Geoderma 285 (2017) 141–150

Contents lists available at ScienceDirect

Geoderma

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

Plant-soil reinforcement response under different soil hydrological regimes

Alejandro Gonzalez-Ollauri *, Slobodan B. Mickovski

School of Engineering & Built Environment, Glasgow Caledonian University, Glasgow, UK

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 26 September 2016
Accepted 1 October 2016
Available online 7 October 2016

Keywords:
Plant-soil
Reinforcement
Hydrological regimes
Suction stress

ABSTRACT

The use of plants against shallow landslides and erosion has received considerable attention over time as it is believed that vegetation provides mechanical and hydrological reinforcement to the soil. However, neither the soil-root mechanical reinforcement under different hydrological regimes, nor the hydrological effects of vegetation on soil reinforcement have been properly studied.

This paper explores how plants are able to provide mechanical and hydrological reinforcement to soil under different soil hydrological regimes. To do this, we first defined a novel, simple and reproducible laboratory protocol to investigate how changes in soil moisture affect the mechanical effects of vegetation on soil reinforcement. We then explored how plants modify the relevant soil properties and what implications this may have on soil reinforcement. We finally attempted to evaluate the suction stress functions for both fallow and vegetated soil, as a proxy to quantify the hydrological plant-derived soil reinforcement.

The results showed that plants significantly increased the soil organic matter and the angle of internal friction, both with relevant hydro-mechanical implications. Vegetation presented a significant mechanical soil reinforcement that was higher at the soil's hydrological transition regime, suggesting the existence of optimum soil moisture content for an effective soil-root reinforcement response. The hydrological regimes also imposed differences in terms of the hydrological reinforcement, which differed between fallow and vegetated soil. However, the derived suction stress function for the fallow soil in the experiments showed differences when compared to the theoretical predictions.

Our findings provide a good basis for future research to enhance our understanding of the nature of plant-soil composites and shed light on the sustainable use of vegetation against shallow landslides.

1. Introduction

The use of plants against landslides and erosion has received considerable attention during the past decades (e.g. Wu et al., 1979; Stokes et al., 2014). Plants effectively provide reinforcement to the soil matrix (Waldron, 1977). In engineering, the soil-root reinforcement is normally attributed to the transfer of mechanical energy from the roots to the soil (Ekanayake and Phillips, 1999) given the differences between both root and soil materials (Greenway, 1987) converging into plant-soil composites (e.g. Thorne, 1990).

The provision of plant-soil hydrological reinforcement, however, has received less consideration (Stokes et al., 2014). In part, this is due to the difficulties of integrating the hydrological effects of vegetation into the evaluation of soil strength. Moreover, the performance of the plant-soil reinforcement response may also be influenced by the soil's hydrological conditions (e.g. moisture content). A few studies have tried to address this gap (e.g. Pollen, 2007; Fan and Su, 2008; Mickovski et al., 2009), but overall it has largely been neglected.

Soil moisture content is subject to seasonal variations (Rodriguez-Iturbe and Porporato, 2004). Given the increased likelihood of landslide occurrence associated to certain seasons and hydrological conditions (Lu and Godt, 2013), it is of the utmost importance to enhance our understanding on how the plant-soil reinforcement response may change under these soil moisture variations.

Within a mass instability context, the soil strength (τ) is measured as the soil resistance to shear. This is commonly quantified with the Coulomb's law, which represents the maximum possible state of soil stress by means of a graphical line known as the 'failure envelope' (Head and Epps, 2011). A failure envelope is defined through the cohesion and angle of internal friction of the soil (c' and ϕ', respectively). It is believed that ϕ' does not change when roots are present in the soil (Waldron and Dakessian, 1981; Gray and Ohashi, 1983; Ghestem et al., 2013) and, consequently, failure envelopes are not normally portrayed for vegetated soils. The same methodology used to find a

* Corresponding author at: SEBE, Glasgow Caledonian University, Cowcaddens Road, G4 0BA Glasgow, UK.
E-mail address: alejandro.ollauri@gcu.ac.uk (A. Gonzalez-Ollauri).

http://dx.doi.org/10.1016/j.geoderma.2016.10.002
0016-7061/

soil's failure envelope, known as shear testing (Head and Epps, 2011), is also used to evaluate the additional shear strength roots provide to soil (Waldron, 1977; Ekanayake and Phillips, 1999; Mickovski et al., 2009; Ghestem et al., 2013).

Shear tests carried on vegetated soil are normally performed under saturated (e.g. Waldron and Dakessian, 1981) or constant moisture levels (e.g. Mickovski et al., 2005; Mickovski et al., 2008; Ghestem et al., 2013). As it has been observed that the moisture content may determine the mode by which plant roots confer energy to the soil (i.e. influence the mode of root failure within the soil-root continuum; Ennos, 1990), the moisture content should be taken into consideration. The few studies attempting to explore the effects of the moisture content on soil-root reinforcement have taken care to mimic natural conditions of root reinforcement (e.g. Pollen, 2007; Fan and Su, 2008), but have not considered the range of different soil hydrological regimes possible (Vanapalli et al., 1996).

The soil hydrological regimes must be defined on the basis of the soil water characteristic curve (SWCC; van Genuchten, 1980). They can be divided into Saturated Regime (i.e. all soil pores are full of water), Transition Regime (i.e. air begins to enter in the soil-pore space) and Residual Regime (i.e. just films of water are retained around the soil particles) (e.g. Lu and Likos, 2004). The hydrological regimes are relevant because it is known that soil shear strength changes with the amount of water kept within the soil-pore space (Vanapalli et al., 1996).

To include the soil shear strength effects from the mechanisms that take place within the soil-pore space under variable hydrological regimes, Coulomb's law has been updated over the years (i.e. *effective stress principle*: Terzaghi, 1943; Bishop, 1954; Fredlund and Morgenstern, 1977). The effects conferred by the soil-root mechanical reinforcement have also been included (e.g. Wu et al., 1979). In an attempt to unify the different stresses that act within the soil-pore space (i.e. pore-water pressure, pore-air pressure, physical-chemical forces at the particle contacts), Lu and Likos (2004) developed the *unified effective stress principle*, which considers a unique stress variable, the suction stress (σ^s), featured in the Coulomb's law (failure envelope) for variably saturated conditions as:

$$\tau = c' + (\sigma - u_a - \sigma^s)\tan\phi'$$

where u_a is the pore-air pressure, normally assumed to be at the atmospheric pressure and assigned a value of 0 kPa; σ is the normal stress; c' and ϕ' are the soil effective cohesion and the angle of internal friction, respectively, and τ is the shear stress (strength) of the soil.

The suction stress (σ^s) is meant to have the form of a characteristic function of the soil (i.e. SSCC; Lu and Likos, 2006) based on the SWCC fitting parameters – i.e. α: inverse of the air entry pressure and n: pore-size distribution parameter (Lu et al., 2010; Song et al., 2012). In addition, σ^s is directly related to the soil apparent cohesion (c'), which actually mobilises the suction stress to shear resistance under the shear failure of soils (Lu and Godt, 2013). Thus, SSCC could be appraised by means of shear testing under different moisture contents or matric suction levels (Lu and Likos, 2004, 2006) by extrapolating the failure envelopes to intercept with the negative side of the abscissa axis (i.e. $\sigma^s = -c'/tan\phi'$), provided that changes in the degree of saturation, or matric suction ($u_a - u_w$), will lead to the upward shift of the failure envelope (Vanapalli et al., 1996; Lu and Likos, 2006; Kim et al., 2013).

The direct dependency of σ^s on $u_a - u_w$ allows the former to be considered as a proxy to quantify the plant-soil hydrological reinforcement. The matric suction increase derived from plant water uptake or evapotranspiration processes is one of the most recognisable hydrological effects provided by the vegetation on the soil (Rodriguez-Iturbe and Porporato, 2004). However, it cannot be employed alone to quantify the plant-soil hydrological reinforcement as the mechanisms occurring within the unsaturated soil-pore space are complex (Lu and Likos, 2004). Hence, the soil hydro-mechanical properties (e.g. α and n) must be regarded in combination with $u_a - u_w$ for the quantification of σ^s (e.g. Lu et al., 2010) and, thus, approaching the plant-soil hydrological reinforcement.

In addition, plants, as living organisms, modify the environment they live in and, in particular, plant roots alter the surrounding soil (i.e. *rhizosphere;* e.g. Hinsinger et al., 2009) in many ways. These changes are demonstrated not only as enhancements of the soil matrix structure and strength but also as alterations of the mechanisms governing soil physicochemical processes, such as the retention and flow of water in the soil (Carminati et al., 2010; Scholl et al., 2014). Hence, when plants are present in the soil one should consider a new material (i.e. plant-soil composite) with specific hydro-mechanical properties (Scanlan, 2009). However, testing the properties and behaviour of plant-soil composites, in general, and soils under unsaturated conditions, in particular, is difficult – there is a need to develop simpler and quicker protocols.

The aim of this paper is to explore how plants are able to provide mechanical and hydrological reinforcement to the soil under different soil hydrological regimes. To do this, we first define a novel, simple and reproducible laboratory protocol to investigate how changes in soil moisture modify the mechanical response of vegetation upon soil reinforcement. We then look at how plants modify the soil properties and what implications this may have for soil reinforcement. Finally we attempt to evaluate the suction stress functions for both fallow and vegetated soil, as a proxy to quantify the plant-derived soil hydrological reinforcement.

2. Materials & methods

2.1. Soil type and testing program

A silty sand soil (Sand: 79.82%; Silt: 5.85%; Clay: 3.08%; BS 1377 Part 2, 1990) was collected from three sampling points at the crest of a landslide-prone slope in Catterline Bay, Northeast Scotland, UK, from a depth of between 300 and 600 mm below ground level (b.g.l). The soil had intermediate to low plasticity, (liquid limit, w_L, of 36.07%; plastic limit, w_P, of 10.45%; BS 1377 Part 2:, 1990) and a low organic matter (OM) content (1.16 ± 0.01%; OM baseline; Schulte and Hopkins, 1996).

The soil was oven-dried at 100 °C for 48 h after which it was pulverized with pestle and mortar and sieved through a 2 mm sieve. Then, the sample was split into two replicate treatments – i.e. fallow and vegetated, respectively.

The fallow replicates (4 in total) were progressively taken to saturation level by adding deionized water while mixing the soil-water mixture thoroughly with a spatula. Water was added until no soil aggregates were present and a shiny film was observed atop. Once saturated, the replicates were covered with aluminium foil and refrigerated for 48 h at 4 °C, after which they were removed from the fridge and let to dry at 20 °C up to the desired moisture regime prior to shear testing (Fig. 1a).

The vegetated replicates (4 in total) were placed in 650 ml plastic trays (46.2 mm deep) and sown with 7 g of alfalfa (*Medicago sativa* L.) seeds spread evenly over the soil surface. Each sample was gently watered, covered with a plastic lid and left in darkness until the seeds germinated. Once they germinated, the trays were placed under an incandescent bulb of 60 W and the alfalfa was left to grow for 3 weeks without any fertiliser (Fig. 1b and c). Each sample was watered daily with 100 ml of tap water. Once the vegetated replicates were ready for shear testing, they were taken to water-saturation level and left to dry until they reached the desired moisture regime, as with the fallow samples.

Each replicate from both the fallow and vegetated treatments was tested in shear under three different hydrological regimes (I: saturated regime, II: transition regime and III: residual regime; Vanapalli et al., 1996). The hydrological regimes were identified on the basis of the soil water characteristic curve (SWCC; Fig. 2) to mimic the natural environmental conditions. SWCC was evaluated onsite at the three different