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Methods to measure the mechanical behaviour of tree roots: A review

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ABSTRACT

The presence of forests on hillslopes significantly reduces the slopes susceptibility to rainfall triggered shallow landslides. This is due largely to the reinforcement of the hillslope soil by tree roots which increase the shear strength of the soil, and in some instances, anchor the soil mantle to the underlying bedrock by deeply penetrating roots. Quantifying the reinforcing effects of tree roots within soils and the evaluation of hillslope stability using geomechanical and numerical models relies on a realistic representation of the characteristics of tree roots distribution within the hillslope and the mechanical strength of those roots. The variety of experimental methods that have been developed since the 1960s and are used to generate these root strength and rooted-soil shear-strength data are reviewed. The majority of these studies have focused on determining the tensile strength of individual roots by loading the root in a pulling device until it breaks and/or determining the shear-strength of rooted soil in comparison to non-rooted soil in a Coulomb-type shear-box test. These studies have also generally either examined mature root systems in the field or relatively young plants grown in special containers specifically designed for tensile tests or laboratory shear-box tests. A particular difficulty that most studies have encountered is fixing or securing the ends of roots in the attachment device of the testing apparatus (so called root-pullers or tensile testing machines) as the various styles of clamping employed can easily damage the root which reduces the measured strength or otherwise results in an unrealistic test result. Laboratory shear-box tests encounter a similar difficulty in that the roots are not generally fixed or constrained at the base of the shear-box; field shear-box tests tend to avoid this problem as the roots are present in their natural anchoring characteristics in the soil and rock substrate. A result universally reported in rooted soil shear-box test studies is that the peak shear-strength of rooted soil significantly exceeds the peak shear-strength of that soil in a non-rooted condition and that the rooted-soil peak strength is typically recorded at a shear-displacement distance several times that of the non-rooted soil. This result fundamentally explains the reduced susceptibility of forested hillslopes to shallow landslides. A variety of solutions developed to deal with the difficulties that root and rooted-soil tests present are outlined. A set of suggested protocols for conducting root tensile tests and field pullout tests are also presented. It is intended that the adoption of these protocols will enable more effective and direct comparisons of test results and more confident interpretation with respect to the similarities and differences between test results generated from different species and field sites.

1. Introduction

Plant roots play an important role for the protection of slopes against rainfall induced shallow landslides, river bank stability, and in soil bioengineering structures (Stokes et al., 2009, 2014; Docker and Hubble, 2008, 2009; Hubble et al., 2013; Watson et al., 1999). Mechanically, roots contribute to the stabilization/reinforcement of soil through an additional apparent cohesion, a term usually added to the Mohr–Coulomb failure criteria (O'Loughlin, 1974a). The importance of roots for slope stability is seen when comparing the order of magnitude

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Table 1
Summary of early studies of the increased shear strength of soil due to the presence of roots (O'Loughlin, 1974a).

Authors	Soil and vegetation types	Increased soil shear strength due to tree roots (kPa)
Swanston (1969)	Mountain till soils under coniferers	3.35–4.35
Endo and Tsuruta (1969)	Silt loam soils under alder	2.00–12.00
Takahasi (1968)	Silt loam soils under birch	1.50–9.00
O'Loughlin (1972)	Mountain till soils under conifers	1.00–3.00

of this additional cohesion (c_r) with other components of soil cohesion. Cohesive forces are electrostatic forces (e.g., in stiff overconsolidated clays) that may be lost through weathering and have values ranging between 5 and 24 kPa; cementing forces (e.g., by Fe_2O_3, $CaCO_3$, or NaCl) that can reach hundreds of kPa; apparent cohesion in unsaturated soil due to suction (as soil dries out a water meniscus forms at grain contacts so that cohesion disappears with wetting) that is usually less than 1 kPa (Lu and Godt, 2008). The apparent cohesion of roots originates mainly from the root tensile strength. It is this quantity that is usually referred to as mechanical root reinforcement. Root reinforcement ranges from 1 to 12 kPa (Table 1). This cohesion can be lost partially or entirely during soil liquefaction, wildfires, or by removal of vegetation (Vergani et al., 2016, 2017).

Root reinforcement can operate on the basal shear plane (basal root reinforcement) or on the boundaries of the landslide in zones of tension or compression near the scarp or the toe of the landslide (lateral root reinforcement). Basal root reinforcement is effective if the shear plane of the landslide lies within the rooting zone (in temperate zones this depth is usually less than 1 m, but can extend to several meters deep in tropical zones (Kim et al., 2017). Vertical root distribution usually decreases non-linearly with increasing soil depth (e.g. Bischetti et al., 2005). During loading, roots that cross the basal shear plane are bent at the edges of the shear zone and are in tension inside the shear zone.

Lateral root reinforcement acts on a shallow landslide as a combination of tensile and compressive forces within the failing soil mass and at its edges (Fig. 1). Studies have shown that the effectiveness of this type of reinforcement is limited to landslides with a volume of less than about 1000 m^3 (depending on slope angle and soil mechanical parameters, Schwarz et al., 2010c).

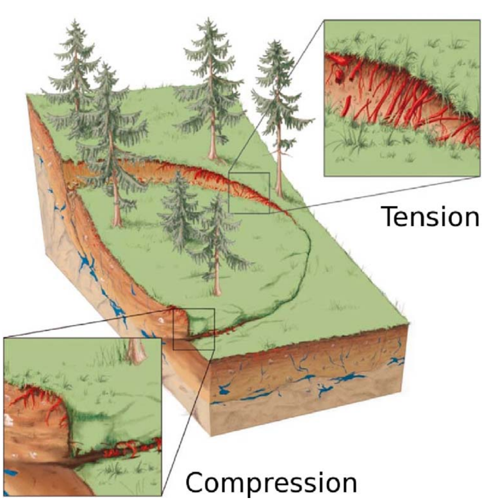

Fig. 1. Loading of roots under tension and compression depending on their position (lateral or at the toe of the slope) during the triggering of a shallow landslide. The unstable soil mass pushes down,creating passive earth pressure conditions in the downslope edge. From Schwarz et al. (2015), licensed under a Creative Commons Attribution.

In the last decade, research on root reinforcement has focused on several aspects: qualitative descriptions of mechanisms, quantitative estimates through experiments, the development of theoretical models, and slope stability calculations. In all these cases, an experimental measure of root reinforcement is necessary to feed models and assess the mechanical role of vegetation on slope stability. These experiments require significant field and laboratory studies on roots, soils, and/or a combination of both. Such experimental investigations are time consuming, difficult to reproduce owing to the intrinsic variability of the materials, and often destructive. However, a large body of experimental work has been performed over the last 50 years, demonstrating the use of different techniques for measuring root reinforcement (e.g., root tensile strength in the field or in the laboratory and shear/tensile/compressive strength of rooted soils). These data have often been obtained with a specific application in mind that cannot always be transferred to other objectives. The choice of the testing method may influence the type of results and calculations of slope stability if all experimental factors are not taken into account. For example, tests used to estimate root tensile behaviour are affected by the intrinsic variability of roots and by a variety of methodological constraints. Thus, it is important to clearly understand, identify, and classify methods that quantify the effects of roots in soils so that experimental results can be applied in different situations and by a larger community of researchers and practitioners. In this context, there is a need to review, classify, and discuss the types of experimental methods currently used for the quantification of root reinforcement. This review aims to: (1) summarize the experimental methods used for the quantification of root reinforcement; (2) discuss advantages and drawbacks of each of these methods for different types of application; (3) define the best possible combination of experimental efforts that should be used to quantify different types of root reinforcement mechanisms; (4) highlight knowledge gaps and provide direction for future work to improve the application of root reinforcement understanding for different problems.

2. Experimental methods for root reinforcement

Early studies on root reinforcement focused on the quantification of the mechanical behaviour of roots (e.g. Endo and Tsuruta, 1969; O'Loughlin, 1974b). The quantification of root reinforcement then became a specific branch of research since the late 1970s, and developed over the following decades. In particular, the mechanical behaviours of roots, their geometries, distribution in the soil, and interaction with the rhizosphere was studied in detail. In this context, different approaches to quantify root reinforcement were developed or conceptualized.

We have distinguished two main types of mechanical tests for roots: (i) the root is woody, then the data obtained from the test represent a direct measure of a specific behaviour of the root. Therefore we obtain the strength and stiffness of the woody material conditioned by biophysical factors such as moisture contents, anatomical and chemical properties, as well as external conditions related to test conditions. Laboratory tensile strength/force tests, buckling tests and pullout tests are included in this group. These tests can be carried out on a single root (as in the case of tensile strength/force tests), or buckling, or on a bundle of roots, in the field or in the laboratory. (ii) A combination of soil and roots are tested as a matrix. In this case roots are part of the soil system and the effect of each one cannot be separated but can only be considered within a global behaviour. The friction at the root–soil interface and at branching points determines the stress yield curve of the rooted soil. Shearing of a block of rooted soil in the field or of a rooted soil column in the laboratory, direct shear test, and rooted soil under compression are examples of tests in this group.