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Method for synchronisation of soil and root behaviour for assessment of stability of vegetated slopes

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ABSTRACT

A new methodology to incorporate the mechanical root anchorage effects in both short- and long-term slope stability analysis is proposed based on observed and assumed behaviour of rooted soil during shear failure.

The main focus of the present work is the stress–strain range comparison for both soil and roots and development of a stability model that would incorporate relevant root and soil characteristics based on the fact that available soil–root composite shear resistance depends on the magnitude of the shear strain. This new approach, combining stress–strain analysis, continuum mechanics, and limit equilibrium stability assessment, allows for a more realistic simulation of the rooted soil composite whereby the stabilising effect of the rooted soil is incorporated in the slope stability calculations by means of the synchronisation of root and soil mechanical behaviour during failure.

The stability of vegetated terraces in a study area in Spain is used as a case study to demonstrate the proposed methodology and to compare the results with the traditional use of the perpendicular root reinforcement model. The results of the study show that as the shear displacement (strain) increases, the stress is transferred from the soil that provides most of the resistance at low strains onto the roots that provide the most of the resistance to shear at high strains. Including this behaviour in the overall resistance to failure of the root–soil continuum resulted in a more conservative and realistic assessment of the stability of a vegetated slope immediately after a precipitation event when a progressive failure is most likely to be triggered.

1. Introduction

The development and use of plant root reinforcement models to assess the effects of vegetation in slope stability analysis has become a prominent research area all over the world in the last 10 years with research developments in root anchorage models (Pollen and Simon, 2005; Norris et al., 2008; Stokes et al., 2009; Preti and Giadrossich, 2009; Schwarz et al., 2010; Fan, 2012; Bourrier et al., 2013) and their application in practical stability problems such as shallow landslides or soil erosion (Coppin and Richards, 2007; Danjon et al., 2007; Schwarz et al., 2010; Comino and Druetta, 2009; Mickovski and van Beek, 2009; Thomas and Pollen-Bankhead, 2010).

From a mechanical point, rooted soil behaviour can be simulated by using different root reinforcement models. Some of them are based on traditional limit equilibrium (LE) approaches (e.g. Greenwood, 2006), other are based on more advanced numerical analysis (e.g. Dupuy et al., 2007; Bourrier et al., 2013). The most common mechanical root reinforcement models are the perpendicular and inclined root reinforcement model (Wu et al., 1979; Gray and Leiser, 1982), the fibre bundle model (Pollen and Simon, 2005; Schwarz et al., 2010), the energy approach model (Ekanayake et al., 1997) and a number of LE, finite element (FE), and finite difference (FD) numerical methods integrating the above models (Gray and Sotir, 1996; Chok et al., 2004; Fourcaud et al., 2007; Briggs, 2010; Mickovski et al., 2011; Bourrier et al., 2013).

All of the above approaches consider a composite material comprising soil matrix and roots and, therefore, must include two different mechanical behaviours in the analysis. Although attempts have been made in the past to account for this (Dupuy et al., 2007; Lin et al., 2010; Bourrier et al., 2013), the modelled root system and soil properties were either assumed or simplified to suit the particular model which made it difficult for practical application.

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The existing strain based rooting models (e.g. fibre bundle model, root bundle model) have simulated the failure mechanisms of a group of roots without accounting for varying strength of the materials at different strains which are important in both the rooted soil simulation and the stability analyses at a slope scale. To exceed these limitations, there is a need for a methodology that would combine the simplicity of the LE approach while incorporating continuum mechanics concepts and strain compatibility within the realistically modelled soil–root composite in order to provide the basis for wider, practical application.

Similar to the geosynthetic reinforcements used in geo-environmental engineering, plant roots enhance the soil strength by transferring shear stresses from the soil onto the roots that, due to different elastic properties, are better suited to resist it (Mickovski et al., 2009). It is conceivable that, as with other reinforcement elements, in the case of rooted soil the strain level corresponding to the root peak strength is higher than the one for soil peak strength due to differences in elastic properties of the roots and the soil. Although this premise has been investigated in the past for other composite materials (Jewell and Milligan, 1989; Prisco and Nova, 1993; Morel and Gourc, 1997; Zornberg, 2002; Hatami and Bathurst, 2006; Michalowski, 2008; Jonathan et al., 2013), it has never been explored in the context of sustainable use of vegetation for soil reinforcement.

Based on this concept, in this paper we propose a methodology that takes advantage of both the design for stability and the strain compatibility methodologies incorporating roots as reinforcing elements. We illustrate our approach through application in a case study of terraced slopes in Spain exhibiting instability and compare the results of this analysis with the results from other existing models.

The aim of this paper is to propose a practical framework for realistically accounting for the mechanical effect of roots on soil reinforcement in the design for slope stability. The objectives are to explore the behaviour of the soil–root continuum at failure comparing it to the behaviour of a reinforced soil, and apply it into the existing rooting models as an input into a LE slope stability analysis. Linking the soil and roots strain in an iso-strain state (equality of strain of both soil and roots) of the root–soil continuum and demonstrating its application in a representative case study not only provides a more realistic representation of the root–soil interaction in terms of stress transfer processes and soil reinforcement, but also provides a mode of application of relatively easily measured and analysed parameters into stability assessment of vegetated slopes which, in turn, could increase the confidence of practitioners about the use of eco-technological solutions.

2. Material and methods

2.1. Background

In traditional slope safety factor (SF) calculation (Eq. (1); Zheng et al., 2006) for a slope to be safe, the SF has to be greater than unity (SF > 1), i.e. the available strength (e.g. by the root–soil continuum) has to be greater than the required strength. At the same time, all terms included in the numerator are assumed to have compatible stress–strain behaviour (similar development of stresses in all elements at any strain level), while the effects included in the denominator do not depend on the strain level (Leshchinsky, 1997).

$$\text{Safety\_Factor\_(SF)} = \frac{\text{Available\_Strength}}{\text{Required\_strength}} \quad (1)$$

To realistically model the behaviour of a composite material such as the soil permeated with roots, the different contributions to the strength of the root–soil continuum by the elements of the continuum (roots and soil) that have differing elastic properties have to be made compatible before including them in Eq. (1).

In the case of Mohr–Coulomb failure criterion (Smith and Smith, 1998), the soil shear strength τ [kN/m^2] is expressed in terms of its cohesion c [kN/m^2] and its internal friction angle φ [°] for different normal stress σ [kN/m^2].

$$\tau = c + \sigma \times tg(\phi) \quad (2)$$

The values of both cohesion and internal friction angle shown in Eq. (2) can be either peak or residual depending on the level of strain (Fig. 1), but in the case of reinforced soils, the strain level at which extensible reinforcements may develop their peak values will usually be higher than the strain when the soil develops its peak value (Leshchinsky, 2002; Schwarz et al., 2010). This is particularly true for small diameter roots which can be considered as flexible reinforcements (Wu et al., 1979; Mickovski et al., 2007), and which provide ductility for the root–soil continuum, reaching the peak strength at high strains (e.g. Mickovski et al., 2007; Mickovski and van Beek, 2009). This suggests that at high strain (displacement) level the soil may be developing its residual strength value while, at the same time, the roots (reinforcements) are developing their peak strength—a concept which has to be taken into account in the analysis of slope stability and factor of safety calculation for vegetated soil.

The reinforcement effect due to the plant roots (excluding the major structural roots) can be expressed in terms of an "added cohesion" ΔS which is added on to the strength of the non-rooted soil (Eq. (2)) and can be calculated, for example, for a known root tensile strength t_R [KN/m^2] and root area ratio (RAR; the ratio of area of roots crossing the shear plane and shear plane area; Waldron (1977) and Wu et al. (1979); Eq. (3)) as:

$$\Delta S = 1.2 t_R \quad (3)$$

To make the soil and root mechanical behaviour compatible, the displacement at which the soil reaches its peak strength can be linked to the corresponding root elongation (Shewbridge and Sitar, 1985; Abe and Ziemer, 1991) as:

$$\varepsilon = (1 + B^2 b^2 e^{-2bx})^{1/2} - 1 \quad (4)$$

where ε = root strain [mm/mm]; x = shear displacement [mm]; B = half of the shear displacement [mm]; b = coefficient depending on root diameter D [mm] and RAR (Abe and Ziemer, 1991) expressed as:

$$b = 0.2262 - 0.0715\text{RAR} - 0.0016\text{D} \quad (5)$$

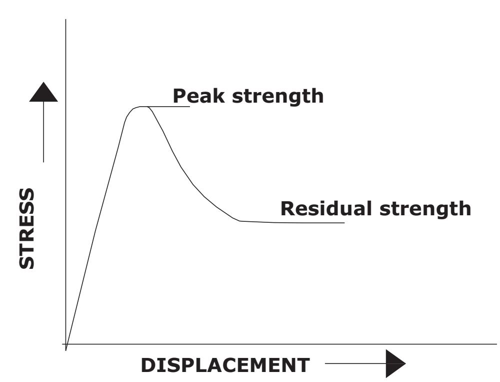

Fig. 1. Typical behaviour of soil under shear. The stress-displacement curve of a non-reinforced soil shows that as the displacement increases, the soil stress increases up to the soil peak shear strength value before decreasing and levelling off to the residual soil shear strength value at very large displacements.