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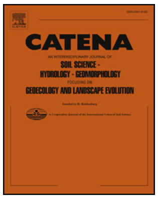

Determination of the shearing behaviour of root-permeated soils with a large-scale direct shear apparatus

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ABSTRACT

Soils with roots or root-like inclusions have often been tested in direct shear to quantify the effects of vegetation on the shear strength of soil, and in turn, the stability of slopes. However, a straightforward evaluation of root reinforcement is challenging due to the complex nature of roots, and the dependency of soil behaviour on many factors. An Inclinable Large-scale Direct Shear Apparatus (ILDSA) was built to study the shearing behaviour of root-permeated soils. Planted specimens, consisting of two different sets of species, were prepared with a moraine, sampled from a recent landslide location, and tested in direct shear subsequent to saturation. Relationships of peak stress ratio with dry weight of roots, maximum dilatancy angle and void ratio were investigated to evaluate the behaviour of root-permeated soil. The combined approach, of taking both presence of roots and dilatant behaviour of soil into consideration, results in a more realistic understanding and quantification of the effects of root reinforcement, at least, for laboratory testing of root-permeated soils.

1. Introduction

Soil bioengineering methods, the use of vegetation to prevent surficial erosion or shallow mass movement (Gray and Sotir, 1995), serve as a promising alternative to traditional civil engineering applications to stabilise either man-made or natural slopes against superficial failure. Roots improve the slope stability both mechanically, with roots crossing a potential failure surface (Waldron and Dakessian, 1982), and also hydrologically by evapotranspiration resulting in increased suction in the ground (Blight, 2003; Springman et al., 2003), and to a lesser extent by altering the soil structure (Graf and Frei, 2013; Loades et al., 2010). Roots perform their mechanical reinforcement function by working as tension-carrying fibres that transfer the shear stresses in the soil matrix into tensile resistance via the interface friction along their surface (Gray and Barker, 2004).

Although the physical explanation and interpretation of the mechanism of root reinforcement are simple, a satisfactory way of quantifying and incorporating the biological effects into the conventional slope stability analyses is still a major challenge. This is a considerable disadvantage of soil bioengineering methods (Graf et al., 2009), compared to well-established methods of design and calculation of conventional civil engineering infrastructure, such as retaining walls or soil nailing.

Giadrossich et al. (2017) provided an exhaustive review on the measurement methods of mechanical behaviour of the root-permeated soils. Direct shear tests (Fan and Tsai, 2016; Gonzalez-Ollauri and Mickovski, 2017; Veylon et al., 2015), tensile strength tests on roots (Giadrossich et al., 2016; Leung et al., 2015; Pollen and Simon, 2005), blade penetrometer tests (Meijer et al., 2017a, 2017b) and centrifuge testing (Liang et al., 2017, 2015; Sonnenberg et al., 2010) have been used to assess the vegetation effects on shear strength. The quantification of shear strength of root-permeated soils based on direct shear test results has generally been performed by drawing failure envelopes to Mohr circles in a shear stress (τ) - effective normal stress (σ') diagram either assuming an angle of internal friction equal to that of the fallow soil (Operstein and Frydman, 2000) or without any constraints (Ali and Osman, 2008). The intercept on the shear stress axis is denoted as "*root cohesion*" (c_R) value.

Alternatively, the difference between the peak shear stress of rooted and fallow soils can be recorded as the contribution of roots to the shear strength. These were compared with the c_R values calculated from various models based on measurement of the tensile strength of roots (Comino et al., 2010; Loades et al., 2010; Mickovski et al., 2009); correlated to different root traits (Ghestem et al., 2014) or used in slope stability calculations (Mickovski and van Beek, 2009).

The methods commonly adopted to compare peak shear stress

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parameters of root-permeated and fallow soil may both hinder and complicate the quantification of root reinforcement effects. These parameters are dependent on many factors, such as confining pressure, relative density and dilatancy (Das, 2010; Terzaghi et al., 1996), of which the latter presents more difficulty. Dilatancy can be defined as the volume increase of the soil during shearing along a shear surface. Bolton (1986) defines a relative density index (I_R), as follows:

$$I_R = I_D(10 - \ln p') - 1 \quad (1)$$

where I_D is the relative density and p' is the mean effective stress at failure, in kPa. Furthermore, the peak angle of shearing resistance ($\phi'_{\max}$), the angle of shearing at the critical state with zero dilation (ϕ'_{crit}) and maximum dilatancy angle ($\psi_{\max}$) are related to a relative density index under plane strain conditions as defined in Eq. (2).

$$\phi'_{\max} - \phi'_{crit} = 0.8\psi_{\max} = 5I_R \quad (2)$$

As shown in Eqs. (1) and (2), the peak shear strength parameter is directly dependent on the dilatant behaviour of the soil, which in turn is dependent on the relative density and confining stress. Furthermore, Jewell and Wroth (1987) showed with direct shear tests on reinforced sand that considerably less deformation is required to generate reinforcement forces in dense sand than in loose sand, since the ratio of the principal incremental tensile and compressive strains increases with the dilatancy angle. Therefore, a higher dilatancy angle means higher tensile strains, and in turn, higher tensile forces developing in the roots. It can be expected that dilatancy does not only directly increase the peak shear strength parameters due to interlocking of particles, but amplifies the effects of the roots resulting in even greater changes in peak shear strength.

Some of the stress-displacement, or strain, graphs given in the aforementioned studies exhibited a clear peak and a subsequent reduction in shear stress, which can be attributed to root breakage or pulling out, but it can also be due to particle interlocking and dilatancy. Thus, the comparison of peak shear strength parameters of root-permeated and fallow soil obscures the effects of dilatancy. The increase in the shear strength may not result solely from the contribution of the roots, but from the dilatancy as well. Dilatancy in root-permeated soils has been of interest very recently, although it has been a well-established topic in soil mechanics for many years. Muir Wood et al. (2016) introduced a new modelling framework for root-permeated soils, considering also the dilatancy. Otherwise, quantification of dilatant behaviour of these soils is rare in the literature. Therefore, a laboratory study was conducted with specimens prepared with different combinations of plant species with the following objectives:

i. to investigate the shearing behaviour of root-permeated soil specimens exhibiting dilatancy under saturated conditions,
ii. to propose a combined method of dilatancy and root biomass to explain the shear strength of root-permeated soils.

2. Materials & methods

2.1. Soil

The soil used to prepare the samples was collected from the moraine of a subalpine landslide location, Hexenruebi in Dallenwil, in canton Nidwalden, Switzerland. The area is a gully, where biological and technical stabilization measures have been taken and investigated over three decades by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) (e.g. Burri et al., 2009).

The soil was dried in an oven at 105 °C for 24 h and subsequently sieved to discard the particles having a size > 20 mm. The particle size distribution, as illustrated in Fig. 1, was obtained from two representative samples from the main batch by wet sieving in combination with the hydrometer method (ASTM D 422, 2007). The particle sizes separating the clay, sand and gravel were chosen according to ASTM D 2487 (2006). The liquid and plastic limits were determined by using a Casagrande tool and applying the thread-rolling method, respectively (ASTM D 4318, 2010). The liquid limit was 13.3%, while the plastic limit was calculated to be 16.8%. As the plastic limit was found to be higher than the liquid limit, the soil is classified as non-plastic (Allen, 1942; White, 1949). The specific gravity was determined by using a water pycnometer (ASTM D 854, 2010), and was calculated as 2.69. Soil was classified as SP-SM according to the Unified Soil Classification System (USCS).

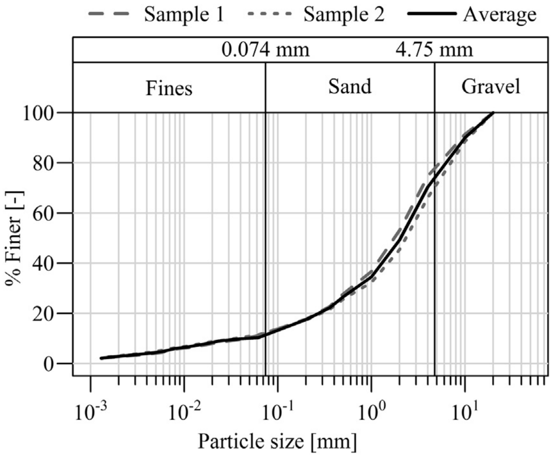

Fig. 1. Particle size distribution of two samples of Hexenruebi soil from the main batch obtained by wet sieving and hydrometer method.

2.2. Sample preparation

The preparation of a planted specimen consists of several steps, including the compaction of soil in the shear boxes, as well as previous plant breeding and growth. First of all, oven-dried Hexenruebi soil ($D_{\max}$ < 20 mm) is filled into wooden split boxes (500 × 500 × 400 mm) and compacted in three layers up to a height of 300 mm by applying 15 blows per layer using a 4.5 kg compaction rammer with a drop height of 460 mm. The compaction was performed at heights of 120, 220 and 300 mm from the bottom of the box, in order that the compaction zones did not coincide with the pre-defined failure surface.

Plant breeding starts by filling germination pots of 100-mm-diameter with a peat-sand mixture of high water retention capacity. Seeds from each species are obtained from the WSL seedbank, distributed randomly on the surface of the mixture in the pots and covered with an extra 1–2 mm thick layer of peat-sand mixture. After a 6–8 week growth period of individual plants in the germination pots, four individual plants from each species are transferred carefully to eight defined spots that are distributed on the surface of the soil in the shear boxes. Each spot had a total of 12 individual plants (4 individual plants of 3 species each) for the HLP6 set, while there were 24 individual plants (4 individual plants of 6 species each) in each planting spot for the HHP6 set. This resulted in a total number of 96 plants and 192 for HLP6 and HHP6, respectively. No intervention was made during the plant growth. The approximate locations are shown schematically in Fig. 2a, and on a planted shear box in Fig. 2b.

Germination pots and shear boxes are kept under controlled temperature and humidity in a climate chamber, where the daylight conditions are 24 °C, 70% humidity and 2400 lx light intensity between