Effect of Vegetation on Stability of Soil Slopes: Numerical Aspect

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Abstract. Soil bioengineering makes use of living plants to enhance soil stability against erosion and failure. Its practice is strongly dominated by empiricism. Recently much effort has been made towards quantifying soil bioengineering measures. This paper provides a critical review of the numerical modelling of some soil bioengineering measures. We discuss the application of the numerical methods including the finite element method and the limit equilibrium method for the composite of soil-plant root. A detailed review of the mechanical and hydrological models for the complex interaction between soil, plant, water and atmosphere is provided.

Keywords: soil bioengineering, slope stability, numerical methods, root reinforcement, root water uptake, limit equilibrium methods, finite element method.

1 Introduction

Soil bioengineering (SBE) is becoming increasingly popular in riverbank restoration and in the management of hill and upland slopes. In general, both living and dead plants can be used to stabilize soil against erosion and slope failure. There are numerous successful applications of SBE in different climatic zones worldwide. In spite of this success, however, SBE is still far from the sophistication of conventional engineering practice with the safety factors coded in standards and norms. This state of affairs is mainly due to the difficulties in quantifying the effect of vegetation in the slope stability. Moreover, there are some ambiguities in SBE applications concerning safety level, life time and load combinations. In this paper, some recent developments in the numerical modelling of vegetated slopes are reviewed.

We differentiate between natural slopes and engineered slopes. Typical engineered slopes are met in cuts and embankments. For natural slopes, the probability of slope failure or factor of safety requirements is often not a matter of concern unless there are specific demands from stakeholders. For engineered slopes, however, safety factors for different load combinations and life time are required. Not all SBE measures

W. Wu (ed.), *Recent Advances in Modeling Landslides and Debris Flows*,
Springer Series in Geomechanics and Geoengineering, DOI: 10.1007/978-3-319-11053-0_15

can be and need be taken into consideration in the stability analysis. If SBE is used as complimentary to conventional engineering measures, the stability analysis is usually performed without considering the effects of SBE measures, which is on the safer side. However, if SBE is used alone, the stability analysis is to be performed according to the conventional engineering standards. In general, vegetation can be beneficial for slope stability in several ways.

(a) The leaves of plants cushion the impact of raindrops, reduce the surface runoff and the susceptibility of surface erosion and soil degradation. The canopy of plants provides a protective cover against precipitations. The positive effect of vegetation in erosion control is well recognized but difficult to quantify. Since the safety is usually not relevant for erosion control, a quantitative analysis of the effect of vegetation is not necessary. However, plant canopy has significant influence on the amount of surface runoff and infiltration water, which have important bearing on the stability of slopes. Moreover, the infiltration water is used as boundary condition for some advanced analyses. Often the runoff and infiltration depend on the climatic conditions, vegetation cover and species and soil conditions.
(b) Plants consume water from ground for their growth by transpiration. The water content in the vicinity of plant roots is often reduced, which gives rise to lower pore water pressure and higher suction force. Transpiration by plants may have large influence on the pore water pressure and water content in soil. A detailed study of the problem requires a coupled analysis of the hydrological and mechanical systems of soil and plant roots. Moreover, climatic boundary conditions and initial conditions of water content need to be specified. Transpiration is most active in dry weather with high temperature but negligible in wet weather with low temperature.
(c) Plant roots penetrate through soil to acquire water and nutrients, which gives rise to a composite material of soil and fibrous plant roots. Stronger roots can grow across failure surfaces to provide strong anchoring points. Compared with (a) and (b), soil reinforcement by plant roots is highly relevant for the structural stability of slopes and can be reliably quantified. The degree of reinforcement depends mainly on the root architecture and root mass. As plants and their roots grow, the root reinforcement will change along with time. For SBE slopes, the slope stability immediately after the installation of plants is usually the most critical phase since the plants grow and become stronger.

The above mentioned positive effects of vegetation on slope stability are impaired by a number of negative effects. The wind throw of trees on slopes may aggravate the slope stability. Moreover, rotten roots of dead plants may form channels for water flow and eventually lead to piping failure. As a consequence, trees and bushes are not allowed on and near embankments. The so-called grass carpets on embankments provide effective protection against surface erosion and overflow. However, grass carpets of same species with the same root depth are often held responsible for shallow slides along the root tips, below which the permeability soil is usually lower than the root permeated soil above. Because of the limited depth of plant roots, SBE measures are only relevant for erosion control and prevention of shallow slides. For deeply seated slides, conventional measures remain the only choice e.g. retaining walls, soil nails and dowels. As stated above, the most critical phase for SBE is the time immediately after plant installation. However, if the slope has sufficient safety reserve at this stage, an increase of the longterm safety is a nice-to-have but not a must-have. This is the main reason why SBE measures are seldom used in lieu of conventional measures in construction practice, where a minimum safety factors are required for short and longterm stability.

2 Numerical Methods

The stability analysis of SBE slopes is carried out based on the established methods in soil mechanics. There are mainly two methods available for the analysis of slope stability, i.e. limit equilibrium method (LEM) and finite element method (FEM) [5], [12]. Although the slope stability analysis is a classic topic in soil mechanics, there are still some phenomena that cannot be properly modelled by the numerical methods. Usually slope failure begins as spontaneous formation of shear band from the slope shoulder. The shear band with the thickness of few millimeters (about ten times of the mean grain diameter) propagates, forms a continuous failure surface and eventually leads to slope failure. During this process, the soil within the shear band experience very large shear deformation and volume change. In spite of intensive research in the last decades the localized deformation still cannot be properly modelled. The reason lies in the multi-scale nature of the problem, i.e. the small thickness of the shear band (few millimeters) and the large dimension of the slopes (tens of meters).

2.1 Limit Equilibrium Methods

The LEM assumes the equilibrium along a failure surface, where the soil strength is fully mobilized simultaneously, e.g. the slice method of Bishop. The LEM is easy to use and requires few material parameters (unit weight, friction angle and cohesion). Usually the minimum safety factor is obtained by comparing the safety factors of many possible failure surfaces.

The simplest case of LEM is an infinitely long slope. This failure surface is relevant for shallow slides, where the sliding plane is parallel to the slope surface [6]. Forces due to anchorage (soil nail), geogrid reinforcement, earthquake and seepage can be easily incorporated. The LEM can be easily adapted to consider the reinforcing effect of SBE. Plant roots can be considered individually as discrete elements or collectively as enhancement of the soil shear strength. Individual plant roots can be treated similar to anchor elements and geogrid reinforcement. In this case, the root orientation relative to the sliding surface need be considered. For plants with large number of fibrous roots, a smeared approach of increasing soil cohesion seems more appropriate. The advantage of LEM is its simplicity and the fact that a safety factor can be easily obtained. The major difficulty is the characterization of root architecture and root mass.

The LEM has also its shortcomings. Usually the soil along the sliding surface does not attain its full strength at the same time. This gives rise to the progressive failure of slopes, which cannot be accounted for by LEM. Moreover, the failure patterns of plant roots during pullout tests follow also the pattern of progressive failure. For soil and plant roots, the use of peak strength parameters usually leads to an overestimation of the safety factor. As a consequence, the failure process cannot be modelled by LEM, which considers limit equilibrium on a predefined failure surface. Neither is LEM able to model the coupling between mechanical and hydrological process such as rainfall infiltration process and transpiration by plants.

2.2 Finite Element Methods

Some shortcomings of LEM can be overcome with the methods of finite element or finite difference. These methods allow more sophisticated constitutive models and more realistic initial and boundary conditions. Unlike the LEM, where the soil is regarded as rigid body, the FEM together with sophisticated constitutive models is in the position to describe various soil properties such as nonlinearity, plasticity, anisotropy, viscosity and coupling between mechanical and hydrological processes. The soil above the ground water level can be modelled as partially saturated soil, where suction gives rise to additional strength in form of apparent cohesion. The water content of soil prior to a rainfall event is known to have large influence on the slope stability. This water content can be considered as the initial condition. Rainfall duration and intensity can be modelled as boundary conditions (Fig. 1). In a coupled analysis, the water infiltration into the soil is accompanied by the partial loss of soil strength through the reduction of suction. The propagation of the failure surface and the progressive failure can be modelled, whereas the failure surface is pre-defined in LEM. A further advantage of the FEM is its strength to model construction process. Excavation of soil and installation of structural elements, e.g. anchors, geogrids and plant roots, can be easily simulated through death and birth of elements.

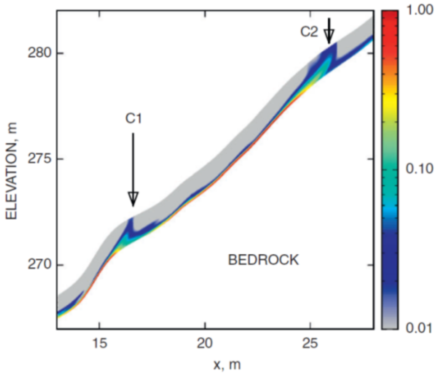

Fig. 1. Plastic strain (color bar) in a shallow slope simulated with a hydro-mechanical continuum model for rainfall rates of 6mm/h for 24h followed by 40mm/h for 1.7 h [1]

However, the sophisticated constitutive models usually require more parameters and their identification goes well beyond the conventional laboratory tests. In practice, however, the test data for the model calibration are often not available, not even for well-designed engineered slopes. The detailed data about initial water content and meteorological situation are also often not available. Moreover, it is very difficult to quantify the wide spatial and temporal variations of the soil parameters. In view of these factors, it remains questionable whether refined numerical methods will provide more reliable results.

The SBE slope parameters such as transpiration and root reinforcement can be easily incorporated into FEM. Fig. 2 shows the effect of plants on the water content of soil in the vadose zone [2]. It is usually assumed that the root density decreases with depth. The mechanical effect of roots can be considered either smeared as an enhancement of soil cohesion [10] or discrete as reinforcing elements [7]. However, the major difficulty is the reliable quantification of effects plant roots. The temporal and spatial distribution of plant roots depends on numerous factors such as species, age and location, which can be hardly described and taken into consideration in numerical calculations [8, 9].

Soil reinforced by plant roots can be regarded as a composite material. For a soil, which is homogeneously permeated by plant roots of the same diameter and strength, the composite properties can be obtained by homogenization of soil and roots similar to steel fiber reinforced concrete [11]. However, the root properties are more complex than fibers. The root density, root size and root strength change with location and depth. Moreover, unlike the random orientation of steel fibers, the roots usually show preferential directions (vertical or horizontal). In what follows, some development in characterizing the mechanical and hydrological properties of the soil-root system is briefly reviewed.

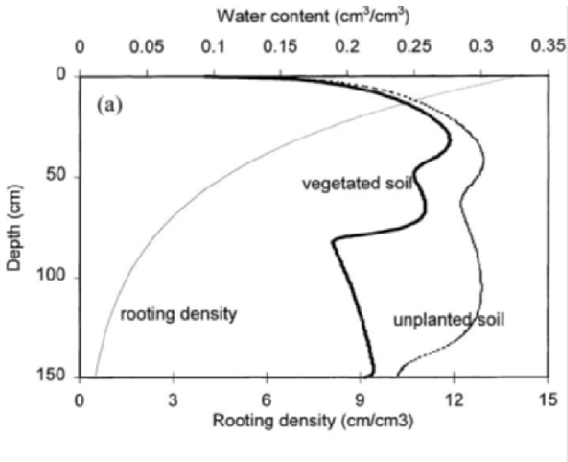

Fig. 2. Effect of plants on water content of soil [2]

3 Mechanical Features of Soil-Plant System

The first studies concerning the impact of vegetation on slope stability were conducted in the 1970s. Laboratory and in situ tests were conducted and analytical models were developed in order to quantitatively assess the mechanical contribution of plant roots to soil strength. The soil reinforcement by plant roots can be compared to reinforced concrete containing steel fibers. Both soil and concrete are strong in compression and weak in tension.

Numerous tests were conducted to study the behavior of the soil-root composite system. Most tests were carried out with direct shear devices [16], [18, 19]. Brenner [20] conducted tests on an inclined model of the vegetated slope, where both live and dead roots after clear-cutting were used. The pull-out behavior of plant roots was also the subject of numerous investigations [18], [21, 22]. The tensile strength of plant roots was shown to be dependent on the root diameter. A threshold diameter exists above which roots are more prone to breakage than pull-out. However, this threshold may change with the soil moisture. In moist soils the friction between root and soil is lower and the threshold diameter for the pull-out resistance increases.

Some pioneer works in the quantitative modelling of root reinforcement were carried out by Wu, Waldron and Wu et al. [16, 17, 18]. The Wu [16] model with some latter amendments is very simple and based on a number of approximations. The enhancement of strength by plant roots is considered as an additional cohesion, which is introduced into the Mohr-Coulomb failure criterion. The cohesion is dictated mainly by two factors, namely the average root tensile strength and root area ratio (RAR), which is the ratio of area occupied by roots on a certain plane. The model assumes that all roots are initially perpendicular to the slip surface and break at the same time.

The contribution of plant roots to the shear strength is dependent on the angle of shear distortion of the root and can be formulated as follows:

$$s_r = \sigma_r \tan\phi' + \tau_r = t_r(\cos\theta \tan\phi' + \sin\theta) \tag{1}$$

where σ_r and τ_r are normal and shear stress respectively, ϕ' is the friction angle of soil, θ is the angle of shear distortion of the root, t_r is the mean traction of plant roots, which is defined by the traction force T_r over the area A

$$t_r = \sum T_{ri}/A \tag{2}$$

Some test results show that the value of $(\cos\theta \tan\phi' + \sin\theta)$ can be taken as 1.2 for the distortion angle θ in the range 48° – 72°. The contribution of plant roots to the shear strength of the soil can be then included into the Mohr-Coulomb failure criterion as follows:

$$s^* = s + s_r = c' + \sigma' \tan\phi' + s_r \tag{3}$$

where s and c' are the shear strength and cohesion of the bare soil respectively.

The above approach is widely used in simulating the strength of soil-root composite. Recently, some improvements are made towards better understanding of the process and more realistic description of the deformation mechanism of the soil-root composite [21, 22, 23]. The authors introduced a fiber bundle model (FBM), where the main assumption of the previous model by Wu and Waldron, i.e. the breakage of all roots at the same time is removed. Roots in FBM are assumed to break progressively from the weakest to the strongest. The excessive load due to root breakage is redistributed into the remaining elements. The proposed model works by apportioning the total load applied to the bundle of N parallel fibers and then monitoring whether the load applied to the fiber exceeds its strength. Three different load apportioning methods were reported, i.e. apportioning by root cross section area, by root diameter and by root number. Two failure mechanisms, i.e. breakage and pull-out, can be considered [22].

The recent study by Schwarz et al. [24, 25] showed that the spatial distribution of roots should be taken into account, when considering the reinforcement of the soil with roots. The Root Bundle Model (RBM), proposed by Schwarz is based on the pull-out force – displacement relationship, coupled with the model for lateral root distribution. The RBM, similar to the FBM considers the progressive failure of the roots. The load is apportioned among all the roots by root diameter. RBM allows the estimation of the maximum value of soil reinforcement by plant roots, the root bundle elongation (displacement) as well as the secant Young's modulus.

Recently, a simplified version of the root bundle model was proposed [26] by considering the variability of the root strength. The Weibull survival function was used to describe the strength variation of the roots. This function is also known as complementary cumulative distribution function. All roots in the bundle are assumed to be linear-elastic fibers and break at the threshold displacements. This model is simpler than the previous RBM and can be easily implemented in numerical codes.

An important aspect of modelling the root reinforcement is the characterization of the root architecture. This is very challenging, when taking into account different plant species, growing conditions and available growing space. In numerical modelling, especially in the slope stability models, it is almost impossible to implement complex root architectures, which take into account all these features. Due to this limitation, only simplified root architecture can be used in numerical modelling.

Recently, a new approach to characterize the root growth and distribution was proposed by Dupuy et al. [27, 28], where a density function is introduced to describe the root structure (Fig. 3). This model allows the description of the relationship between the dynamics of meristem distribution and root architecture. Three density distributions are considered: the root length density ρ_n– which defines the geometrical properties of root architecture; the branching density ρ_b – which defines the plant topology; and the root apical meristem density ρ_a– which characterizes the regions of primary growth and links the dynamic of root length and root branching density. The model is based on two concepts. Firstly, root distribution at a given point in space is prescribed by representative volume (typically between 100 cm^3 and 200 cm^3). Secondly, the variations in time and space in the representative volume are assumed to be smooth. This approach has certain advantages over the traditional models. However, the computational time is rather long. Therefore it is mainly restricted to modelling single plant.

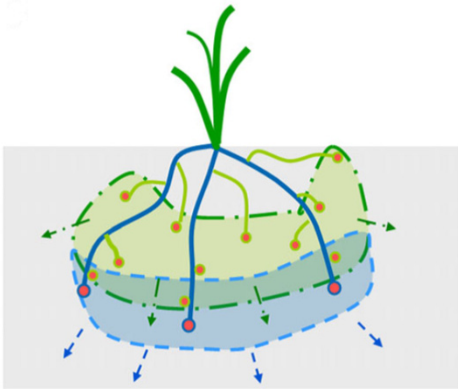

Fig. 3. The development of root systems as waves of meristems [27]

In all models mentioned above the soil-root composite is regarded as continuum. Recently, a discrete approach was presented by Bourrier et al. [29]. They investigated the influence of plant roots on slope stability using the discrete element method (DEM). The DEM code Yade [30] was used to model the direct shear tests on rooted and non-rooted soil samples. This modelling approach requires the development of new specific discrete elements – flexible cylinders which can be connected to model the complete root architecture (Fig. 4). The soil is modelled as an assembly of spheres. The root elements are considered as elastic, perfectly plastic beams, which are capable to sustain normal, shearing, twisting and bending forces. Plant roots are modelled as a set of chained cylinders and spheres. The deformation of the root is defined by the orientations and positions of the nodes, which are defined at the centers of spheres at the end of the cylinders. Three different types of interactions between the discrete elements can be defined: sphere-sphere, sphere-cylinder and cylinder-cylinder. All interactions are assumed to have the same contact formulation with different constitutive parameters.

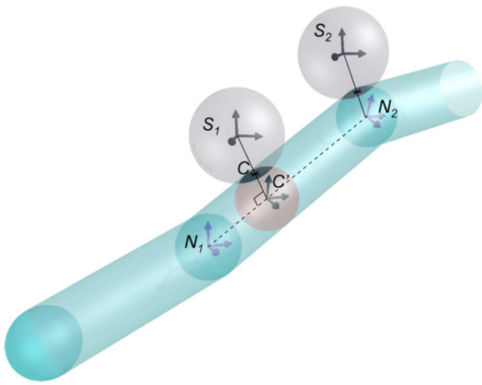

Fig. 4. The geometry of interactions between a sphere and chained cylinders [29]

The failure mechanisms of root reinforcement are tensile breakage, bending loading and pull-out. One of the important observations is that the soil-root reinforcement cannot be considered as constant additional shear resistance, because the mobilization of root strength is dependent on the shear strain.

4 Hydrological Features

Vegetation has great impact on the moisture content of soil and the suction, as well as the permeability and preferential flow paths of ground water. The suction contributes to the development of bonds between soil particles, which gives rise to an increased strength called "apparent cohesion".

The evapotranspiration is the governing process of water uptake by plant roots and has been investigated by many researchers in agricultural engineering. In geotechnical engineering, however, evapotranspiration has received little attention. A numerical model which accounts for both mechanical and hydrological features of the soil-root system has to be developed. In fact, the increase of apparent cohesion due to water uptake by plant roots can be significant. However, the safety factor of slope is usually obtained without considering the apparent cohesion due to suction. A realistic model is needed, which consider not only mechanical, but also hydrological impact of the roots presence on the slope stability and enable the calculation of realistic FOS.

Evapotranspiration is the water vapor exchange between the vegetated soil surface and atmosphere. Its maximum value, when the soil moisture content is not restricted is called the potential evapotranspiration. In assessing the evapotranspiration, the current atmospheric conditions and the plant characteristics need be considered. This evapotranspiration is defined as the actual evapotranspiration. The estimation of its value is rather complex, and dependent on many factors. The Penman-Monteith equation first formulated by Penman [32] and further modified by Monteith [31] can be used to calculate evapotranspiration from the vegetated surface [33].

The root water uptake depends largely on the matric suction in the soil. The higher the matric suction, the more difficult it is for plant to extract water from soil. Therefore, the matric suction is a reducing factor for the rate of the root water uptake. It is experimentally proved, that for most plants the value of the suction above which a plant cannot extract water is about 15 bars. This threshold is defined as "the permanent wilting point". The value, at which the water uptake reaches the maximum, is called "field capacity". It can be defined as the amount of the soil moisture, which remains in the soil a few days after wetting and when free drainage has ceased. A matric potential corresponding to this soil moisture content has a value between 1/10 and 1/3 bar. Between these threshold values, the water is available for plant and becomes more restricted when approaching to the permanent wilting point.

Usually the development of the root water uptake (RWU) models, started from simple analytical models. The first model was based on the analogy to Ohm's law for the sink term $S(z,t)$ [34]:

$$S(z,t) = [(\Phi_s - \Phi_L)/R_{sl}]\ S_{act}(z,t) \tag{4}$$

where $\Phi_s - \Phi_L$ is the difference between soil and leaf water potential, R_{sl} is the effective hydraulic resistance to water flow from soil to leaves, dependent on the depth below the soil surface and S_{act} is the specific surface of the active part of roots depth below the surface. The presented concept is rather theoretical, due to the fact that the determination of the hydraulic resistance is rather difficult. Nonetheless, the above simple model provides the basis for the further development of improved models.

Gardner [35] developed an approach which connects the RWU with Darcy's law. The water extraction function describes a steady flow of water into the root zone, which is defined as an infinitely long cylinder. Feddes et al. [36] proposed an equation to describe the root water uptake as a sink term.

The above equations are analytical models and contain many assumptions, which often cause the over- or underestimations of the amount of water uptake by plant roots. Some computer codes, e.g. CHASM, were also developed, which enable the calculation of the slope stability and take into account both mechanical and hydrological influence of the plant roots [37, 38]. In CHASM the forward explicit finite difference scheme is used in calculations. The slope is divided into rectangular columns subdivided into regular cells. The detention storage, water infiltration as well as evapotranspiration can be simulated. Richard's equation with the unsaturated conductivity based on the Millington-Quirk formulation is incorporated in order to model the unsaturated vertical water flow. Darcy's law governs the horizontal water flow between the columns. Unsaturated flow is assumed to take place only in the vertical direction.

In CHASM, slope stability is calculated using limit equilibrium method. The calculations are made at each major time step. Both positive and negative pore pressures are incorporated directly into the effective stress and the Mohr-Coulomb failure criterion. Vegetation can affect the slope hydrology through the evapotranspiration, root water uptake, interception and changes in the soil saturated conductivity. The root reinforcement is considered according to the simple model in [16, 17, 18]. The vegetation-slope interactions are shown in Fig. 5.

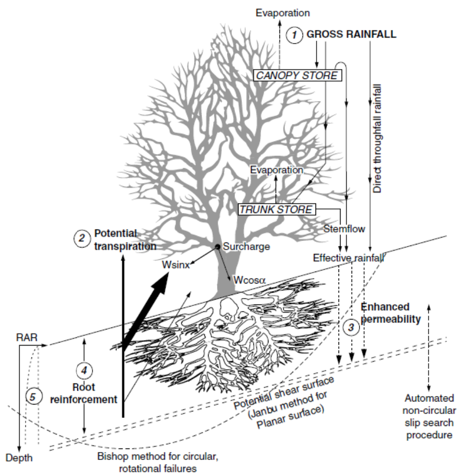

Fig. 5. Vegetation-slope interactions [37]

The extraction of water from the soil via root network and the loss of water from the leaf surface, result in reduced pore-water pressure in the slope, which leads to increase in the effective shear strength and thus enhanced stability of the slope. The maximum rate of water uptake is described using the formula proposed by [36], assuming a homogeneous root distribution:

$$S_{max} = T_v / z_r \tag{5}$$

where S_{max} is maximum uptake rate, T_v is the transpiration rate and z_r is the root depth. The model accounts also for the changes in the soil hydraulic conductivity caused by the root network distribution in the soil mass. The increase in this parameter can be described by relating the RAR to the saturated hydraulic conductivity as follows:

$$\Delta K_s = \alpha + \beta RAR \tag{6}$$

where ΔK_s is the increase in the soil hydraulic conductivity, α and β are material parameters.

The FOS of the slope can be calculated using either Bishop's method for circular slip surface or Janbu's method for non-circular slip surface [39]. Numerical models like CHASM are quite simple, but contain all salient features which should be taken into consideration for stability analysis of vegetated slopes.

Greenwood (2006) developed a simple numerical tool (SLIP4EX), which allows calculations of the stability of the vegetated slope. SLIP4EX is based on MS Excel spread sheet. Due to its simplicity, the program can be used for preliminary analysis of the problem and may serve as a tool for parameter study of the effect of plant on slope stability. The spread sheet computes the change in pore pressure and the increase of apparent cohesion. Moreover, the mass of vegetation, wind forces and mechanical root reinforcement can be considered. The FOS is calculated using different limit equilibrium methods, considering the influence of vegetation on the slice forces.

Fatahi [41] developed the root water uptake model and implemented the model in a finite element code. The RWU is regarded as a sink term in the Richard's equation, which takes the following form:

$$\partial\theta/\partial t = \nabla(k\nabla\psi) - (\partial k_z)/\partial z - S(x,y,z,t) \tag{7}$$

where θ is the soil moisture content, k_z is the vertical permeability and $S(x,y,z,t)$ is the sink term, i.e. the root water uptake. This equation can be applied for both homogenous and heterogeneous porous media.

The three important features which are considered in his model are the change in soil suction, the root distribution in soil and the potential transpiration from the vegetated surface. The rate of transpiration is assumed to be equal to the root water uptake and hence has the following form:

$$T(t) = \int_{v(t)} S(x,y,z,t)dV \tag{8}$$

where $T(t)$ is the transpiration rate at time t, $S(x, y, z, t)$ is the root water uptake at point (x, y, z) at time t and $v(t)$ is the volume of the root zone at time t. The developed RWU model was implemented and tested in the commercial FE code ABAQUS. The numerical results were compared with in-situ measurements. Moreover, Fatahi et al. [42, 43] analyzed the rate of water uptake by plant roots in comparison with the matric suction caused by the prefabricated, vertical, vacuum preloaded drains.

Wan et al. [44] developed a simple, two-dimensional model for the stability analysis of slopes and considered both mechanical and hydrological aspects of plants. The model includes the role of the main vegetation features influencing the stability of slopes, i.e. the root water uptake, the apparent cohesion, i.e. the additional soil shear strength and the increase in the soil hydraulic conductivity. They assumed a linear correlation between the saturated infiltration coefficient of root-permeated soil and the RAR. Moreover, rainfall boundary conditions are also introduced in the model. The mechanical root reinforcement was accounted for, using simple perpendicular model [16, 17, 18].

5 Conclusions

The soil-plant system presents a complex coupled problem, which poses great challenge for numerical modelling. It is not possible to simulate all problems precisely with numerical modelling, because some parameters cannot be put in numbers. A grass carpet is known to be effective against surface erosion. However, it is difficult to prove it through a mathematical model. When SBE measures are considered in slope stability, however, their effect needs to be quantified, e.g. to reach a required FOS. In doing so, some salient features of the soil-vegetation system should be taken into account and combined into a physically consistent model in order to model the complex interaction between soil, plant, water and atmosphere.

Acknowledgement. The authors wish to thank the European Commission for the financial support within its 7th Frame Work Program to the following projects: MUMOLADE (Multiscale Modelling of Landslides and Debris Flows), Contract Agreement No. 289911 within Marie Curie ITN; REVENUES (Reinforced Vegetation Numerical Evaluation of Slopes), Grant Agreement No.: 324466, within the Industry-Academia Partnerships and Pathways (IAPP); HYDRODRIL (Integrated Risk Assessment of Hydrologically-Driven Landslides), Grant Agreement Number: 295225, within the International Research Staff Exchange Scheme (IRSES).

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