Models for the quantification and upscaling of root reinforcement effects on the stability of shallow landslides

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The positive effects of vegetation contributing to the stabilization of slopes prone to shallow landslide are well recognized and considered to be effective in soil bio-engineering measures and protection forests. However, the methods for the quantification of these effects are still discussed in the literature. In addition to the hydrological effects of vegetation, root reinforcement is the most effective contribution of vegetation to stabilize shallow landslides, depending on the type of vegetation and the dimensions of the landslide. In this contribution we present an analysis of the root reinforcement mechanisms that are activated during the triggering of shallow landslides and how these mechanisms can be quantified and implemented in slope stability models.

The term „root cohesion“ or „root reinforcement“ in the analysis of shallow landslides is usually referred to the forces mobilized along roots crossing a shear plane. Based on field observations, it is clear that this definition is too restrictive. We suggest to extend this concept and to distinguish between three main root reinforcement mechanisms: basal root reinforcement (case 1 in figure 1), lateral root reinforcement (cases 2 and 4 in figure 1), lateral stiffening of soil mass (case 3 in figure 1). In order to properly consider the contribution of each of these mechanisms in slope stability calculations it is mandatory to characterize the force-displacement characteristics of those root reinforcement mechanisms during the deformation of the rooted soil in the initial phases of the landslide triggering. Specifically, force-displacement behaviors of root bundles solicited to shearing, tension, and compression need to be quantified.

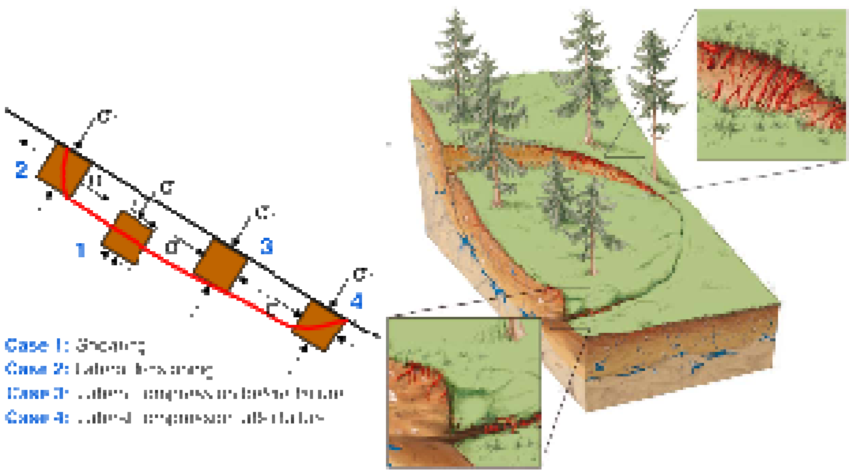

Fig. 1: Activation of root reinforcement in tension crack (top inset) and in compression zone (bottom inset) during shallow landslide initiation. Left side image shows the representative soil volume elements under different stress configurations at different locations in the landslide (Schwarz et al. 2015).

The Root Bundle Model (RBM) is a model developed to calculate the force-displacement behavior of root bundles on the base of a strain-step fiber bundle model approach (Schwarz et al., 2013). Recently we developed a series of tools in order to optimize the work needed to calibrate and fit the coefficient of the RBM, called the RBM_toolbox. The main characteristics of the RBM are: considering the progressive breakage of roots based on field pullout experiments (Giadrossich et al., 2017), and considering the variability of root mechanical properties (Schwarz et al., 2013). In our contribution we will give an overview about the application of the RBM.

Over the years, data about the root distribution and field pullout experiments were collected for different tree species. Combining the information of root distribution and root mechanical properties it is possible to characterize the spatial distribution of root reinforcement (Schwarz et al., 2012). In this contribution we will discuss the quantification of horizontal and vertical distribution of root reinforcement for three tree species (*Picea abies, Fagus silvatica, Castanea sativa*).

The calibrated RBM for different tree species is used as a module in three different categories of slope stability models to consider root reinforcement under shearing, tension, and compression. The three types of slope stability models have different levels of detail and consequently different types of applications:

- The SOSlope model (available under ecorisq.org)(Cohen and Schwarz, 2017) is a spring-block model, where the mechanical properties of bonds between blocks are quantified considering the spatial distribution of root reinforcement - based on the position and dimension of trees, as well as the tree species, the force-displacement effects of passive earth pressure, and the saturated-unsaturated soil mechanics. This model is developed for the assessment of stabilization effects of bioengineering measures (Schwarz et al., 2017) or protection forests at the slope scale (up to 1 km^2). Figure 2 shows an example of the results of this model.
- The SlideforMAP model (Schwarz et al., 2010) is a 3D probabilistic limit equilibrium stability model that implements the spatial distribution of maximum root reinforcement in the calculations and consider the progressive mobilization of root reinforcement under tension or compression. This model is developed for the assessment of the protective service of forests and the optimization of protection forest management at the regional scale.
- The SlideforNET model (available under ecorisq.org)(Schwarz et al., 2014) is a 3D probabilistic limit equilibrium stability model that calculated the failure probability of a slope, analoge to the SlideforMAP model, without considering a spatial resolution of root reinforcement. Instead of it, the SlideforNET model calculates a minimum value of lateral and basal root reinforcement based on general characteristics of the forest stand (mean tree diameter - DBH-, number of tree per hectar, and tree species). This model is developed for a quick field assessment of the protection effects of forests using smart-phone or tablet devices.

In our contribution we discuss the details for the quantification of root reinforcement and we present case studies where slope stability models are applied to assess the stabilization effects of roots on slopes prone to shallow landslides. In view of the increasing interest in green based solution for the mitigation of risks due to natural hazards, and the need to quantify ecosystem services at different scales, the implementation of our results in praxis oriented tools aims to improve the efficiency and quality in the management of soil bioengineering measures and protection forests.

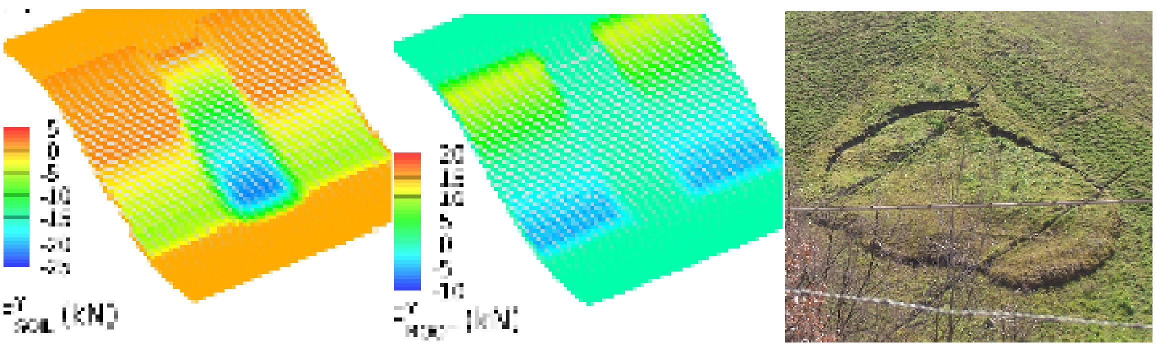

Fig. 2: Example of the SOSlope results showing the distribution of activated forces in the soil (left) and in the root bundles (middle), where positive value indicate tension and negative ones compression (for details see Cohen and Schwarz, 2017). The image on the right shows and analogue real situation where the activation of passive earth pressure at the bottom of the landslide prevent from complete failure.

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