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Spatial characterization of root reinforcement at stand scale: Theory and case study

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ABSTRACT

We propose a new upscaling approach for quantify root reinforcement at the stand scale using the spatially explicit root bundle model (RBM) for describing pullout force-displacement behavior coupled with a model for lateral root distribution. The root distribution model was calibrated using data of two excavated soil profiles, and validated with measurements of root distribution along the scarp of an artificially rainfall-triggered landslide in a vegetated hillslope above the Rhine river in northern Switzerland. Results show that the model overestimates small root density (1–3 mm diameter), leading to an error in estimated maximum root reinforcement of about 28%. For comparison, the most commonly used model of Wu overpredicts root reinforcement by a factor of 3. The spatial variability of estimated maximum root reinforcement within the forest stand is high, ranging from 0 to 20 kPa. Most soil reinforcement by roots occurs close to the tree stem or in zones where root systems overlap. The new approach provides a detailed description of maximum root reinforcement on a slope, an essential element for the prediction of shallow landslides and the management of protection forests.

1. Introduction

Plant roots strongly influence the morphology, spatial distribution, and triggering mechanisms of shallow landslides in vegetated slopes (e.g., Schmidt et al., 2001; Roering et al., 2003). Parameters such as the canopy index, stem-diameter distribution, and species composition of forest stands are routinely used qualitatively to define strategies for optimizing forests management under the risk of natural hazards such as landslides, rockfall, avalanches, and floods (e.g., Brang et al., 2006). For protection against shallow landslides, the importance of the mechanical effects of roots is now widely recognized (e.g., Sidle and Ochiai, 2006): roots impart additional strength to soils, an effect traditionally approximated as an increased soil cohesion term of the Mohr–Coulomb failure criterion. Despite considerable progress in understanding root reinforcement mechanics (e.g., Pollen and Simon, 2005; Cohen et al., 2009; Schwarz et al., 2010a; Cohen et al., 2011), realistic descriptions and analyses of the spatial distribution of root reinforcement in vegetated hillslopes remain lacking. Most existing models consider root reinforcement as a constant, homogeneously distributed, apparent basal cohesion: TOPOG and SHALSTAB (Montgomery and Dietrich, 1994); dSLAM (Sidle and Wu, 2001); SHETRAN (Bathurst et al., 2007); GEOtop (Simoni et al., 2007). However, Schmidt et al. (2001) showed, with detailed measurements along several landslide scarps, that values of root reinforcement can vary at the stand scale. Few models implement such heterogeneities due to tree distribution (Sakals and Sidle, 2004; Genet et al., 2008) and none considered dynamic aspects of lateralroot reinforcement.

Quantifying root reinforcement necessitates upscaling of reinforcement mechanisms from an individual root, to a root bundle, to interacting tree root systems (Schwarz et al., 2010a). Root–soil interactions and mechanical properties have been studied extensively and recently reviewed in the context of triggering of rapid mass movements (Schwarz et al., 2010a). Previous studies highlighted the importance of the progressive failure of roots (e.g., Pollen and Simon, 2005; Schwarz et al., 2010a,b). Experiments by Schwarz et al. (2011) indicated that activation of roots strength within a bundles is not synchronous, and progressive root failure must be considered for quantifying effective root reinforcement. The common assumption that all roots failed together as in the model of Wu et al. (1979) may lead to errors in excess of 100% (Schwarz et al., 2010c; Cohen et al., 2011). In recent years the framework of fiber bundle model (FBM) was introduced for more realistic estimation of progressive root reinforcement along a soil profile (Pollen and Simon, 2005; Schwarz et al., 2010a,b; Cohen et al., 2011).

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These models, however, have not been applied to the larger scale of a forest stand. The dynamics of progressive failure and the upscaling of root reinforcement are intimately linked with the spatial distribution of roots of different sizes.

Recent studies recognized the importance of lateral root reinforcement for shallow landslides mitigation (Schmidt et al., 2001; Roering et al., 2003; Schwarz et al., 2010b). In many cases, the mechanical reinforcement due to lateral roots is greater than that associated with basal roots. This is because most roots in a forest stand are confined within the first meter of soil and vertical roots only occasionally reach the depth (usually 1–2 m) of potential shear planes of shallow landslides (Schmidt et al., 2001; Danjon et al., 2008). Hence, including lateral roots is critical for realistic stability analyses of shallow landslides. The studies of Schmidt et al. (2001) and Kokutse et al. (2006) were the first to perform three-dimensional slope-stability analyses considering both basal and lateral root reinforcement. Kokutse et al. (2006) assumed, for each root system, constant values of root reinforcement but did not consider lateral interactions between neighboring root systems. Schmidt et al. (2001) included spatial variations of lateral root reinforcement within each root system. Neither of these studies considered progressive failure of roots and the effects of strain on lateral or basal root reinforcement. More recently, Schwarz et al. (2010b) proposed a modeling framework for the estimation of root distribution at the stand scale. In combination with the root bundle model of Schwarz et al. (2010a) which computes progressive root reinforcement of root bundles, this framework allows quantitative upscaling of lateral root reinforcement at the stand scale.

The main objective of this work was to present a quantitative method for characterizing the distribution of lateral root reinforcement on a vegetated slope. Building on results of previous studies (Wu and Sidle, 1995; Dhakal and Sidle, 2003; Sakals and Sidle, 2004), we combine the modeling framework of Schwarz et al. (2010b) with the force–displacement characterization of root bundles (Schwarz et al., 2010a,b) to obtain quantitative estimates of root reinforcement at the stand scale. Computations include estimating the maximum value of root reinforcement, the root bundle elongation (displacement) at maximum reinforcement, and the secant Young's modulus (maximum reinforcement divided by displacement). The model described in Section 2 is used in Section 3 to characterize the theoretical spatial distribution and dynamics of root reinforcement of interacting root systems. In Section 4 we describe field characterization and calibration of model parameters for an rainfall-triggered shallow landslide in a vegetated slope above the banks of the Rhine river near Rüdlingen, Switzerland. We compare model results with measurements of root distribution collected along the landslide scarp. The outcome of this comparison will help refine the range of mechanical reinforcement roots can impart to vegetated slope and provide a stand-scale modeling framework for quantifying the effects of protection forests, and optimizing their management, against shallow landslides.

2. Modeling root reinforcement by interacting root systems

We estimate the spatial distribution of root reinforcement by upscaling the mechanical behavior of a single root to a large number of roots distributed in a forest stand using the model framework of Schwarz et al. (2010b). The framework combines two independent models: (1) a root distribution model for secondary lateral roots, and (2) a root bundle model for computing pullout force. For simplicity, we assume that:

1. Root distribution of a single tree is radially symmetrical;
2. Root distribution is not influenced by neighboring trees;
3. The pullout force behavior of a single root is not influenced by neighboring roots;
4. Lateral root reinforcement is independent of direction (isotropic).

2.1. Root distribution of interacting root systems

First, we use the root distribution model of Schwarz et al. (2010b) to estimate the number of roots in diameter class size i (i = 1, …, N) that cross a vertical soil profile of unit width and depth at a distance d from an isolated tree stem of diameter at breast height (DBH) ϕ_t. That number is

$$N_{i,t}(d,\phi_t) = D_{fr}\frac{[ln(1+\phi_{max})-ln(1+\phi_i)]}{ln(1+\phi_{max})}\left(\frac{\phi_i}{\phi_o}\right)^{\lambda}, \quad (1)$$

for $d<d_{max}$ and $\phi_i<\phi_{max}$, and zero otherwise. Here d_{max} is the maximum rooting distance from the stem, D_{fr} is the density of fine (less than 1 mm) roots (units of number of roots per square meter), ϕ_i is the mean diameter of roots in class size i, ϕ_o is a reference diameter (here equal to 1 mm), ϕ_{max} is the maximum root diameter, and λ is an empirical exponent that depends on the bin diameter interval. d_{max} is given by

$$d_{max}(\phi_t) = a_o\ \phi_t, \quad (2)$$

where a_o is a proportionality constant. Both D_{fr} and ϕ_{max} depend on the distance d from the tree stem:

$$D_{fr}(d,\phi_t) = \frac{\mu\phi_t}{d_{max}}\frac{\left[0.7+0.3\frac{d}{5\phi_t}\right]}{2\pi(5\phi_t)}\quad d<5\phi_t \quad (3)$$

$$D_{fr}(d,\phi_t) = \frac{\mu\phi_t}{d_{max}}\frac{1}{2\pi d}\quad d\geq 5\ \phi_t \quad (4)$$

where μ is a pipe-theory coefficient (units of number of roots per meter), and

$$\phi_{max}(d) = s\frac{d_{max}-d}{b}A_{fr},\quad d<d_{max} \quad (5)$$

$$\phi_{max}(d) = 0,\quad d\geq d_{max}, \quad (6)$$

where s is a scaling factor (units of one over meter), b is the average distance between root branches (branching distance), and A_{fr} (= π/4 mm) is the reference cross-sectional area of a 1 mm root. Note that fine root density initially increases with distance from the tree stem (Eq. (3)). The number of roots, $N_{i,t}$ (Eq. (1)), depends on two independent variables, d and ϕ_t, and indirectly on five parameters (λ, μ, a_o, s, and b). These parameters can be obtained directly from root measurements (see Schwarz et

Table 1
Values of calibrated parameters for the root distribution and root bundle models. λ, μ, a_o, F_0, and ξ are calibrated from measurements on roots collected at Rüdlingen, Switzerland (see Section 4). b, s, L_0, and γ are calibrated using spruce roots from a forest site in Uetliberg, Switzerland (see Schwarz et al., 2010a). E_0, β, and r are based on literature data (Operstein and Frydman, 2000; Schwarz et al., 2010a,b. λ was calibrated using 20 one mm-bin root diameter classes.

Symbol	Parameter	Value	Unit
λ	Exponent	−1	–
μ	Pipe coefficient	0.09	roots m^{-1}
a_o	Proportionality constant	18.5	–
b	Mean branching distance	90	mm
s	Scaling factor	0.36	mm^{-1}
L_0	Characteristic length	285	mm
γ	Exponent root length	0.7	–
E_0	Characteristic Young's modulus	600	MPa
β	Exponent Young's modulus	1	–
r	Tortuosity coefficient	0.3	–
F_0	Characteristic tensile force	21.8	N
ξ	Exponent breaking force	1.3	–