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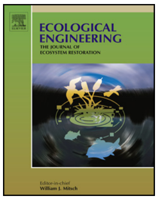

Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge

T. Liang[a,*], A.G. Bengough[a,b], J.A. Knappett[a], D. MuirWood[a], K.W. Loades[b], P.D. Hallett[c], D. Boldrin[a], A.K. Leung[a], G.J. Meijer[a]

[a] School of Science and Engineering, University of Dundee, Dundee DD1 4HN, UK
[b] James Hutton Institute, Invergowrie, Dundee DD2 5DA, UK
[c] School of Biological Sciences, University of Aberdeen, Aberdeen AB24 3UU, UK

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ABSTRACT

Understanding root-reinforcement of vegetated slopes is hindered by the cost and practicality of full scale tests to explore global behaviour at the slope scale, and the idealised nature of smaller-scale testing to date that has relied on model root analogues. In this study we investigated the potential to use living plant roots in small scale experiments of slope failure that would use a geotechnical centrifuge to achieve soil stress states comparable to those in the field at homologous points. Three species (Willow, Gorse and Festulolium grass), corresponding to distinct plant groups with different root architecture and 'woodiness' were selected and cultivated for short periods (2 months for Willow and Festulolium grass, 3 months for Gorse). The morphologies, tensile strength and Young's modulus of these juvenile root samples and their effects on increasing soil shear strength were then measured (via tensile tests and direct shear tests) and compared with published results of more mature field grown specimens. Our test results show that when all juvenile root samples of the three species are considered, the commonly used negative power law does not fit the data for the relationship between root tensile strength and root diameter well, resulting in very low R^2 values ($R^2 < 0.14$). No significant differences in tensile strength were observed between roots with different diameter for Willow and Gorse, and the average root tensile strength for all juvenile root samples was 8.70 ± 0.60 MPa (Mean ± SE), 9.50 ± 0.40 MPa, 21.67 ± 1.29 MPa for Willow, Festulolium grass and Gorse, respectively. However, a strong linear relationship was observed between tensile strength and Young's modulus of the roots of the juvenile plants ($R^2 = 0.55$, 0.69, 0.50 for Willow, Festulolium grass and Gorse, respectively). From a centrifuge modelling perspective, it was shown that using juvenile plants could potentially produce prototype root systems that are highly representative of corresponding mature root systems both in terms of root mechanical properties and root morphology when a suitable growing time (2 months) and scaling factor ($N = 15$) are selected. However, it remains a challenge to simultaneously simulate the distribution of root biomass with depth of the corresponding mature plant. Therefore, a compromise has to made to resolve the conflicts between the scaling of rooting depth and root reinforcement, and it is suggested that 1:15 scale would represent a suitable compromise for studying slope failure in a geotechnical centrifuge.

1. Introduction

Vegetation as an effective and environmental-friendly approach to improve slope stability has been recognised in geotechnical and ecological engineering practice to prevent shallow landslides and erosion. Planting trees, shrubs or grasses on slopes not only improves aesthetic appearance, but more importantly: (i) controls the groundwater regime and slope hydrology (e.g. Smethurst et al., 2006, 2012, 2015) and (ii) directly increases shear strength as roots act like miniature anchors/piles for soil reinforcement (Stokes et al., 2009; Schwarz et al., 2010b). The approach can be more cost-effective than traditional engineering approaches of soil nails or micropiles, but uncertainty that remains about the effects of roots on slope stabilisation hinders uptake of the use of vegetation to stabilise slopes by practitioners (Stokes et al., 2014; Kim et al., 2017). To quantify the mechanical effect of roots on soil shear strength, many studies have been performed either in the laboratory (Waldron, 1977; Operstein and Frydman, 2000; Normaniza et al., 2008; Mickovski et al., 2009; Loades et al., 2010; Veylon et al., 2015) or the field (Hengchaovanich and Nilaweera, 1996; Wu

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* Corresponding author.
E-mail address: tzliang@dundee.ac.uk (T. Liang).

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and Watson, 1998; Ekanayake et al., 1998; Van Beek et al., 2005; Cammeraat et al., 2005; Docker and Hubble, 2008; Fan and Su, 2008; Fan and Chen, 2010; Comino and Druetta, 2010; Comino et al., 2010) using direct shear tests. However, most of these existing studies focus on the strength of soil reinforced by young trees and herbaceous plants. While this is important for understanding short-term improvement in stability of slopes planted with trees, only a few studies report the contribution of roots of well-developed mature trees to soil strength (important for long-term stability assessment), predominantly because of the large size of mature tree root systems and the limited size of available field shearing apparatus (Sonnenberg et al., 2011). Field monitoring of full-scale slopes could provide invaluable data on real slope behaviour. However, implementing a field trial is usually expensive, time consuming and it is often difficult to trigger a failure to identify the failure mechanism for safety reasons. Geotechnical centrifuge modelling, on the contrary, can provide a good balance between keeping expense low while maintaining a high level of fidelity and is potentially therefore a better method for investigating the global performance of vegetated slopes under known boundary conditions (Sonnenberg et al., 2010; Liang et al., 2015).

In previous applications of centrifuge modelling to study vegetated slopes, plant roots have been modelled either using root analogues (e.g. Sonnenberg et al., 2011; Eab et al., 2014; Liang et al., 2015; Ng et al., 2014, 2016) or live plants (e.g. Sonnenberg et al., 2010; Askarinejad and Springman, 2015). Root analogues have a major advantage of high repeatability of architecture and properties and they can be easily and quickly produced. The major difficulty of this modelling technique, however, is to identify a suitable material which can simultaneously model the stiffness, strength and complex architecture of live roots, though some progress has recently been made by Liang et al. (2014, 2017) and Liang and Knappett (2017), who employed the 3-D printing technique using Acrylonitrile butadiene styrene (ABS) plastic to produce root analogues of complex geometry, while simulating strength (T_r) and stiffness (E) much more realistically than previously used materials (e.g. wood or rubber dowels). However, these are limited to use in dry cohesionless soils due to the necessity of pluviating the soil around the analogues for installation.

Use of live plants in the centrifuge can potentially model both mechanical and hydrological effects. Compared to root analogues, live plants could provide not only representative root strength and stiffness, but also more correct stress-strain response, including the maximum strain and stress localisation, and highly representative root-soil interaction properties (Hinsinger et al., 2009). However, previous studies using live plants (e.g. Sonnenberg et al., 2010; Askarinejad and Springman, 2015) did not consider in detail the scaling of the properties in the model. For example, for the 290-day-old Willow used by Sonnenberg et al. (2010), tensile strength of root sample with a diameter of 0.2 mm is approximately 80 MPa at model scale. If this root is being tested in a centrifuge at a gravitational acceleration of 15g (i.e., $N = 15$), according to the centrifuge scaling laws, the root diameter at prototype scale would be 3 mm, where the root tensile strength of Willow in the field is less than 20 MPa for roots larger than 3 mm (Mickovski et al., 2009). Such over-representation of root strength could lead to over-prediction of root reinforcement and its contribution to slope stability.

Previous studies on root biomechanical properties have revealed that root tensile strength and stiffness often decrease with increasing root diameter for mature plants (e.g. Bischetti et al., 2005; Genet et al., 2005; Pollen and Simon, 2005; Zhang et al., 2014), and also that they increase with root age (Loades et al., 2015; Sonnenberg et al., 2010). Due to the counteracting effects between root diameter and root age on the root biomechanical properties, it might be possible to use juvenile fine roots to simulate the biomechanical behaviour of mature coarse roots of the same species (for similar root architecture) in centrifuge models. Docker and Hubble (2009) have previously applied a similar concept to simulate the root system architecture of mature trees using field excavated juvenile trees to study the role of mature trees on slope stability at field scale.

Table 1
Scaling laws for centrifuge testing related to this study (After Schofield, 1981; Taylor, 2003; Muir Wood, 2003).

Parameter	Scaling law: Model/Prototype	Dimensions[a]
Length/Depth	$1/N$	L
Area	$1/N^2$	L^2
Volume	$1/N^3$	L^3
Seepage (Consolidation Time)	$1/N^2$	T
Density	1	M/L^3
Mass	$1/N^3$	M
Stress/Tensile Strength	1	M/LT^2
Strain	1	–
Force	$1/N^2$	ML/T^2
Bending moment	$1/N^3$	ML^2/T^2
Young's modulus	1	M/LT^2
Second moment of area	$1/N^4$	L^4

[a] L = length; M = mass; T = time.

The aim of this paper is to identify candidate species to better represent scale root morphologies and mechanical characteristics for use in centrifuge modelling. After preliminary assessment of suitable species, three species, which represent three distinct plant functional groups, were selected and cultivated for limited periods of time. A series of direct shear and axial tensile tests were undertaken to quantify root morphologies, tensile strength and Young's modulus of these juvenile root samples and their effects on increased soil strength. Based on the test results, the potential uses of the juvenile root systems to model biomechanical behaviour of mature coarse roots in centrifuge were discussed through a comparison with published results of more mature field grown specimens.

2. Materials and methods

2.1. Principles of centrifuge modelling

A geotechnical centrifuge is a device which can provide an enhanced gravity field to a reduced-scale physical model via centripetal acceleration. When testing a small scale model in a geotechnical centrifuge, similitude of stresses (and therefore the non-linear stress-strain behaviour of soil) at homologous points within the model and full-scale prototype can be achieved. In this way, the global performance of a full-scale soil slope prototype can be simulated to a high level of fidelity at a small scale model. Relevant scaling laws for centrifuge modelling used in this study are show in Table 1 (Schofield, 1981; Taylor, 2003; Muir Wood, 2003). These are principally based on the concept that the model is scaled purely geometrically, with model material properties (e.g. T_r, E) scaled 1:1.

2.2. Soil properties

All plant specimens were grown in 150 mm diameter tubes 530 mm long packed with mechanically compacted Bullionfield soil (mineral portions consisting of 71% sand, 19% silt, and 10% clay, James Hutton Institute, Dundee, UK) with a pH of 6.2 (Loades et al., 2015). The length/height of the tubes was selected to be the same as the maximum depth of soil that could be modelled in a centrifuge strong-box at the University of Dundee, UK. The liquid limit and plastic limit of the soil were determined to be 0.297 gg^{-1} and 0.192 gg^{-1}, respectively, following the fall-cone test and moulding tests, described by the British Standard (BS1377:1990 Part 1). The base of each tube was covered with a mesh membrane (1 mm

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