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Effects of roots and mycorrhizal fungi on the stability of slopes

Effets des racines et des champignons mycorhiziens sur la stabilité des pentes

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ABSTRACT Heavy rainfall periods initiate not only floods and debris flows, but may also trigger shallow landslides on both scree and vegetated slopes. This has had serious consequences in recent years in Switzerland, causing considerable damage to infrastructure, ecosystem, goods and services, even loss of lives. Although vegetation provides significant improvement in stabilizing steep slopes, conventional slope stability analyses generally neglect this entirely. Moreover, mycorrhizal fungi associated with plants contribute to stability, too, by promoting plant, and particularly root growth, and by supporting soil aggregate formation, which results in a further increase in apparent cohesion. It is intended to quantify the effect of biological interventions on the stability of soil and slopes in this study. Specimens consisting of combinations of a tree (*Alnus incana*), legume (*Trifolium pratense*), and grass (*Poa pratensis*) were prepared to investigate the root reinforcement effect. Direct shear tests were conducted in an inclinable large-scale direct shear apparatus on specimens with and without roots, following a six month growth period. The results of some preliminary direct shear tests are presented.

RÉSUMÉ Les périodes de fortes précipitations ne provoquent non seulement des crues et des laves torrentielles, mais peuvent aussi déclencher des glissements de terrain superficiels sur des éboulis ou des versants couverts de végétation. Ceci a récemment entraîné de lourds dégâts en Suisse, allant de dommages à l'infrastructure et aux biens et services écosystémiques jusqu'à la perte de vies. Bien que la végétation améliore la stabilité de pentes raides de façon significative, ceci est généralement négligé dans les analyses de stabilité conventionnelles. Les champignons mycorhiziens contribuent également à la stabilité en favorisant la croissance de plantes, plus particulièrement de racines, et la formation d'agrégats du sol, ce qui mène à une augmentation de la cohésion apparente. Le but de cette étude est de quantifier l'effet d'interventions biologiques sur la stabilité de sols et de pentes. Des spécimens de sol ont été plantés d'une combinaison d'arbres (*Alnus incana*), de légumineuses (*Trifolium pratense*) et d'herbacées (*Poa pratensis*) pour examiner l'effet de renforcement des racines. Des essais de cisaillement ont été conduits sur des spécimens de sol plantés et non plantés sur un appareil de cisaillement direct inclinable ä grande échelle, suivant une période de croissance de six mois. Les résultats de quelques essais de cisaillement direct préliminaires sont présentés.

1 INTRODUCTION

Effects of vegetation on the stability of slopes have been recognized and studied extensively over recent decades. Vegetation, in general, has both positive and adverse effects on the hydrological and mechanical aspects of slopes with respect to triggering mechanisms of shallow landslides. Increased interception and evapotranspiration are among the most prominent hydrological effects of vegetation, whereas root reinforcement has been considered as the main mechanical contribution of vegetation to the stability. Roots help to stabilize a slope by acting as fibres that are transferring the shear stresses developed in the soil matrix into tensile resistance via the interface friction along their surface (Gray & Barker 2004). Root reinforcement, as the main stabilizing agent, has been investigated based on different approaches. These include force-equilibrium models of root-soil interaction (Wu et al. 1979), laboratory or in-situ shear tests with root-permeated soil or soils with fibre inclusions (Askarinejad & Springman 2014; Gray

& Ohashi 1983), and further investigations based on the Fibre Bundle Model (Pollen et al. 2004).

Basic analytical models assume that roots act perpendicular to the slip surface, and that the tensile strength of the roots is fully mobilised. However, it can easily be proven that the assumption of roots crossing the slip surface only in a perpendicular direction is unrealistic in nature. Furthermore, not only will roots pass through the shear surface but roots extending laterally will also contribute to the strength (Schwarz et al. 2010). Pollen et al. (2004) demonstrated differences in the uptake of strain in roots and soil, showing that the roots are not necessarily stressed to their maximum tensile strength when the soil reaches peak shear stress. Therefore, it is essential to quantify the contribution of roots to the shear strength of soil, when determining the shear strength of the soil matrix with root inclusions. For this reason, a robust Inclinable Large-scale Direct Shear Apparatus (ILDSA) was built for testing root-permeated soils. The design and mechanical aspects of the apparatus are presented herein, as well as results from some preliminary tests.

2 BACKGROUND

Direct shear tests have been used in the practice and research of geotechnical engineering since the paradigm shift attributed to contributions of Hvorslev (1937). This is largely due to the simplicity of the test and ease in the procedure. There has been a wide variety of testing equipment in use throughout the lifespan of the direct shear test. The most common and commercially available type of apparatus accommodates 60x60 mm square samples. Size limitations on particle size to key equipment dimensions, as described by ASTM D 3080, led to development of larger sized apparatuses for testing soil (Bareither et al. 2008; Springman et al. 2003), and also in tests on marginal materials, such as fly ash pellets (Baykal & Döven 2000) and municipal solid waste (Zekkos et al. 2010).

Either laboratory or in situ large-scale direct shear testing is widely employed to determine the shearing behaviour of root-permeated soil. Operstein & Frydman (2000) conducted direct shear tests on 200 mm diameter samples of chalky soil reinforced with *Pistacia lentiscus* and *Myoporum parvifolium* and concluded that the increase in shear strength due to roots was $0.25T_r$, where T_r represents the tensile strength of the roots. This is significantly less than the suggestions of Wu et al. (1979), in which the increase in shear strength is defined as $1.2T_r$ with the assumption of full mobilisation of tensile strength of the roots. Goldsmith (2006) performed direct shear tests on samples obtained from the field with a dimension of 250x250x250 mm. The experiments were conducted under saturated conditions and a nominal normal load was applied with a 2 kg metal plate. The shear stress values for specimens with and without roots at a predefined value of shear displacement were compared, and it was found out that specimens planted with *Salix nigra* and *Panicum virgatum* yielded shear stress values of 36.0 kPa and 37.8 kPa at a shear displacement of 7 cm, respectively, whereas the shear stress of specimens without roots was 6.6 kPa at the same shear displacement.

3 TESTING PROGRAMME

3.1 Soil

All specimens are prepared with a moraine obtained from a subalpine landslide location, Hexenruebi, in Central Switzerland, which is classified as SP-SM according to Unified Soil Classification System. The index properties of the soil used in the study are summarized in Table 1.

Table 1. Classification of Hexenruebi moraine.

Gravel (%)	26	LL – PL (%)	13.3 – 16.8
Sand (%)	63	PI (%)	0
Fines (%)	11	G_s	2.69
C_c - C_u	4.1-70	e_{min} - e_{max}	0.19 – 0.42

The soil collected from the field is oven-dried at 105 ºC for 24 hours, and, subsequently, sieved so that particles greater than 20 mm can be removed. Oven-dried soils, with particles that are smaller than 20 mm, are filled into shear boxes (500x500x400 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.

3.2 Reinforcement by vegetation

Specimens with roots are prepared with a combination of a tree (*Alnus incana*), legume (*Trifolium pratense*), and grass (*Poa pratensis*). Plant breeding includes the following steps: germination pots of 100-mm-diameter are filled with a peat-sand mixture with high water retention capacity and a mixture of two commercially available mycorrhizal fungi inoculum (INOQ Forst, INOQ Agri). Seeds, obtained from the seedbank of the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, are distributed randomly on the surface and covered with an extra layer of 1-2 mm thick peat-sand mixture. Eight plots are marked on the surface of the soil in the shear box, as shown in Figure 1, and four individual plants from each species are transferred to each plot following a growth period of 6-8 weeks in the germination pots. Additional inoculation, *Paxillus involutus* and *Melanogaster variegatus s. l.* from WSL culture collection, for *Alnus incana* is added after the transfer of individual plants into shear boxes. Specimens with roots are maintained in shear boxes inclined at 30º in order to simulate the natural growth of roots on a slope. Both the germination pots and shear boxes are kept under controlled conditions in a climate chamber, where the temperature and humidity are maintained at 24ºC and 70%, respectively, between 05:00 and 20:00, and at 17ºC and 55% for the rest of the day.

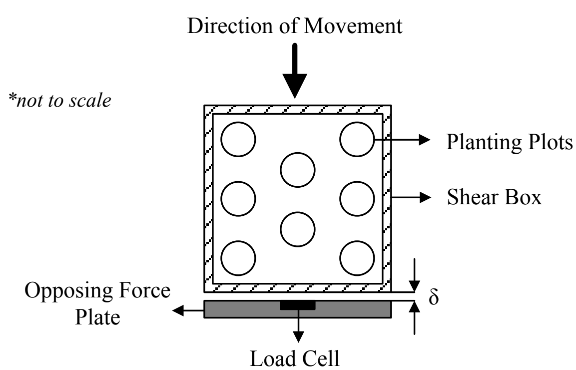

Figure 1. Top view of a specimen with roots prior to shearing.

3.3 *Preparation of combined test*

The specimens with roots are tested in the ILDSA after a total growth period of 6 months, including the time in germination pots. As shallow landslides are triggered generally after a heavy rainfall period due to saturation and loss of strength, the specimens are subjected to an artificial rainfall event according to Gehrmann et al. (2007) prior to shearing at a constant intensity of 100 mm/h for 60 minutes, followed by a 30-minute break, and a final rainfall with the same intensity for 30 minutes. Matric potential is monitored using tensiometers (UMS T5x) during the rainfall and brought as close as to zero around the shear plane. Direct shear tests are conducted both horizontally, and at an inclination of 30º from the horizontal axis, on specimens without roots at a constant rate of horizontal displacement of 1 mm/min and at different normal stress levels, ranging between 6 kPa, and 18 kPa. Specimens with roots are also tested at the same rate of horizontal displacement and same normal stresses, which are chosen to be comparable to typical depths of shallow landslides (Rickli & Graf 2009; Springman et al. 2003).

4 DESIGN PRINCIPLES OF THE ILDSA

It has been shown that the inherent mechanical aspects of the apparatuses have direct effects on the measured shear strength parameters (Wu et al. 2008), and these effects may be exacerbated in a large apparatus. Shibuya et al. (1997) describes three main types of direct shear apparatuses in use, with respect to the freedom of the upper half of the shear box and the loading platen. Both the top platen and the upper half of the shear box are allowed to move freely in the vertical axis and to rotate in type A, whereas they are connected in type B so that they move vertically together and the rotation of the loading platen can be adjusted. The upper half of the box is prevented from movement and rotation in type C, and also a fixed loading platen, which can move vertically but cannot rotate, is used in this configuration. It is suggested that a type C configuration shear box with a non-rotating loading platen would be optimal. The normal load can be measured either conventionally with an external load cell, which will yield the value W_{upper}, or it can be measured at the bottom of the box, which will yield the value W_{lower}. It has also been shown that peak friction angle values calculated with the normal load value that has been measured conventionally are overestimated in a type C shear box. Therefore, the conventional load measurement will not be appropriate with the optimum shear box, especially at the residual state and large shear displacements (Wu et al. 2008).

The ILDSA was designed and built taking the suggestions of Shibuya et al. (1997) into consideration in order to test large-scale specimens with roots in direct shear. Sample size is a crucial consideration, not only in terms of soil mechanics, but also in terms of plant growth. A small container filled with an inert solid medium or soil implies a limited amount of water and nutrients and higher chance of pot-bound roots, leading to undesirable secondary consequences. It is suggested to use a container that is large enough to produce a value of the total plant dry mass per unit rooting volume less than 2 g/l to prevent this (Poorter et al. 2012).

5 MECHANICAL SETUP OF THE ILDSA

The ILDSA was built to test soil blocks having dimensions of 500x500x400 mm, which are placed in split wooden boxes. The schematic drawing of the ILDSA, describing the main components of the apparatus, is shown in Figure 2. The normal load is applied directly on a steel plate, which is fixed against rotation but allowed to move freely along a vertical axis, by a linear driving unit consisting of a linear actuator (Thomson T 60), coupled with a synchronous servomotor (Beckhoff AM3032-0C40-0000). It is monitored during testing with a load cell (HBM C2). The maximum normal load that can be applied is 10 kN. The movement of the loading platen is measured with a laser displacement sensor (Baumer OADM 13U6475/S35A) and the inclination of the loading platen is monitored with a 2D inclination sensor (Micronor MR401-3).

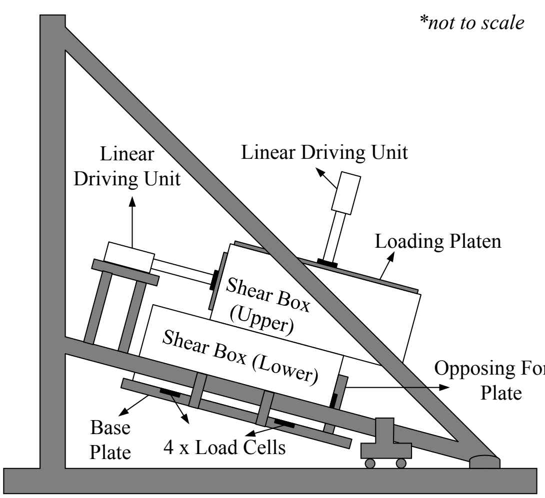

Figure 2. Schematic drawing of the ILDSA.

The shear load application system, with a capacity of 20 kN, is similar to that of the normal load. A linear actuator (Thomson T 90) is coupled with a synchronous servomotor (Beckhoff AM3042-0E40-0000) to apply the shear load. A load cell with a capacity of 20 kN is used to measure the shear force during testing. The horizontal displacement is measured with a potentiometric linear transducer (Megatron MMS33). The shear box is placed on a base plate, equipped with two load cells at the front and two load cells at the back, and supported with an opposing force plate. A load cell is mounted into the opposing force plate to monitor the force that has been applied to the plate by the shear box.

6 RESULTS & DISCUSSION

6.1 *Mechanical friction of the apparatus*

The shear box is placed on a base plate, equipped with four load cells, and supported with an opposing force plate. A frictional force develops between the shear box and the base plate in order to eliminate the gap between the bottom half of the shear box and the opposing force plate, which is shown in Figure 1 as δ. Start of shearing is considered as the instant when the shear box contacts the opposing force plate. A correction force is defined in order to take the frictional force into account in calculating the shear force. The readings of the load cell embedded into the opposing force plate were evaluated and threshold values of the opposing force have been chosen as 100 N for horizontal tests, and 600 N for tests inclined at 30º, to ensure that contact has occurred. The correction force to eliminate the gap can be formulated, based on data from horizontal and inclined tests on soil, as follows:

$$F = 420.03\delta + 302.81 \quad (1)$$

where F is the correction force in N and δ is the gap between the bottom half of the shear box and the opposing force plate in mm.

6.2 *Tests on specimens without roots*

A series of direct shear tests was conducted on specimens without roots that were prepared with the same compaction energy to have medium dense samples with relative densities ranging between 47% and 64% in order to study the effect of inclination of the box on the transfer of applied normal load to the shear surface. The load values measured beneath the shear box are compared for horizontal and inclined tests, and illustrated for applied normal loads of 1500 N and 4000 N under dry conditions in Figures 3a and 3b, respectively. It can be seen that, although the values measured with the load cells embedded into the base plate were different at the front and back of the shear box for different configurations, they showed similar trends during shearing.

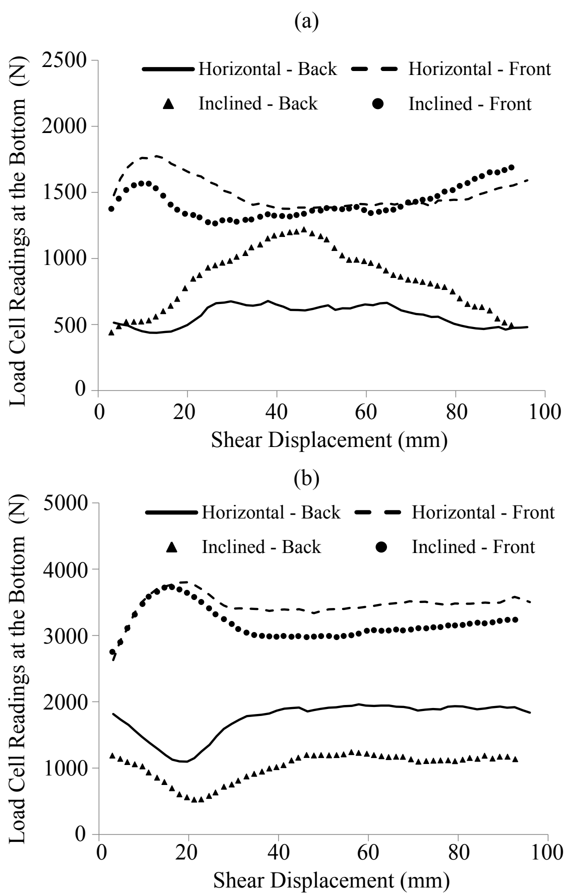

Figure 3. Measured values of applied normal load from the load cells at the bottom of the shear box a) 1500 N b) 4000 N.

6.3 *Tests on specimens with roots*

Figure 4 shows the results of inclined direct shear tests that were conducted on specimens with roots and without roots. Specimens without roots in this series of experiments were saturated with the same rainfall intensity and over the same duration as the specimens with roots, unlike the previous tests on specimens without roots, which were conducted under dry conditions. The experiments were carried out at two different normal load levels, namely 1500 N and 4000 N, which results in applied normal stresses of 6 kPa and 16 kPa, respectively, excluding the weight of the soil above the shear surface. The results indicate that the peak shear force was 65% greater for the specimen with roots tested under saturated conditions at 1500 N applied load than the peak shear force of the specimen without roots tested, also, under saturated conditions at the same normal load. The increase in peak shear stress was 35% when both of the specimens were tested at 4000 N applied load under saturated conditions. The decrease in contribution of root reinforcement to the peak shear force with increasing normal stress under saturated conditions, thus a bilinear failure curve, is a trademark of all fibre reinforced soils regardless of the type of test or reinforcement (Maher & Gray 1990).

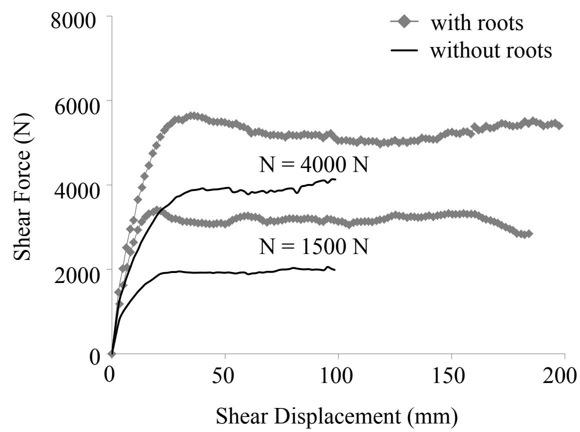

Figure 4. Shear force – displacement graphs for specimens with, and without roots

The peak shear strength parameters, drained cohesion intercept, c', and angle of internal friction, ϕ', for specimens with and without roots are summarized in Table 2. Calculations were performed both with the applied normal load values and also the values measured with the load cells at the bottom of the shear box. The failure envelope of root-permeated soil was forced to have the same inclination as that of soil. When the sample is dilating, soil grains will move relative to the side walls of the shear box, thus, due to the wall friction, W_{lower} will be higher than W_{upper}.

Both the conventional measurement of normal load and the measurements underneath the shear box yielded similar results in the case of the specimens without roots. The apparent cohesion due to root reinforcement is slightly larger if it is calculated based on the conventional normal load measurements.

Table 2. Peak shear strength parameters of specimens with, and without roots

	Without roots		With roots	
	c' (kPa)	ϕ' (°)	c' (kPa)	ϕ' (°)
W_{lower}	0	40.4	6.3	40.4
W_{upper}	0	39.8	7.5	39.8

7 CONCLUSIONS

An inclinable large-scale direct shear apparatus was built in order to test the shear strength of root-permeated soil, and the design principles of the apparatus, as well as the initial results are presented in this study. The preliminary experiments showed that the normal load transferred to the bottom of the box is changing during shearing, with a similar trend both for the horizontal and inclined tests, although the applied normal load is regulated at a constant value throughout the test. An apparent cohesion, calculated with the conventional measurement of normal load, is slightly larger compared to the value calculated with the measurements of the load cells at the bottom of the shear box. This study contains only the results of the preliminary experiments, and the further work, based on the preliminary results, will be performed and analysed with the same methodology.

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