008), Switzerland (Schwarz et al., 2011) and Malaysia (Normaniza et al., 2011). Yet, as far as the authors are aware, there was no field data showing the performance of species native to Hong Kong when they were under uprooting.

Leung et al. (2015) recently quantified the effects of plant roots on slope stabilization by investigating the root distribution and root properties of four woody species native to Hong Kong. The safety and stability of plants are always of prime concern. It is anticipated that a plant's stability can be reflected by the anchorage ability of its root system, which can be evaluated from the uproot resistance (Nilaweera and Nutalaya, 1999; Norris and Greenwood, 2006; Docker and Hubble, 2008). In other words, a plant with greater uproot resistance should have stronger root anchorage ability and is preferable given otherwise-equal performance. Undoubtedly, it would be beneficial if one can predict the maximum uproot resistance of a woody plant from its size parameters without the need to carry out any destructive plant uproot tests. Furthermore, it is appealing if the credibility levels of prediction can be quantified.

Theoretically, unlimited number of empirical models each having different degree of complexities can be formulated. A frequently asked question is how one should select between a simple and a complex empirical formula. It is well-known that a complex empirical formula can yield a higher degree of fitting when compared to the measurements owing to its higher number of fitting coefficients that one can play around. Therefore, if the goodness-of-fit is the sole criterion to select a model among the candidates, a complex one would be chosen due to its high level of goodness-of-fit. Such a higher fitting capacity, however, also means that the complex formula is sensitive to measurement noise and model uncertainty. Its predictive ability and robustness become questionable. As a result, there should be a scientific way to strive for a balance between model complexity and fitting ability. Bayesian inference provides a key to resolve this issue. In the past, the minimum Bayesian information criterion (BIC) has been frequently adopted (e.g., in Arnberger et al., 2010) to identify the most plausible model. In this study, however, a Bayesian model class selection method is introduced as an alternative approach to select the most plausible model among a list of model candidates by examining not only their fitting ability but also the robustness of the models.

The objectives of this study were: (1) to conduct field vertical uproot tests on four shrubs and trees native to Hong Kong; (2) to present a Bayesian model class selection method that suggests the most plausible empirical formula among a list of model candidates to predict the maximum vertical uproot resistance ($P_{\max}$) of a woody plant from its size parameters; and (3) to apply the technique to the four studied species and to examine the credibility levels of the prediction. This investigation therefore paves the way for a nondestructive and reliable method of predicting the anchorage of woody plants from their sizes and provides a useful tool with which to evaluate the stability of native shrubs and trees in roadside slope rehabilitation.

2. Materials and methods

2.1. Studied species

Four native woody species were selected, including two shrubs, *Rhodomyrtus tomentosa* (Aiton) Hassk. and *Melastoma sanguineum* Sims, and two trees, *Schefflera heptaphylla* (L.) Frodin and *Reevesia thyrsoidea* Lindl. The plants were recommended for ecological slope rehabilitation in Hong Kong (Hau and So, 2003; GEO, 2011) and are widespread on its natural hillsides. The four species have shown promising survival and growth rates and high ornamental and ecological values when planted on roadside slopes (Hau et al., 2005; Halcrow China Limited, 2011; Or et al., 2011). Furthermore, they are highly tolerant to the sunlight and drought conditions that are typical to roadside slopes (GEO, 2011).

R. tomentosa and *M. sanguineum* are common pioneer species in Hong Kong's shrubland. To attract birds, rats, civets and macaques as dispersal agents, *R. tomentosa* and *M. sanguineum* have berry fruit and fleshy capsulate fruit (Hau and Corlett, 2002; Hong Kong Herbarium, 2008), respectively. *S. heptaphylla* is highly resistant to unfavorable growing conditions and has good propagation ability even in man-made environments (Hau and So, 2003; Halcrow China Limited, 2011). Ecologically, it is a keystone species for forest restoration (Hau and So, 2003). *R. thyrsoidea* has dense white-petaled flowers that blossom in spring, providing great ornamental and ecological value (Halcrow China Limited, 2011). It effectively enriches the floristic composition of woodlands (AFCD, 2012) and is suitable for ecological greening on slopes (Or et al., 2011). The plants provide fruit for birds and nectar for a variety of insects (Corlett, 1998, 2001; Halcrow China Limited, 2011).

2.2. Field vertical uproot tests

Field vertical uproot tests were performed on naturally grown and planted samples. The naturally grown samples were found in Tai Lam Country Park, Hong Kong. The planted samples had been planted from seedlings on slopes at the Kadoorie Centre, The University of Hong Kong (HKUKC) 2–3 years before the uproot tests were conducted (Leung, 2014). Before each test, the plant's size characteristics, including the height (*H*), basal diameter (*BD*), and canopy size (*C*), were recorded. Canopy size (*C*) was defined as the length of the major axis of the plant crown. After measurement, the plant was cut at 0.15 above the ground, and the entire above-ground parts (including leaves and branches) were brought to the laboratory to determine the above-ground dry weight (*W*) after oven-drying overnight at 105 °C. An upper bound value for each size parameter was defined for each species (denoted by H_{bound}, BD_{bound}, C_{bound} and W_{bound}). The bound was decided according to field observations and our understanding of the species, which was believed to be the maximum value of each particular size parameter. Each size parameter was then normalized by the corresponding bound (e.g., normalized height, $H_N = H/H_{\text{bound}}$) such that the normalized values (H_N, BD_N, C_N and W_N, respectively) fell between 0 and 1. In addition, a parameter called normalized volume V_N was defined, where $V_N = H_N \times (BD_N)^2$. Measurement of a plant's dry weight can be time consuming and difficult in many cases; therefore, it is hypothesized that V_N can be used as a substitute for W_N in the predictive formula. This hypothesis is tested by examining the correlation between V_N and W_N based on the collected data. It should be noted that the soil water content adjacent to the uprooted plant was recorded in most cases. Yet, the moisture data were not