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# Novel approaches to quantification of the vegetation effects on soil strength

## Les nouvelles approches de quantification des effets de la végétation sur la résistance du sol

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ABSTRACT: Vegetation has the potential to reinforce the soil through the mechanical and hydrological effects of the roots. Increased soil strength would contribute towards reducing the risks of mass wasting on slopes in terms of erosion and shallow landslides. The investigations of the vegetation effects in the past have been usually restricted to either mechanical or hydrological and have usually been carried out at a micro, meso or macro scale. However, for full understanding of the effects of vegetation on and slope stability soil strength in general, a holistic approach should be used that will include investigations of the combined effects and at different scales. For this study we outline a number of novel methods and approaches that can be used to enhance the understanding of the mechanisms of soil root reinforcement. These methods range from micro scale assessment of suction stress induced by the vegetation, through meso scale assessment of root growth on slopes, to the macro scale assessment of slope stability risks. The results of this study show that multidisciplinary knowledge of the processes taking place at different scales is needed together with input from relevant disciplines in order to inform the geotechnical modelling and eco-engineering design.

RÉSUMÉ : La végétation a le potentiel pour renforcer le sol par les effets mécaniques et hydrologiques des racines. la force accrue du sol contribuerait à réduire les risques de mouvements de masse sur les pentes en termes d'érosion et de glissements de terrain peu profonds. Les enquêtes sur les effets de la végétation dans le passé ont été généralement limitée soit mécanique ou hydrologique et ont généralement été effectuées à un micro, méso ou macro échelle. Cependant, pour comprendre pleinement les effets de la végétation sur le sol et la force de la stabilité des pentes en général, une approche holistique doit être utilisé, qui comprendra des enquêtes sur les effets combinés et à différentes échelles. Pour cette étude, nous présentons un nombre de nouvelles méthodes qui vont de micro évaluation à grande échelle du stress d'aspiration induite par la végétation, à travers méso échelle d'évaluation de la croissance des racines sur les pentes, à l'évaluation macro échelle des risques pour la stabilité des pentes. Les résultats de cette étude montrent que les connaissances pluridisciplinaires des processus qui se déroulent à différentes échelles est nécessaire ainsi que les contributions de disciplines pertinentes afin d'informer la conception de la modélisation et de l'éco - ingénierie géotechnique.

KEYWORDS: root, soil reinforcement, suction stress, tensile strength, slope stability.

## 1 INTRODUCTION

Landslides and erosion are global phenomena affecting natural and man-made slopes in urban, rural or non-inhabited areas globally. Each year, an estimated 24 billion tonnes of fertile soil are lost due to erosion and mass wasting globally, of which 970 million tonnes in Europe.

Eco-engineering (or ground bio-engineering) solutions form part of environmental geotechnics and it entails the use of vegetation, either alone or in combination with traditional geotechnical structures, for control of soil erosion and shallow landslides. In these solutions, the vegetation performs an engineering function (soil reinforcement) but also enhances the resilience capacity of the bioengineered area due to the self-repairing characteristics of the vegetation used. The eco-engineering solutions provide a combination of sustainability benefits such as protection against soil erosion in the short-term and the long-term stabilisation due to the reinforcement effect of the roots on the soil. The advantages of eco-engineering solutions over traditional civil engineering solutions include value for money, ease of construction, and low landscape impact. The main disadvantage in the design of these solutions include the unknowns related to the living material, i.e. plants with their roots, such as their distribution underground as well as the mechanical and hydrological characteristics which tend to vary with the type and age of the plants used.

Root reinforcement of the soil is demonstrated through the mechanical and hydrological effects of the vegetation. Mechanically, the roots can bind the soil together and contribute to both a higher soil bearing capacity and shear strength while hydrologically, they can decrease the soil pore water pressures and, therefore, effective soil stresses.

From a mechanical aspect, rooted soil behavior can be simulated by root reinforcement models based on traditional limit equilibrium (LE) approaches, (e.g. Greenwood, 2006) or advanced numerical analysis (e.g. Bourrier et al., 2013) where the fine roots are simulated as discrete or bundled flexible inclusions or modelled as an added soil cohesion. However, these models do not account for the varying strength of the root and soil materials at different strains which are important in both the rooted soil simulation and the stability analyses at a slope scale. To this effect, there is a need for a practical approach that would combine LE with continuum mechanics concepts based on realistic input of parameters easily measured on site or in the laboratory (Tardío and Mickovski, 2015).

From a hydrological aspect, vegetation contributes to soil reinforcement through an interaction of different wetting and drying mechanisms occurring at the soil-plant-atmosphere interface. The above-ground part of vegetation contributes towards the interception and attenuation of the rainfall while the below-ground part can decrease the soil pore water pressures by evapotranspiration and foster drainage by providing preferential flow paths along the roots. These effects, although acknowledged (Collison and Anderson, 1996), have been rarely reported in the literature (Stokes et al., 2014, Briggs et al. 2016) and there is a need for appropriate quantification and modelling in order to practically apply them in the ecoengineering design.

The aim of this study is to demonstrate the development of a novel conceptual framework incorporating different approaches for quantification of hydrological and mechanical effects of vegetation on soil strength. The objectives comprise outline of approaches at different scales as well as determination of relevant input and output data necessary for design, modelling and risk assessment.

## 2 METHODOLOGY

### 2 .1 *Micro scale*

Suction stress induced by the evapotranspiration (ETP) of vegetation is the mechanical equivalent of soil inter-particle stresses. The direct relationship of suction stress with the soil matric suction and the hydro-mechanical properties of the soil make it a good proxy for quantifying the plant hydrological reinforcement capacity (González-Ollauri and Mickovski, in review). Plant-derived suction stress can be measured using porous tip tensiometers (Fig1 a,b,c) at a variety of hydrological conditions (Vanapalli, 1996) before sampling and testing the vegetated soil in shear .

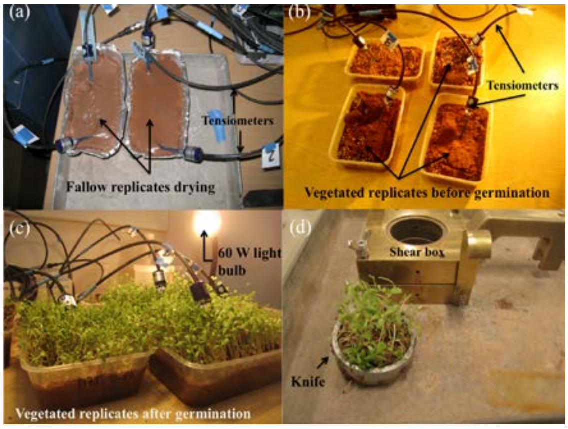


Figure 1. Determination of suction stress induced by the vegetation in the lab. Adapted from (Gonzalez-Ollauri and Mickovski, 2015).

The mechanical reinforcement effect due to the plant roots can be expressed in terms of "root cohesion" which is added on to the strength of the non-rooted soil. This additional cohesion value depends on the root tensile strength which, in turn, can be measured in a laboratory by means of a Universal Testing Machine (Tardio et al. 2016).

### 2 .2 *Meso scale*

The hydrological effects of vegetation on soil strength can be quantified using simple in situ investigations. Under wetting conditions, the relationships between gross rainfall and its partitioning into throughfall and stemflow (Fig.2) can be measured using rain gauges and tubes spiraling around the tree stem, respectively. Under drying conditions, the effects derived from plant water uptake can be quantified with the use of field tensiometers installed around the stem within the root zone (i.e. 0-500 mm b.g.l; Gonzalez-Ollauri and Mickovski, 2016).

The distribution of roots in the soil can be ascertained using portable and non-destructive techniques such as Ground Penetrating Radar (GPR; Fig3.). To test the root tensile strength in the laboratory, a small number of different diameter roots can be sampled from location identified by the GPR.

### 2 .3 *Macro scale*

In order to determine the hydrological properties of vegetation stands and the effect on the soil reinforcement and slope stability, an appropriate and representative sample of vegetation will have to be selected and the processes such as interception and stemflow have to be measured continuously for a period of time. Similarly, soil matric suction and soil moisture content will have to be assessed continuously to allow determination of any temporal patterns (e.g. dormant vs growing season) and ensure accuracy in the long-term predictions. Additionally, the gross rainfall should be measured and monitored in reference to the vegetation growth seasons.

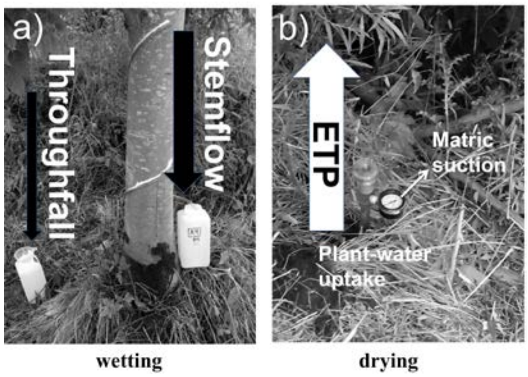


Figure 2. Determination of hydrological effects of vegetation on soil strength in situ: a) wetting and b) drying.

Figure 3. Determination of root distribution using GPR

The mechanical properties and distribution of roots within the soil will be subject to temporal changes and should be investigated on a catchment scale by selecting representative communities, subsampling from them, and testing either in the laboratory or in situ (Sections 2.1. and 2.2).

The results of the investigations on different scales can then be used as an input into numerical and probabilistic models which, in turn, will decrease the need for more often and more intrusive investigations.

### 2 .4 *Modelling (numerical and probabilistic)*

*Hydro-mechanical modelling:* An existing conceptual model (Gonzalez-Ollauri and Mickovski, 2014, 2015) can be applied to assess the hydrological and mechanical effects of vegetation on slope stability. This model considers the quantified hydrological processes at the soil-plant-atmosphere interface (i.e. rainfall interception, stemflow and evapo-transpiration leading to changes in soil suction stress) and mechanical processes (root distribution, changes in soil cohesion and/or angle of friction due to root growth; Root Profile Distribution

Model (RPDM; Gonzalez-Ollauri and Mickovski, 2016) as driving functions that feed into the unified effective stress constitutive equation.

In order to model the behavior of the composite material, the properties of each material (soil and roots) together with any interaction need to be determined usually on micro or meso scale. Traditional GI that include in-situ and laboratory strength of the soils would need to be supplemented by equivalent tests (usually shear, to mimic failure in shear during soil mass movement) on rooted soil at different depths where failure planes are likely to occur and material tests (usually tensile, to mimic the root anchorage into the soil during a failure at shallow soil depths) on roots with different diameters. The analysis of the force-displacement and stress-strain curves in these tests will provide information on the root contribution to the strength of the root-soil continuum at a range of displacements (Tardio and Mickovski, 2015).

*Probabilistic modelling*: Once the behavior of the materials involved (roots, soil, root-soil continuum) is modelled based on the climate and environmental variables for the site, the distribution of the root reinforcement over the whole slope, together with the soil stratification can be modelled using the data from the GPR and RPDM analyses. This information could then serve as an input into a traditional limit equilibrium (Tardio et al., 2016) or probabilistic analysis of slope stability.

## 3 RESULTS AND DISCUSSION

The investigations above allow a compilation of data that can be used as an input into a conceptual framework for assessment of the effects of vegetation on slope stability (Fig.4).

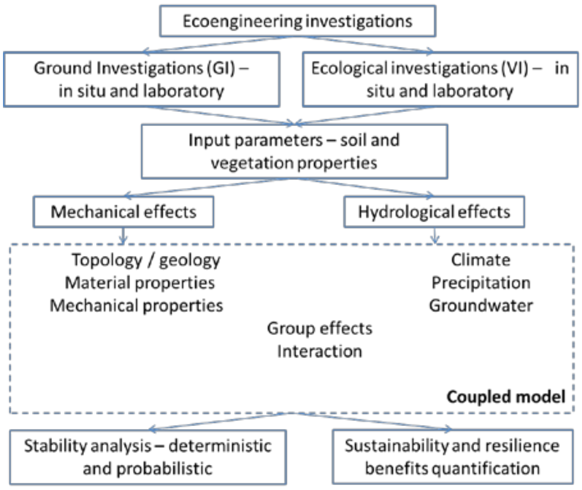


Figure 4. Conceptual framework for vegetation effect assessment.

This framework was applied to the ecoengineering investigations carried out throughout one vegetative season on a failure-prone coastal slope in North-Eastern Scotland. The hydro-mechanical reinforcement effects of vegetation were most effective under the transition hydrological regime, where the shear strength of the vegetated soil increased by more than 100% when compared to fallow soil. Vegetated soil tested in shear had an angle of internal friction up to 20 % higher than the corresponding fallow soil.

The stemflow and rainfall interception followed a linear relationship with the gross rainfall. Soil matric suction time series followed similar trends under vegetated and fallow soil as a consequence of the climatic conditions. However, the matric suctions under vegetated soil had peaks which were up to 10 times higher than the surrounding fallow soil confirming findings reported in the literature (Stokes et al 2014).

The soil hydro-mechanical properties differed between vegetated (α=0.001 n=2) and fallow soil (α=0.05 n=0.6) confirming the need for further research on characterization of vegetated soil under unsaturated conditions With regard to the suction stress experiments, a larger sample size would have led to more illustrative results. More repeats under a wider variety of soil matric suctions within the soil hydrological regimes and the measurement of more plant variables (e.g. root moisture) would aid in delineation of the factors behind the observed results. These factors, together with plant allometry (Gonzalez-Ollauri and Mickovski, in press) can be directly used for design and management of slopes (e.g. irrigation or drainage to maintain an optimum reinforcement).

The mechanical behavior of vegetated soil compared well with rooted soil shear test outcomes (Tardio and Mickovski, 2015) which showed increased ductility of the vegetated soil. The root tensile strength played a major role in the strength of the root-soil continuum after the soil peak strength was exceeded. Both root tensile and pull out strength values obtained can be implemented into the eco-engineering design at the short, medium and long term analyses (Tardio and Mickovski, 2016), showing the eco-engineering work evolution throughout its service life and the sustainability and resilience benefits it can have over the traditional reinforcement options.

The investigations revealed a number of issues of scale that need to be taken into account when using the framework (Fig.4). At *micro scale*, the fallow and vegetated specimens can be easily prepared for testing under laboratory conditions. However, if grown from seeds, the test plants can only be grown for a limited time period due to growing conditions limitations (e.g. light, container size). In addition, handling saturated soil samples in a direct shear testing machine can be difficult as high normal loads may not be applicable due to specimen consistency issues. In such conditions, our investigations showed a great variability between the tested soil samples which necessitated a larger number of tests on each soil type in order to provide statistically significant sample. Additionally, the root system characterization in the lab was successful but time-consuming. Root tensile strength values were obtained for both *Salix caprea* and *Acer pseudoplatanus* individuals. To improve this method in the future, an automated method (e.g. image processing method) could be employed. At this scale, there is a need for more root types and more complex root architectures to be analyzed. Such analysis will require incorporating both flexible and rigid root mechanical behavior.

*At meso scale*, matric suction and soil moisture differences between vegetated and fallow were observed and successfully measured. However, a significant moisture content-matric suction relationship could not be established for the vegetated soil. The stemflow and rainfall interception patterns with respect to the gross rainfall were successfully determined with the use of a simple field setup, albeit the large stemflow volume was difficult to handle, especially on steeper slopes in wet conditions. In terms of the root spread and strength characterization, herbaceous plants were relatively easy to sample from their natural environment in dry conditions. Root pull out strength values were obtained for both 3 year old and 6 year old willow individuals (Tardio and Mickovski, 2016). In relation to the hydrological effects of vegetation against erosion and shallow landslides, more measuring stations under specific trees, along with specific tree metrics (e.g. tree-crown area, DBH) could have contributed to elucidate vegetated SWCCs. Matric suction measurements over the longer term and monitoring of soil moisture dynamics under a wider variety of soil covers would help in enhancement of the existing numerical model in order to be able to predict plant-derived matric suctions. Regarding the rainfall interception, increasing the number of gauges below the canopy or changing the experimental design to cover a bigger canopy area would have contributed to the control of the canopy heterogeneity effect. On the other hand, shortening of the stemflow monitoring time, along with specific individual morphological information could have better illustrated the observed inter-specific variability.

GPR radargrams were obtained for *Acer pseudoplananus* and *Fraxinus excelsior* individuals and verified using trenching (Tardio et al., 2016). The GPR bandwidth chosen allowed for determination of rooting depth and bulk distribution. The meso scale experiments showed that GPR bandwidth must be carefully selected taking cognizance of the soil type and root system type. For determining bulk root system properties such as root distribution patterns and root depth values, lower central frequency values can be used. On the other hand, for determining root diameter values higher central frequency values must be used.

*Macro scale:* Linear relationships between interception /stemflow and gross rainfall were found. These were directly used to evaluate the macro scale effects on slope stability using the proposed coupled model.

The allometric relationships between above and belowground plant parts for three different species of pioneer plants were obtained. These were used for estimation of the root spread in light of the aboveground plant biomass and subsequent reinforcement. Similarly, the available long-term data related to the rainfall during the growth season was employed for obtaining estimates of the rooting depth based on the results of the laboratory tests (Gonzalez-Ollauri and Mickovski, 2016).

*Modelling*: Regarding the synchronization of root-soil mechanical behavior, the shear failure progress of the rooted soil samples was realistically depicted by the change of the safety factor value as the strain level increased. Nevertheless, the normally consolidated nature of the analyzed rooted soil prevented from a more conspicuous variation of the safety factor values variation.

Pioneer herbs showed shallow root systems with spread successfully predicted in light of the site's pedoclimatic conditions. Similarly, the theoretical root distribution models were comparable with the post-processed GPR radargram outcomes, showing the potential for the use of GPR as a non-invasive tool for gathering information for vegetated slope stability analysis. Regarding the root spread and distribution, addition of various plant samples from sites in different or contrasting eco-geo-climatic differences would contribute to the support of the suggested model. Geo-positioning of the sampling locations and adding temporal information (Tawelian and Mickovski, 2016) could greatly improve the predictive capacity of the model.

## 4 CONCLUSIONS

Ecoengineering investigations at different scales were introduced in order to explore the behavior of root-reinforced soil. These comprised the traditional ground investigations that cover soil and soil-water relationships and ecological investigations into the soil-water-plant relationships.

A conceptual framework for assessment of the vegetation effects on soil reinforcement was proposed with its elements demonstrated through application on a failure-prone coastal slope in Scotland (Gonzalez Ollauri and Mickovski, 2014, 2015, 2016; Tardio and Mickovski 2015, 2016; Tardio et al 2016). The framework used the results of ecoengineering investigations and modelling at different scales in the assessment of stability of vegetated soil.

The results of the investigations showed that the soil-root reinforcement performance and the identification of plant-related features was closely connected to the different soil hydrological regimes. The hydrological effects of vegetation against landslides should be considered together with the root and soil mechanical characteristics in order to gain more accurate knowledge of the reinforcement potential of given plant species. The relationship between the plant allometry, climate and root-soil reinforcement, along with root tensile strength, should be further explored in light of an effective and sustainable selection of plant species. It is also recommended to test the proposed framework on various plant species and communities and on different sites for validation.

The use of GPR proved to be a useful tool for incorporating the role of vegetation on slope stability or erosion protection. The collection of root information data for different root types, plant species and different plant ages can generate very useful information at the eco-engineering design level. Furthermore, the use of GPR could be integrated in eco-engineering monitoring works as a non-invasive field work tool.

Methodologies able to assess the overall effect of plant communities on slope protection will allow for a better understanding and assessment of ecosystem services. The proposed framework and models within it could both represent an input in the overall value assessment of green infrastructures and contribute with new ways for determining the beneficial effects of eco-engineering design and works. Future work should include the thermal effects on plant-soil reinforcement performance, the development of simple models able to capture the effects of big structural roots in sloped environments as well as development of plant-derived matric suction prediction models.

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