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Enhancement of slope stability by vegetation considering uncertainties in root distribution

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ABSTRACT

Root length, position and orientation on a soil slope are random but key elements when evaluating the stability of the vegetated slope. The main objectives of this note are to understand the effects of natural characteristics of vegetation on slope stability and to investigate how the variability in root features propagates to the variability in slope stability. A batch of randomly sized roots at given root densities are randomly positioned over a slope, and the stability of the slope for each combination of roots is evaluated. Traditional analysis considering uniform identical roots overestimates the factor of safety of the slope.

1. Introduction

Green slope engineering using live vegetation in conjunction with traditional reinforcement measures has been shown to be cost-effective and environmental-friendly [1]. The influence of vegetation on slope stability has been well recognised through centrifuge testing and through numerical modelling using the finite element method or limit equilibrium methods [2–7]. Various root types exist for a tree root system such as hair roots within a few centimetres below ground and main roots that extend deeply and provide high tensile strength and pullout resistance.

Natural slopes are vegetated and the vegetation is inherently variable. Even for the same species, root features including root length (l), position and orientation differ as a result of changes in environmental condition and adaptability of the species itself. Though the reinforcement effect of roots has been investigated extensively, previous studies only considered uniformly distributed identical root reinforcements [8,9]. The assessment of the stability of rooted slopes realistically considering the randomness in root length, root position and root orientation is rarely reported and requires exploration.

This note aims to study how the variability in root length and position propagates to the variability in slope stability. Fig. 1 depicts a typical geological profile encountered in a landslide located at Siu Sai Wan in Hong Kong [10]. A surface decomposed soil layer of about 10 m thick is present, underlain by stiff soil. To reflect such a realistic geological profile in slope stability analysis, this study utilizes an idealised soil profile comprising two layers with the surface layer in completely decomposed granite (CDG) and the bottom layer in the stiff soil. The root length is modelled as a lognormal random variable according to statistics obtained for a measured dataset of maximum rooting depths of woody plants [11]. The individual roots in a group are considered to be independent of each other, randomly positioned along the slope with the varying root density (*RD*, defined as root numbers per unit slope length). Monte-Carlo simulations are then performed, each simulation concurrently showing the random root lengths and random root positions as well as the associated different orientations as a result of random positioning. A sensitivity analysis of the stability of the rooted slope to the thickness (D) of the surface soil layer and root density is also conducted. To limit the scope of this note, evapotranspiration is not taken into account.

2. Methodology

2.1. Consideration of root anchorage and root strength properties

Fig. 2 shows schematic diagrams related to a root-reinforced slope. Fig. 2a presents a root extending below a slip surface. The

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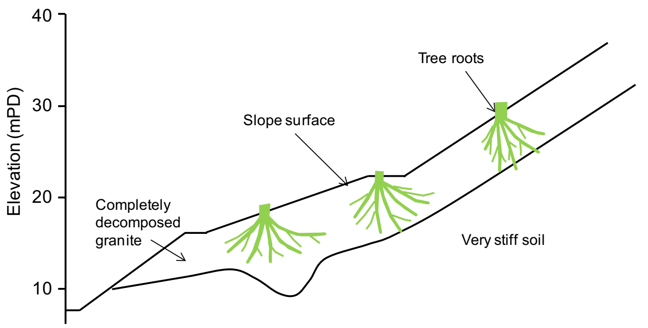

Fig. 1. A schematic diagram showing cross-section of a geological profile for the landslide event occurring at Siu Sai Wan, Hong Kong in April 1992.

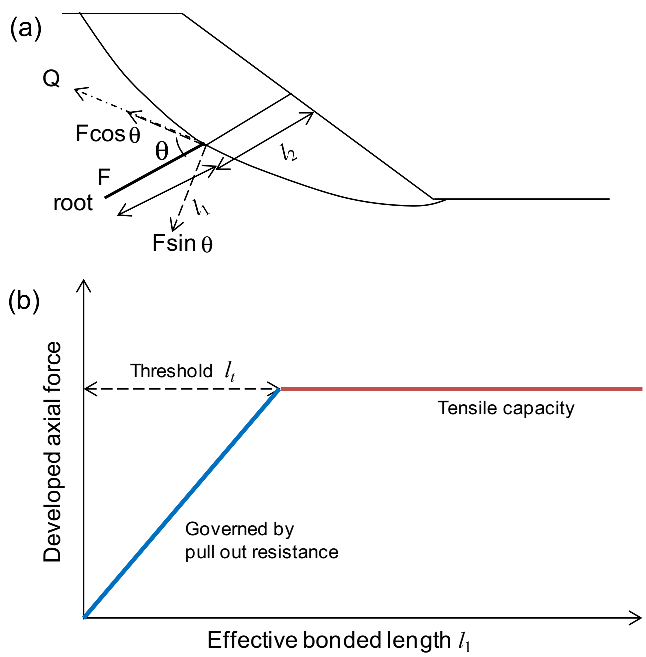

Fig. 2. Schematics showing (a) the force diagram for a root penetrating a soil slope and (b) the developed axial force in root along its effective bond length.

portion of root length below the slip surface is denoted as l_1, which provides an effective tension force to resist shear failure by increasing the normal force and decreasing the driving force at the base of the slip surface. Fig. 2b shows how axial force F in the root is developed as a function of root effective bond length l_1 at a fixed pullout resistance represented by the gradient of the straight line in the figure. Two root strength parameters including root tensile capacity (T in kN) and root pullout resistance (p in kN/m) are required for the stability analysis of the root-reinforced slope. The axial force is governed by the pullout resistance when l_1 is less than a threshold l_t, a value at which the tensile capacity equals the available bond (i.e., $T = pl_t$), while the axial force is governed by the tensile capacity when l_1 is greater than l_t. Values of T and p are readily available in the literature through past extensive field and laboratory tests [12]. A reasonable value of 2.5 kN/m is adopted for root pullout resistance based on the pullout tests on root samples with no or few branches carried out by Norris [13]. According to existing field and laboratory tests, a power law relationship between root tensile strength and root diameter is observed [14]:

$$t = 70d^{-0.7} \tag{1}$$

where t is the root tensile strength in MPa and d is the root diameter in mm. The tensile capacity of root is given by

$$T = \frac{\pi d^2 t}{4} \tag{2}$$

It would be desirable if the three-dimensional architectural system of the roots of a tree can be simulated. This will be computationally challenging particularly when the root systems of a few trees on a soil slope are considered. Without taking into account the secondary or lower level root branches, this note considers single main roots 67 mm in diameter for woody plants with reference to Zhu et al. [15]. A diameter of 67 mm is a reasonable value for the general woody plants found in Hong Kong according to the study by Yeung et al. [16]. Applying Eq. (2), the tensile capacity is taken as 12.5 kN, identical for all roots.Referring to Fig. 2 and adopting the foregoing root strength parameters, the threshold value l_t defined in Fig. 2b is calculated to be 5 m. When l_1 is less than 5 m, the axial force is controlled by the pullout resistance; when l_1 is greater than 5 m, the axial force depends on the tensile capacity. A shear force (denoted as Q) developed in relation to the root lateral bending strength is accommodated at the point where the root intersects with the potential slip. The lateral bending strength of roots was firstly investigated by Stokes and Mattheck [17] who have reported, based on their tests, that the lateral bending strength is equal to one-half to one-thirds of the tensile strength. A value of 6.25 kN is therefore adopted to provide a shear resistance parallel to the slip surface. The following equation describes the contribution of the root axial force and shear force to the shear resist force (ΛS), which is developed upon sliding:

$$\Lambda S = F \sin\theta \tan\varphi + F\cos\theta + Q \tag{3}$$

where θ is the angle between the root and the slip surface. The resistance to shear failure provided by the developed forces in the root is applied to the slice with the root.

2.2. Random root length and root distribution on a slope

Of particular concern in this work is the incorporation of root uncertainty in terms of random root positions along the slope surface and random root lengths for each individual roots. The woody plants of a broad category instead of a particular type are focused on in this study. A dataset of maximum rooting depth for woody plants was well-documented by Schenk and Jackson [11]. Fig. 3 shows the histogram of the dataset along with a fitted distribution. The Kolmogorov–Smirnov goodness-of-fit test performed to the observed values of rooting depths indicates the suitability of a log-

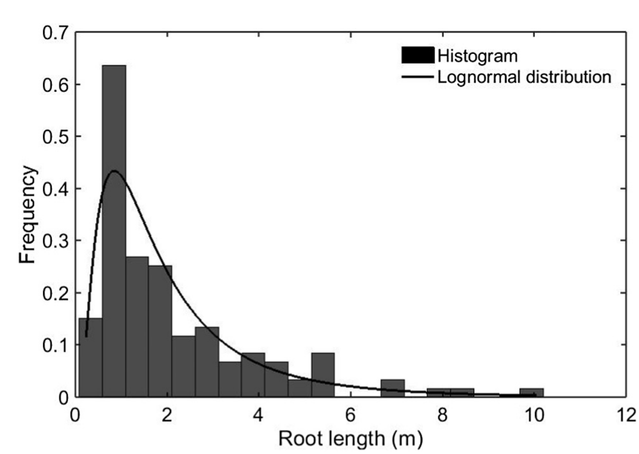

Fig. 3. Frequency diagram and fitted lognormal distribution for root length.