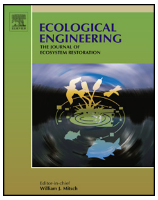
Ecological Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Root biomechanical properties during establishment of woody perennials

D. Boldrin[a,b], A.K. Leung[a,*], A.G. Bengough[a,b]

[a] School of Science and Engineering, University of Dundee, Dundee, DD1 4HN, United Kingdom
[b] The James Hutton Institute, Invergowrie, Dundee, DD2 5DA, United Kingdom

ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form 6 April 2017
Accepted 2 May 2017
Available online xxx

Keywords:
Root biomechanics
Root tensile strength
Young's modulus of roots
Root water status

ABSTRACT

Background and aims: Soil bio-engineering using vegetation is an environmentally friendly solution to stabilise soil slopes. This study investigates tensile strength, Young's modulus, and root diameter relationships for establishing woody perennials.
Methods: Specimens of ten woody European shrubs and small trees were transplanted into sandy loam soil to establish for six months. Root tensile strength and Young's modulus were measured as well as the root length-diameter distribution. The effect of root water status on root diameter was evaluated for Scotch Broom.
Results: More than half of the root length for all species was thinner than 0.5 mm diameter. Typical tensile strengths were <40 MPa, with Young's modulus <600 MPa. Negative power relationships between root strength and root diameter existed only for Gorse and Spindle, whilst Blackthorn, European Box and Holly showed slight increase in tensile strength with diameter. Hawthorn, Hazel and Privet showed rapid initial increase in strength with diameter followed by strength decrease with diameter, post-peak. Young's modulus was linearly related to tensile strength for all ten species ($P < 0.001$; R^2 values 17%–64%). Root diameter, investigated for Scotch Broom, depended strongly on root water potential and root water content by mass. Root water content could influence considerably the calculations of tensile strength.
Discussion and conclusion: Root tensile strength-diameter relationships often do not follow a negative power law, and depends strongly on taxa. Young's modulus was strongly related to tensile strength of roots for certain species. Water status of roots strongly influences root diameter and hence strength and Young's modulus properties, and must be controlled carefully in experiments.

1. Introduction

In recent years, soil bio- and eco-engineering using plants has been recognised as an environmental-friendly and low CO_2-emission solution for soil stabilisation, as compared to existing traditional "hard" engineering solutions such as soil nailing and piling (Inui et al., 2011; Stokes et al., 2008; Stokes et al., 2014). Plant roots can increase soil shear strength through mechanical and hydrological reinforcement (Pollen-Bankhead and Simon, 2010; Leung and Ng, 2013; Saifuddin and Osman, 2014; Leung et al., 2015; Veylon et al., 2015). Whilst soil is generally weak in tension and strong in compression, roots are strong in tension. Root-permeated soil thus represents a type of composite material with enhanced mechanical properties beneficial for slope stabilisation (Simon and Collison, 2002; Fan and Su, 2008; Mickovski et al., 2009).

Root mechanical reinforcement depends on root system morphology, root number, diameter, tensile strength and stiffness (Young's modulus; the initial linear part of a tensile stress-strain curve) (Mickovski et al., 2007; Mickovski et al., 2009; Stokes et al., 2009; Loades et al., 2010; Osman and Barakbah, 2011; Ghestem et al., 2014a; Ghestem et al., 2014b; Saifuddin et al., 2015). Root length is one of the most studied traits, which is often correlated with plant growth rate and plant's ability to stabilise soil in disturbed areas (Stokes et al., 2009). The number and the relative amount of fine and coarse roots play a major role in soil stabilisation. While coarse roots (diameter >10 mm) may act as a structural element like soil nails, fine roots (diameter <2 mm) permeated in the soil can create a membrane-like structure to protect soil from surface erosion (Stokes et al., 2009). Ghestem et al. (2014b) found that (i) the total length of coarse roots above a shear plane and (ii)

---

[*] Corresponding author.
E-mail address: a.leung@dundee.ac.uk (A.K. Leung).

http://dx.doi.org/10.1016/j.ecoleng.2017.05.002
0925-8574/© 2017 Published by Elsevier B.V.

the fine root density below the plane govern the contribution of root reinforcement to the increase in soil shear strength.

Many studies on root mechanical reinforcement have assessed the relationship between root diameter and root tensile strength (Mattia et al., 2005; Bischetti et al., 2009; Preti and Giadrossich, 2009; Mickovski et al., 2009; Ghestem et al., 2014a). A negative power law has been commonly used to describe the variation of root tensile strength with root diameter for several plant species (Mao et al., 2012).

$$T_r = \alpha d^{\beta} \tag{1}$$

where α and β are empirical coefficients that are species-specific. β is always less than zero, so roots with larger diameters would have a lower tensile strength. Mao et al. (2012) listed α and β for 81 species of grass, forbs, shrubs and trees reported in the literature. Eqn (1) has been commonly used as a predictive model to estimate the mechanical reinforcement that can be provided by roots through the so-called root cohesion (Mao et al., 2012). This general negative power law has also been sometimes used in the design of appropriate root analogues for bio-engineering research (Liang et al., 2014, 2015; Meijer et al., 2016).

The common negative power law fitting, however, is often able to explain only a small fraction of the variability in tensile strength-diameter relationship (Mattia et al., 2005; Ghestem et al., 2014a; Vergani et al., 2014). Root biomechanical properties change over time as a function of root chemical composition (i.e., cellulose and lignin content) (Genet et al., 2005; Saifuddin and Osman, 2014; Zhang et al., 2014), root type (Loades et al., 2013), root age (Dumlao et al., 2015; Loades et al., 2015), root decay (Watson et al., 1999), moisture content (Yang et al., 2016) and in response to mechanical stress (Chiatante et al., 2003; Loades et al., 2013). Although the tensile strength-diameter relationship has been generally considered to follow a negative power law model, the physical basis of such relationships is still not clear nor its optimal use for different species or conditions. In particular, there is a lack of information and understanding of root biomechanical properties during early stages of plant establishment (i.e., first year since transplanting or planting), which is the most critical period for slope stabilisation by soil bio-engineering. Live plant material often needs months or even years to develop sufficient strength to stabilise soils (Osman and Barakbah, 2011; Stokes et al., 2014; Sidle and Bogaard, 2016). Based on previous field and modelling studies, a forest re-establishment period of approximately 3–20 years from forest harvesting is needed to recover the pre-harvest conditions of root strength and slope stability (Sidle and Bogaard, 2016). This period represents a “temporal window” that coincides with an increase in landslide rate of about 2–10-fold compared to undisturbed forests. Indeed, a study on the re-establishment of pioneer vegetation (Schmidt et al., 2001) reveals that during the first 7 years since forest harvesting, root cohesion (i.e., the additional strength gain by soil due to roots) remained less than 3 kPa. The root cohesion for coniferous and hardwood vegetation was recovered to values higher than 10 kPa after almost a decade. Moreover, Preti and Giadrossich (2009) highlighted reduced root growth to depth for transplanted plants when compared with naturally regenerated plants of the same age in the same area.

The experiments reported in this paper aim to evaluate the biomechanical properties of ten selected shrubs and small trees widespread in Europe. The objectives are (i) to measure and quantify root biomechanical properties during their early stage establishment, which represents a particularly challenging period for these plants; (ii) analyse and compare the tensile strength-diameter and Young’s modulus-diameter relationships of the ten woody species. Preliminary experiments were also performed on a single species to evaluate the effects of root water status and related diameter change on root tensile strength estimation, as significant changes in root diameter can occur with change in plant water status (Huck et al., 1970; Carminati et al., 2009, 2013).

2. Material and methods

2.1. Selected plant species

Ten woody species, which would grow into shrubs or small trees, were selected for testing in this study. These include *Buxus sempervirens* L., *Corylus avellana* L., *Crataegus monogyna* Jacq., *Cytisus scoparius* (L.) Link, *Euonymus europaeus* L., *Ilex aquifolium* L., *Ligustrum vulgare* L., *Prunus spinosa* L., *Salix viminalis* L. and *Ulex europaeus* L. Their family, common name, height range, age and the acronym used throughout this study are summarised in Table 1. These species have been suggested as suitable plants for soil eco- and bio-engineering applications (Marriott et al., 2001; Coppin and Richards, 2007; Norris et al., 2008; Beikircher et al., 2010) and are suited to a North European wet maritime climate. These species have been previously tested for soil hydrologic reinforcement (Boldrin et al., 2016; Boldrin et al., 2017). Plants that were 30–80 cm tall and older than one year were selected for testing in this study. This plant size range is considered representative of that commonly adopted for soil bio- or eco-engineering projects (see online document 1).

Eight replicates of bare root plants per species were transplanted in pots (0.24 m in diameter; 0.009 m^3 in volume) with arable soil during the dormant season. Following transplanting, plants were kept in a glasshouse, where no additional light or heating was provided. The temperature of glasshouse was thus close to the outdoor temperature during the entire experiment. The soil used in this study was collected from Bullionfield, The James Hutton Institute, Dundee, UK. It was a sandy loam, which comprised of 71% sand, 19% silt and 10% clay contents (Loades et al., 2013). The soil (sieved <10 mm; water content 0.15 g/g) was dynamically compacted in five layers in pots to obtain an initial dry density of 1200 kg m^{-3}. The soil packed at this density had a water content at field capacity (5 kPa suction) equal to 0.25 g g^{-1} and 0.08 g g^{-1} at the permanent wilting point (1500 kPa suction). After soil compaction and transplantation, each planted pot was irrigated depending on the season and glasshouse temperature. No fertilizer was added to all planted pots.

2.2. Measurements of root length per diameter class

After four months establishment, roots of five replicates per species were washed free from soil using a set of sieves from 2 to 0.5 mm and stored in ethanol (70%) at 5 °C. Representative subsamples of the root system (10% of root system by weight) were scanned using WinRhizo (Regent Instruments Inc.) to determine root lengths per diameter classes (0.1 mm interval width). The measured length and dry mass of these root subsamples were used to obtain the specific root length (SRL; root length per unit mass). The entire root system of each species was oven-dried at 60 °C to determine the dry root biomass. The total length per each diameter class was then estimated by multiplying the dry root biomass by the SRL and the percentage of each diameter class. Thick roots (>5 mm diameter), if present, were processed and analysed separately to avoid errors in estimating root length.

2.3. Measurements of root biomechanical properties

Six months after transplanting, three replicates of planted pots per species were used to measure the root biomechanical properties, including tensile strength and Young’s modulus. Root systems were washed free from soil using the identical procedures described above. Then, all root samples were stored at 5 °C in sealed

Please cite this article in press as: Boldrin, D., et al., Root biomechanical properties during establishment of woody perennials. Ecol. Eng. (2017), http://dx.doi.org/10.1016/j.ecoleng.2017.05.002