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Influence of forest stands and root morphologies on hillslope stability

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ABSTRACT

Forest plantations can help to reinforce soil and improve hillslope's stability against shallow landslides. Based on 3D finite element method implemented in SIMULIA software, this paper develops a 3D numerical simulation model to assess impact of forest's stands structure and 3D root system morphologies on hillslope's stability. A preliminary analysis is performed to assess the impact of different stand parameters and root morphologies on the slope's safety factor as well as on the volume of soil mobilized by a landslide. Regarding tree's root morphology, we found that the overall slope's stability mainly depends on the depth of root's system and on additional cohesion provided by the roots. Hence, tap-like block morphology provides the best overall stability improvement. Furthermore, among the stand parameters, inter-tree distance in the slope direction has the greatest influence on the slope's safety factor. The rectangular pattern of stand distribution exhibits the lowest inter-tree distance in the slope direction and significantly improves slope's stability. Finally, the volume of soil mobilized during a landslide shows noticeable variations through root block morphologies. However, for a given root morphology, the stand distribution does not cause significant differences in the volume of soil mobilized during a landslide.

1. Introduction

In several mountainous regions around the world, mechanical instability of deforested slopes and landscapes is an increasing concern that requires a particular attention. Ecological restoration or suitable management practices of existing forest plantations can contribute to reinforce slopes and prevent shallow landslides (Sidle et al., 1985; Sakal and Sidle, 2004; Genet et al., 2010; Ghestem et al., 2013; Bischetti et al., 2015; Kokutse et al., 2015). In a wide range of situations, ecological engineering techniques for slope restoration against erosion and landslides are ecologically viable methods in the long term (Stokes et al., 2004; Norris et al., 2008; Zhou et al., 2015). Vegetation has been recognised to play a major role in the reinforcement of slopes against shallow landslides. The particular stabilizing effect of tree roots is supported by numerous studies based on landslides inventories. These studies reveal an increase in landslide frequencies during the first years following timber harvesting (Bishop and Stevens, 1964; Gray and Megahan, 1981; Kuruppuarachchi and Wyrwoll, 1992). Results obtained by numerical modelling (Wu et al., 1988a; Wu et al., 1988b; Sidle and Terry, 1992; Wu and Watson, 1998; van Beek et al., 2005; Kokutse et al., 2006; Genet et al., 2010; Lin et al., 2010; Ji et al., 2012; Mao et al., 2012; Schwarz et al., 2012a; Fan and Lai, 2013; Mao et al., 2013; Wu, 2013) unveil the same issue as well as observations made by analysing field data (Burroughs and Thomas, 1977; Wu et al., 1979; Terwillinger and Waldron, 1991; Riestenberg, 1994; Genet et al., 2008). Increasing efforts are being made in attempts to better understand how forest plantations and management could improve slope stability (Tsukamoto, 1987; Operstein and Frydman, 2000; Mao et al., 2013). It was also demonstrated that both tree's roots and the diversity of forest species contribute to slope stability. Roots indirectly increase the soil shear strength through water extraction by transpiration (Waldron, 1977; De Baets et al., 2007). The intensity of root reinforcement mainly depends on roots distribution and root tensile strength (Bischetti et al., 2005; Pollen and Simon, 2005; Genet et al., 2008; Kuriakose et al., 2008; Ji et al., 2012; Schwarz et al., 2012b; Naghdi et al., 2013; Schwarz et al., 2013; Leung et al, 2014; Hwang et al., 2015; Schwarz et al., 2015).

Although numerous experimental studies and field investigations have confirmed that vegetation growing on a slope increases its stability, little consideration has been given to define the best strategies of forest management with regards to the risk of soil failure. Mixed forest plantations and natural forests exhibit spatial and temporal variability in species composition, tree distribution

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patterns and density within stands. In the same way, tree root systems, which are the main mechanical components of soil reinforcement, vary following this spatio-temporal dynamics (Schmidt et al., 2001; Pollen, 2007). Part of this root distribution variability is also due to the variability in root system morphologies within and between tree species. In unharvested forests, Burroughs and Thomas (1977) noticed that landslides occur within large gaps of low or non-existent root reinforcement. Based on field investigations, Genet et al. (2008) reported that different stand structures can lead to different responses in terms of slope stability. All these considerations show that different types of forest stands with different mixture in tree species and management strategies can have different impacts on slope stability.

It is plausible to assume that the composition in tree species and their spatial distribution on a given slope have an effect on slope's stability. However, these effects seem to be difficult to investigate using simple field data and observations. Indeed, only few studies (Genet et al., 2008) were based on field data in attempt to quantify the influence of forest composition and tree position within the stand on the stability of a slope. Furthermore, such results relative to individual sites are difficult to extrapolate because the development of a root system of trees is highly variable, even within a single species growing in different environments (Stout, 1956; Coppin and Richards, 1990; Stone and Kalisz, 1991; Schmidt et al., 2001). Hence, modelling and analysis based on numerical simulations appeared to be an interesting alternative that can be used to investigate stability of forested slopes according to plantation characteristics. Reinforcing effect provided to the slope by vegetation's root systems is usually modelled in 2D and considered as homogeneous and continuous in soil layers (Kokutse, 2003; Chok et al., 2004). This approach is suitable for grassed slopes for which root systems usually form a continuous underground network. However, most landslides in forested areas, where different scenarios of plantation lead to heterogeneous root biomass distributions and patterns, do not exhibit plane-strain characteristics. Therefore, more appropriate 3D models are necessary. There are some publications in the literature that deal with three-dimensional slope stability modelling and analysis (Duncan, 1996; Chen et al., 2001). However, those are mainly concerned with geotechnical engineering applications. Nevertheless, it is well recognised that there is a need for continuing development of three-dimensional slope stability analysis models and methods (Stark and Eid, 1998) for a wide spread applications such as eco-engineering.

The present study was carried out in order to understand how forest management and 3D spatial distribution of trees as well as its time variation due to growth dynamics could affect hillslope stability. In this paper, we are using a 3D finite element model and presenting a generic model that considers individual tree root system parameters as well as the spatial distribution of trees within the stand. The model has been used for a simple preliminary study to investigate the influence of specific planting patterns and 3D root system morphologies on slope's stability. Time variation due to explicit stand growth was not considered in this preliminary numerical case study. The results are discussed in terms of the factor of safety of a slope and the volume of soil mobilized during shear (landslide).

2. Material and methods

2.1. Model development

In a general tree-soil-water interactions scheme, only the mechanical reinforcement provided by tree roots was taken into consideration in the current model. The mechanism involving reinforcement of soil by tree roots can be considered as an additional cohesion in the soil matrix (Wu et al., 1979; Waldron and Dakessian, 1981). In a conventional slope design, the effect of fine roots is often taken into consideration by adding this additional cohesion C_r to the classical Mohr-Coulomb failure criterion:

Table 1
Mechanical properties of soil considered for simulations.

Mechanical properties	Values
Specific weight γ_h [kN/m^3]	19
Soil cohesion C [kPa]	4
Young modulus E [MPa]	15
Internal angle of friction ϕ [°]	25
Poisson ratio ν [–]	0.3
Dilatation angle ψ [°]	5

$$\tau = C_r + C'_s + \sigma'_n \tan\phi' \quad (1)$$

where τ is the total soil shear strength and $C'_s + \sigma'_n \tan\phi'$ is the non-rooted soil effective shear strength that is a function of the bare soil cohesion C'_s, the effective normal stress σ'_n and effective soil friction angleϕ'.

Wu et al. (1979) suggested that roots additional cohesion can be expressed as:

$$C_r = 1.2 \times T_r \times RAR \quad (2)$$

where T_r is the mean tensile strength of roots and RAR is the roots area ratio defined as the roots cross section area per unit of shear surface.

This expression shows that additional cohesion depends only on roots' and soil parameters on a given slip surface. It was assumed here that the extrapolation of this model of roots' reinforcement to a whole root system is acceptable for the purpose of this study.

The simulation model is composed of two main groups of modules (Fig. 1). The first group named "*Python modelling modules*" was used to build the reinforced slope by using different input parameters like slope geometry parameters, root systems morphologies, bare and reinforced soil properties, and stand pattern (Fig. 1). The second group of modules called "*Python analysis modules*" was dedicated to analysis of the model's results obtained by finite element (FE) calculations. Since the parameters related to individual tree's root system, stand and slope must be specified prior to any numerical calculations and analysis, the procedures related to the first group of modules shall be completed before finite element computations.

2.2. Description of the model

Slope was described using two different approaches: first consisting of an analytical constant profile (planar, concave or convex surfaces, curvilinear surfaces, etc.) whereas the second technique was a digital elevation model data (Table 2). The structure of the plantation was described at a given stand age, disregarding subsequent growth dynamics. Two groups of parameters were used to describe the whole stand, namely parameters relative to individual trees as well as parameters characterizing the distribution of trees within the stand. The first group of parameters is concerned with the description of tree's root system and its soil reinforcement properties. Individual root systems were considered as embedded in a block of soil of simple axisymmetric geometry. On the other hand, the distribution of trees within a stand followed patterns that are usually used by forest managers (Table 2). All the parameters considered in this study were classified into four categories as shown in Table 2. Input values of all variables are either collected from the available literature or are set to some reasonable theoretical value (after Genet et al., 2008; Pretzsch, 2010; Pretzsch et al., 2014).