Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-550

Physical models of mechanical root-soil interaction

Modèles physiques de l'interaction mécanique entre les racines et le sol

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ABSTRACT: In geotechnical bioengineering, living plant material is used to perform engineering functions. In this context, one of the most complex aspects of the soil-root interaction problem is the interplay between the mechanical reinforcement effect and the hydraulic effect, mediated by suction. Soil-root mechanical interaction has been investigated on 1-g models and at scale, using centrifuge tests. The characteristics of model roots have been explored as well, by means of tensile and direct shear tests, in which the soil-root interface response under different loading conditions was studied. However, in most cases these studies were developed for extreme saturation conditions (dry or fully saturated state). This paper summarizes the advances made so far in the field of physical models applied to the analysis of soil-root interaction, and presents the general characteristics of the models currently under development at the UPC-BarcelonaTECH for the study of soil-root interaction under different saturation conditions, highlighting the advantages and limitations of such experimental methodologies.

RÉSUMÉ: Dans la bio-ingénierie des sols, le matériel végétal vivant est utilisé pour remplir des fonctions d'ingénierie. Dans ce contexte, l'un des aspects les plus complexes du problème de l'interaction sol-racine est l'interaction entre l'effet de renforcement mécanique et l'effet hydraulique, médié par la succion. L'interaction mécanique sol-racine a été étudiée sur des modèles à 1 g et à l'échelle, à l'aide d'essais en centrifugeuse. Les caractéristiques des racines modèles ont également été explorées au moyen d'essais de traction et de cisaillement direct, dans lesquels la réponse de l'interface sol-racine sous différentes conditions de charge a été étudiée. Cependant, dans la plupart des cas, ces études ont été développées pour des conditions de saturation extrêmes (état sec ou complètement saturé). Cet article résume les progrès réalisés jusqu'à présent dans le domaine des modèles physiques appliqués à l'analyse de l'interaction sol-racine, et présente les caractéristiques générales des modèles actuellement en cours de développement à l'UPC-BarcelonaTECH pour l'étude de l'interaction sol-racine dans différentes conditions de saturation, en soulignant les avantages et les limites de ces méthodologies expérimentales.

Keywords: Bioengineering; unsaturated soils; root-soil interaction; interface direct shear tests; 1-g root-soil models.

1 INTRODUCTION

The engineered use of vegetation is referred to as "bioengineering" (Coppin & Richards, 2007; Norris et al., 2008). One of the applications of soil bioengineering is the use of vegetation for slope stabilization. However, although vegetation began to be used for this purpose in ancient times, the formal adoption and development of this technology has been very slow, mainly due to the difficulties faced by engineers when trying to quantify its beneficial effects on slope stability (Coppin & Richards, 2007; Świtała et al., 2018).

The mechanisms of root influence on slope stability can be grouped into hydrological effects and mechanical reinforcement effects (Reubens et al., 2007). From a hydrological point of view, the presence of roots in the soil mass implies a reduction in moisture content do to the evapotranspiration process (which implies an increase in suction), and the generation of macropores during root growth (which results in a greater infiltration capacity). However, it should be noted that these effects occur at different times: the greatest infiltration occur during and immediately after rainfall events, while evapotranspiration predominates between rainfall events. In terms of mechanical reinforcement, it is possible to distinguish three types of root-mediated stabilization mechanisms (see Figure 1): A) *basal reinforcement*, provided by roots crossing a potential failure surface, similar to that provided by an anchor system; B) *lateral reinforcement* provided by the soil-root interface strength when the roots do not reach the failure plane and are located either in the sliding wedge (downstream of the tensile crack) or in the stable part of the ground (above the tensile crack); and C) *soil stiffening* due to the presence of roots in the sliding mass, particularly when there is an interaction between neighboring root systems (Reubens et al., 2007; Wu et al., 2015; Schwarz et al., 2015; Giadrossich et al., 2017).

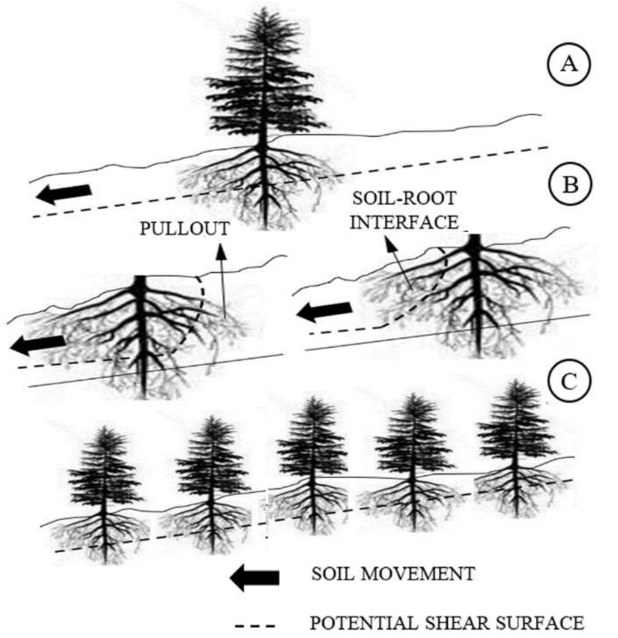

Figure 1. Root stabilization mechanisms: A) basal reinforcement; B) lateral reinforcement; C) stiffening.

Although root systems can penetrate up to 3m into the soil, 80% to 90% of tree roots are concentrated in the upper 0.9m of soil (Coppin & Richards, 2007; Norris et al., 2008). As a consequence, most of soil-root interaction phenomena occur in a low confining stress environment. Thus, during slope failure the unstable soil mass applies a passive pressure or thrust on the wedge soil downstream of the tensile crack and, at the same time, active thrust conditions are generated upstream, when the sliding mass separates from the tensile crack and the soil disaggregates in the form of blocks. This mechanism implies a progressive increase in volume (associated with an increase in void space) and a consequent decrease in total density, leading to a progressive failure.

According to the above, considering that the plant moves together with the sliding mass (because it is rooted in it), when the root system crosses the potential failure surface (Figure 1-A) it will experience displacements that mainly generate bending and predominantly pull-out axial loads. At the same time, lateral roots (Figure 1-B) will mobilize pull-out (when the plant is downstream of the tensile crack) or tensile resistance (when the plant is upstream of the tensile crack), which will depend on the roots themselves and the soil-root interface.

One of the most complex aspects of the soil-root interaction problem is that mechanical reinforcement and hydraulic effects, mediated by suction, interact with each other within a complex root system (Pollen, 2007; Stubbs et al., 2019). This fact seriously complicates purely empirical approaches. However, it must be considered in any soil-roots physical model for an adequate simulation of field conditions.

2 SOIL-ROOT PHYSICAL MODELS

The effects of plant roots on slope stability have been extensively studied over the last 40 years. Early studies on root reinforcement of soil focused on quantifying the mechanical behaviour of roots (O'Loughlin, 1974). In their pioneering work, Wu et al. (1979) studied the increase in shear strength ($\Delta\tau$) provided by a root system using a conventional direct shear test apparatus (63mm square box and 150mm in diameter circular box) to perform drained direct shear tests under constant load conditions (DST_{CNL}), both on natural moisture content and saturated soil-root samples. In addition, measurements of the tensile strength of roots by means a device based on the deformation of a calibrated spring were done.

In the following years, several studies were developed using physical models to analyze the effect of the root morphology and properties, under vertical uprooting stresses and under lateral loads (and moments) associated to wind action. Stokes et al. (1996) conducted a series of 1-g mechanical tests on model young tree root systems made of copper-coated steel wire (1-3 mm thick) and embedded in sand. Each root system was placed in a cylindrical container 300 mm high and 200 mm wide where manually placed damp sand was placed around it. Roots´ anchorage effects were quantified by measuring the pull-out resistance before failure in sand. Operstein & Frydman (2000) developed a simple dead-load application system in which roots were held at each end by specially developed 30 mm in diameter anchor grips, to obtain tensile stress-strain curves for real roots of different plants and diameters. Sonnenberg et al. (2007) performed centrifuge tests applying a scale factor n=15, using a 500x800x500mm height rigid box, with two transparent methacrylate faces. Several sensors were installed in the model: linear variable differential transducers (LVDT), pore pressure transducers (PPT), miniature tensiometers (Ten), and strain gauges attached to woody root analogues. Image processing techniques (Particle-image-velocimetry - PIV) were applied to obtain deformation fields. The model roots were fabricated with lime wood, as a pivoting root structure of L=100mm and A_m=3x3mm^2 size.

Subsequently, some research groups have idealised real root geometries and created artificial roots to assess pull-out strength and quantify the contribution of roots to slope stabilization. This led to the development of scaled tests using centrifuge (Sonnenberg et al., 2012; Ng et al., 2016; Zhang et al., 2020), 1-g modelling (Zhang et al., 2020), and analysis of the hydromechanical behaviour of rooted soils under partially saturated conditions, both in shear apparatus and in centrifuge (Fraccica et al., 2022; Ng et al., 2016). In general, these investigations corroborate the beneficial effect of roots on slope stability, as well as the influence of the geometry and properties of the soil-root interface at low confining stresses, both under static and earthquake conditions. The importance of the scale factor in 1-g models was also highlighted, in order to consider the effect associated with the lack of confinement on such tests.

Some laboratory and field tests (Leung et al., 2015; Ng et al. 2013) have shown that vegetated soil could retain a suction of up to 10-20kPa within the root zone for rainfall with a return period of less than 10 years. However, most of the above-mentioned research has generally ignored the hydrological effects of evapotranspiration and the resulted induced soil suction.

3 MODELS AT UPC-BARCELONATECH

Computational simulation is now considered as key to accelerating research on soil-root system interaction, as it allows to generalize empirical research findings through virtual models (Stubbs et al., 2019). In relation with this, an experimental programme is under development at UPC-BarcelonaTECH with the following main objectives: a) to document the failure modes of the soil-root system under overturning/pull-out tests in a 1-g physical model, using root analogues; and b) to measure the strength at the soil-real root interface under partial saturated conditions, by means DST$_{CNL}$. The obtained data will be used in the development of new soil-root interaction simulation tools based on the G-PFEM platform (Geotechnical Particle Finite Element Method; Carbonell et al. 2022).

3.1 Materials

In this research, two soils are being used: a mixture of 70% BR37 quartz sand and 30% UQ12 silt (Material A); and a silty clay from the Agropolis batch, located in Barcelona (Material B). Particle size distributions are shown in Figure 2, while their physical properties are summarised in Table 1.

Two different 3D root analogue models used in previous studies (Liang et al. 2015; Liang & Knappett 2017; Zhang et al., 2020) are considered in this research (Figure 3a): one with a relatively narrow and deep architecture (ND), and another with a wider and shallower architecture (WS). Both models were created from root architecture data obtained from Pinus pinaster trees grown on predominantly sandy soils in France (Danjon & Reubens 2008). Root models will be printed on Acrylonitrile Butadiene Styrene (ABS) plastic, a material that exhibits similar behaviour to that of real roots (Liang et al., 2015).

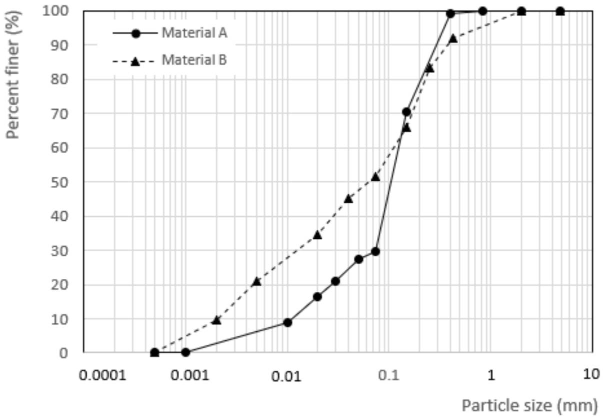

Figure 2. Particle size distribution of materials A and B.

Table 1. Physical properties of materials A and B.

	Material	
	A	B
Mean grain size, d_{50} (mm)	0.11	0.07
Density of solids, ρ_s (Mg/m^3)	2.65	2.70
Dry density, ρ_d (Mg/m^3)	1.61	1.80
Maximum void ratio, e_{max}	0.849	-
Minimum void ratio, e_{min}	0.440	-
Plastic limit, PL	NP	16.5
Liquid limit, LL	NP	28.9
Hydraulic conductivity, k_{ws} (m/s)$^{(*)}$	5x10^{-6}	9x10^{-9}

(*) Under saturated conditions

Considering a weighted average diameter of the printed root model ($d_{r,\,ave}$) equal to 2 mm, an optimum value of N=20 was selected as scale factor for the tree analogues. Such selection is supported on the rate $d_{r,ave}/d_{50}$ (=17 for material A; =28 for material B), which must be graeter than a minimum threshold of 15 to avoid soil-structure interferences in physical models (Wood, 2004).

For the interface tests in the direct shear apparatus, two types of wood samples were used in order to consider the effect of root´s roughness: a) samples of real roots from Pinus halapencis, obtained in the Collserola mountain range, located near Barcelona (relatively high roughness); and b) samples of a commercial treated pine wood (relatively low roughness).

3.2 Overturning/pull-out tests (1-g model)

According to the failure mechanisms outlined above (see Figure 1), it seems appropriate to assume that the overturnig/pull-out tests allow the analysis of the root extraction scenario from a stable soil, analogous to a surface landslide initiating above the tree line, or to tree uprooting associated with wind action.

A rigid box of dimensions 250x700x400 mm in height, constructed with methacrylate, will be used for 1-g physical models (Figure 3). A 10 mm layer of gravel will be placed on the bottom of the box to facilitate drainage, and a 100 mm layer of BR37 sand on top of it. A 1:20 root model will be installed in the central part of the container, and then the soil will be placed around it by compacting successive layers until reaching void ratios of 0.645 for material A (corresponding to a dry density of 1.61 Mg/m^3) and 0.467 for material B (corresponding to a dry density of 1.80 Mg/m^3). The tests will be performed at variable saturation levels {0-40-70-95}%, which will be reached by ascending saturation from the base of the box, and will be controlled by the installation of a METER Group tensiometer TEROS-31, and several SEN0193 sensors for soil moisture measurement. Readings from these devices will be analysed with the SWCC curve of each material, in order to verify the reached saturation degree.

Subsequently, overturning/pull-out tests will be performed. For the overturning tests, the load will be applied at a point located 60 mm above the surface of the model, through a RS Pro 100N Electric Linear Actuator motor, working at a constant speed of 0.15mm/min (material A) and 0.08mm/min (material B). It will be recorded: i) the load applied on the trunk, by means of a CTCM load cell of 15 kg capacity; and ii) the lateral movement, through a CONTROLS displacement transducer of 25 mm capacity. In the case of pull-out tests, the loading system arrangement will be modified, as illustrated in Figure 3b, and the root of the model will be extracted under the same parameters indicated for the overturnig tests, recording the following: i) the load applied on the top of the trunk; and ii) the vertical displacement. For this, the same sensors mentioned above will be used.

Relative root-soil stiffness ratio is being considered to compensate for the lack of confinement in the 1-g model.

3.3 Soil-root interface tests

When trees are above the tensile crack, as occurs in the case of clearings, riverbanks, or cuts for railroads and roads (Giadrossich et al., 2019), the activated force depends mainly on the friction at the soil-root interface, which can be studied from interface direct shear tests.

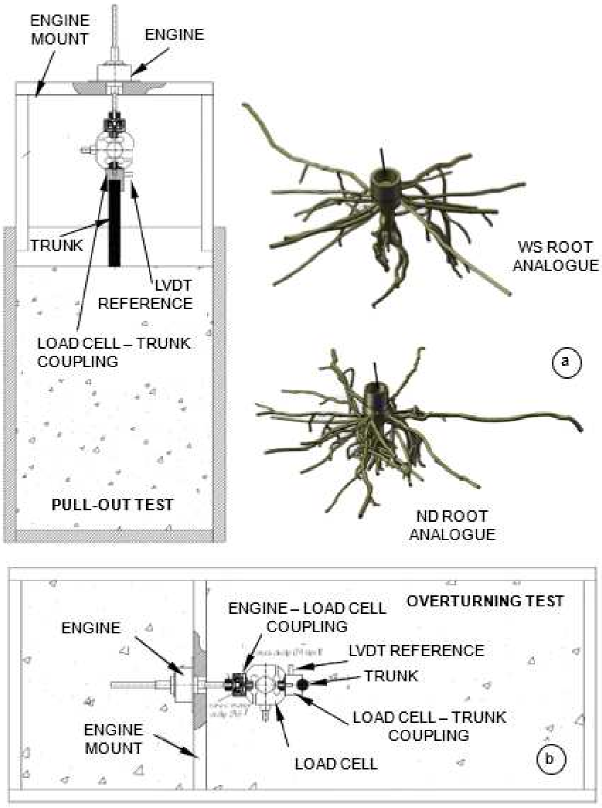

Figure 3. 1-g physical model arrangement: a) root analogues; b) model components.

The research is being conducted on a Wykeham Farrance model 27-WF2160 AUTOSHEAR direct shear machine. The vertical and horizontal displacements in the specimen, and the shear force during the test, are recorded through LVDTs and a 5kN horizontal load cell, using data acquisition software incorporated in the direct shear apparatus. Samples from soils A and B were prepared at the same initial conditions contemplated in the 1-g model. The height of the soil samples was 20mm. For the interface tests, a 14.5mm high and 60x60mm size wood sample was placed in the lower half of the shear box. Then, the soil sample was placed on it. The DST$_{CNL}$ were performed using three initial normal stresses σ_o={7-15-24.5}kPa, on the two types of wood samples mentioned above. The horizontal displacement rate was set at 0.15mm/min (material A) and 0.08mm/min (material B). Figure 4 shows preliminary results obtained in the interface tests on Material A, considering the extension of the Mohr-Coulomb model for partially saturated soils proposed by Fredlund et al. (1978), and the variation of shear strength (τ) as a function of water ratio ($e_\omega = S_{rf} e_f$). This parameter is appropriate as volumetric state variable because it tends to void ratio (e) under nearly saturated states (Romero & Vaunat, 2000).

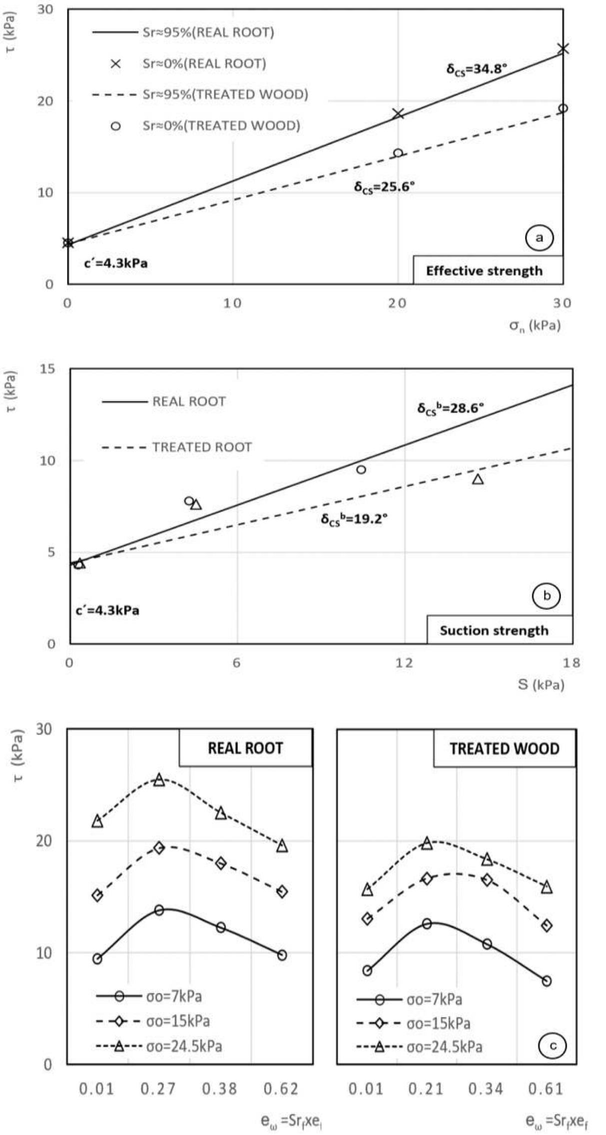

Figure 4. Preliminary results soil-real root interface tests on Material A.

According Figure 4a, from the τ-σ_n graph, the soil-real root (high roughness) effective interface friction angle at the ultimate shear strength is δ_{sc}=34.8º, with an effective soil-root adhesion of 4.3kPa; while the soil-treated wood (low roughness) effective interface friction angle at the ultimate shear strength is δ_{sc}=25.6º, with an effective soil-root adhesion of 4.3kPa. The effect of suction can be seen in Figure 4b. For the real root-soil interface, $\delta_{sc}{}^{b}$=28.6º, while for the treated wood-soil interface, $\delta_{sc}{}^{b}$=19.2º. Finally, from Figure 4c it is evident that for rougher roots, the shear strength at the interface (including the effect of the degree of saturation) is higher than for treated wood, representative of less rough roots.

4 CONCLUSIONS

A review of the physical models used over the last 40 years to study the effect of roots on slope stability, shows the evolution of research from simple root analogues tested in 1-g physical models, to 3D printed root analogous with mechanical properties like those of real roots, employed in 1-g and scaled centrifuge physical models. In addition, direct shear apparatus looks like a useful tool to study the soil-root interface. There is also a trend towards the use of computational simulation in research, as it allows to generalize empirical research findings through virtual models. At the UPC-BarcelonaTECH experimental research is currently underway, which will serve to validate a soil-root interaction simulation tools based on the G-PFEM platform.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by MCIN/AEI/10.13039/501100011033 and Union EuropeaNextGenerationEU/PRTR.

REFERENCES

Carbonell, J. M., Monforte, L., Ciantia, M., Arroyo, M., Gens, A. (2022). The Geotechnical Particle Finite Element Method for the modelling of soil-structure interaction under large deformation conditions. *Journal of Rock Mechanics and Geotechnical Engineering* 14 3: 967-983. https://doi.org/10.1016/j.jrmge.2021.12.006

Coppin, N. J., Richards, I. G. (2007). Use of vegetation in civil engineering. CIRIA. London, UK.

Danjon F., Reubens, B. (2008) Assessing and analysing 3D architecture of woody root systems, a review of methods and applications in tree and soil stability, resource acquisition and allocation. *Plant Soil* 303:1 – 34. https://doi.org/10.1007/s11104-007-9470-7. .

Fraccica A., Romero E., Fourcaud, T. (2022) Tensile strength of a compacted vegetated soil: laboratory results and reinforcement interpretation. *Geomechanics for Energy and the Environment* 30, 100303:1-100303:14 https://doi.org/10.1016/j.gete.2021.100303.

Fredlund D., Morgenstern N., Widger R. (1978) The shear strength of unsaturated soils. Canadian Geotechnical Journal, volumen 15(número 3): 313-321.

Giadrossich, F., Schwarz, M., Cohen, D., Vergani, C., Hubble, T., Phillips, C., Stokes, A. (2017) Methods to measure the mechanical behaviour of tree roots: a review. *Ecological Engineering* 109: 256-271. http://dx.doi.org/10.1016/j.ecoleng.2017.08.032.

Leung, A., Garg, A., Ng, C. (2015) Effects of plantroots on soil-water retention and induced suction in vegetated soil. *Engineering Geology*, 193, 183–197. https://doi.org/10.1016/j.enggeo.2015.04.017.

Liang T., Knappett, J., Duckett, N. (2015) Modelling the seismic performance of rooted slopes from individual root - soil interaction to global slope behaviour. *Géotechnique* 65:995 - 1009. https://doi.org/10.1680/jgeot.14.P.207.

Liang, T., Knappett J. (2017) Centrifuge modelling of the influence of slope height on the seismic performance of rooted slopes. *Géotechnique* 67:855 - 869. https://doi.org/10.1680/jgeot.16.P.072.

Ng, C., Kamchoom, V., Leung, A. (2016) Centrifuge modelling of the effects of root geometries on the transpiration-inducedsuction and stability of vegetated slopes. *Landslides*, 1–14 http://dx.doi.org/10.1007/s10346-015-0645-7.

Ng, C., Woon, K., Leung, A., Chu, L. (2013).“Experimental investigation of induced suction distributions in agrass-covered soil.”Ecol. Eng., 52, 219–223 https://doi.org/10.1016/j.ecoleng.2012.11.013.

Norris, J., Stokes, A., Mickovski, S., Cammeraat, E., van Beek, R., Nicoll, B., Achim, A. (Eds.). (2008). Slope Stability and Erosion Control: Ecotechnological Solutions. Springer Netherlands. https://doi.org/10.1007/978-1-4020-6676-4.

O’Loughlin, C., 1974. The effect of timber removal on the stability of forest soils. *J. Hydrol. (NZ)* 13 (2), 121–134.

Operstein, V. & Frydman, S. (2000) The influence of vegetation on soil strength. *Ground improvement* 4:81-89.

Pollen, N. (2007) Temporal and spatial variability in root reinforcement of streambanks: accounting for soil shear strength and moisture. *Catena*; 69(3),197–205. http://dx.doi.org/10.1016/j.catena.2006.05.004.

Reubens, B.; Poesen, J.; Danjon, F.; Geudens, G.; Muys, B. (2007) The role of fine and coarse roots in shallow slope stability and soil erosin control with focus on root system architecture: a review. *Trees* 21:385-402. http://:doi.org/10.1007/s00468-007-0132-4.

Romero, E. & Vaunat, J. (2000) Retention curves on deformable clays. In: *Experimental Evidence and Theoretical Approaches in Unsaturated Soils, Tarantino & Mancuso* (eds) Balkema, Rotterdam, ISBN 90 5809 1864.

Schwarz, M., Rist, A., Cohen, D., Giadrossich, F., Egorov, P., Büttner, D., Stolz, M., Thormann, J.-J., (2015) Root reinforcement of soils under compression. *J. Geophys. Res.: Earth Surf.* 120 (10), 2103–2120. http://dx.doi.org/10.1002/2015JF003632.

Sonnenberg, R., Bransby, M., Bengough, A., Hallett, P., Davies, M. (2012). Centrifuge modelling of soil slopes containing model plant roots. *Canadian Geotechnical Journal*, 49(1), 1-17. https://doi.org/10.1139/t11-081.

Sonnenberg, R.; Davies, M.; Bransby, M.; Hallet, P.; Bengough, A.; Mickovski, S., Hudacsek, P. (2007) Centrifuge modelling of slope reinforcement by vegetation. In: *XIV European Conference on Soil Mechanics and Geotechnical Engineering.* Madrid, Spain.

Stokes, A.; Ball, J.; Fitter, A.; Brain, P. & Coutts, M. (1996) An experimental investigation of the resistance of model root systems to uprooting. *Annals of Botany Company*. 78: 415-421. http://dx.doi.org/10.1006/anbo.1996.0137.

Stubbs, C., Cook, D., Niklas, K. (2019). A general review of the biomechanics of root anchorage. *Journal of Experimental Botany*, 70(14), 3439-3451. https://doi.org/10.1093/jxb/ery451.

Świtała, B. M., & Wu, W. (2018). Numerical modelling of rainfall-induced instability of vegetated slopes. *Géotechnique*, 68(6), 481-491. http://dx.doi.org/10.1680/jgeot.16.P.176.

Wood, D. (2004). Geotechnical modelling. Spon Press - Taylor & Francis Group. London, UK.

Wu, T., W. McKinnell, Swanston, N. (1979) Strength of tree roots and landslides on Prince of Wales Island, Alaska, *Can. Geotech. J.*, 16, 19-33. https://doi.org/10.1139/t79-003.

Wu, W., Switala, B., Acharya, M., Tamagnini, R., Auer, M., Graf, F., Kamp, L., Xiang, W. (2015). Effect of vegetation on stability of soil slopes: numerical aspect. *Recent Advances in Modeling Landslides and Debris Flows*. Published by Springer International Publishing. (pp. 163-177). https://doi.org/10.1007/978-3-319-11053-0_15.

Zhang, X., Knappett, J., Leung, A., Ciantia, M., Liang, T., Danjon, F. (2020). Small-scale modelling of root-soil interaction of trees under lateral loads. *Plant and Soil*, 456(1-2), 289-305. https://doi.org/10.1007/s11104-020-04636-8.

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The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.