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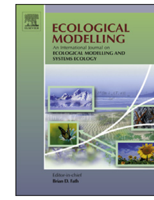

Three-dimensional modelling of slope stability in heterogeneous montane forest ecosystems

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ABSTRACT

Vegetation can play an important role in stabilizing soil against shallow landslides. Using a three-dimensional (3D) finite element method, we developed a model to study the impact of different management scenarios on slope stability in mountain forests. Ground truth data were obtained from a mixed forest ecosystem situated at an altitude of 1400 m a.s.l. in the French Alps. Five scenarios representing the forest at different spatial and temporal stages of management were selected: [A] bare soil, [B] tree island (i.e. tree groups growing in clusters) on bare soil, [C] new gap (i.e. canopy free zones with little understorey) in homogeneous forest, [D] old gap (i.e. canopy free zones with abundant understorey) in homogeneous forest and [E] homogeneous forest. For scenarios [B], [C] and [D], the locations of the vegetated patch along the slope (top, centre and toe) were also tested, to determine if vegetation patterns influenced slope stability. As plant roots play a crucial role in reinforcing soil, we altered the 3D spatial distribution of root density in the model using real data. By calculating the factor of safety (*FoS*), i.e. a measure of the likelihood that the slope will fail, we show that slope morphology, including angle and soil depth, play an essential role in slope stability. Vegetation also exhibited a positive effect on slope stability, but the efficiency of this effect was significantly influenced by slope morphology and root distribution with regard to soil depth. In particular, if a layer of soil beneath the most superficial rooting zone contained few roots, slope integrity was compromised. Compared to bare soil, the *FoS* increase due to vegetation was only ≤0.2 (i.e. ≤15%), when deeper soil layers contained few or no roots. However, if the soil profile contained roots throughout, the *FoS* increase was >25% higher. We highlight the importance of taking into account spatial complexity and refining the output, i.e. *FoS*, during the modelling of slope stability, which can only be achieved through the use of 3D models.

1. Introduction

Shallow landslides are a recurring phenomenon in forest ecosystems in the European Alps (Mao et al., 2012). Although considered a natural disturbance, with positive effects on plant species' diversity (Dislich and Huth, 2012), the increase in anthropogenic pressure and extreme weather events attributed to climate change will likely augment the frequency and intensity of landslides (IPCC, 2012). In this context, the choice of optimal management strategies for mountain forests on landslide-prone slopes is becoming a question of utmost importance for foresters, especially when forests are upslope of infrastructure. It is well documented that forests can stabilize slopes via the action of plant root systems, which provide mechanical reinforcement and regulate hydrological mechanisms (Greenway, 1987; Gray and Sotir, 1996; Sidle et al., 2006; Stokes et al., 2009; Ghestem et al., 2011). However, little information is available concerning the management of mountain forest ecosystems on landslide prone slopes (Genet et al., 2008; Mao et al., 2012).

One of the reasons for the lack of information available to forest managers and slope engineers is that data on tree root growth in the field is difficult to obtain, costly and time consuming. Spatio-temporal patterns in these data are thus far from being clear (Mao et al., 2012). In heterogeneous mountain forests, trees often grow in clusters (or tree islands), with gaps (usually from 40 m^2 to 400 m^2 in size; Yamamoto, 1995) between these clusters (Watt, 1947). Gaps and tree islands therefore represent two different types of ecological patch and are formed naturally by, for example, wind, fire, drought and disease, or artificially, by e.g. thinning (Schönenberger, 2001; Brang et al., 2006). Gaps and tree islands differ greatly in tree and root density, thus leading to disparities in root reinforcement against shallow landslides. In temperate montane forests, Mao et al. (2012) found that despite the abundance of understorey species in gaps, soil reinforcement by roots in gaps was significantly lower than in tree islands, especially at a depth of 0.0 to 0.4 m in the

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soil. Therefore, the location of gaps and tree islands on a slope can potentially have a significant effect on its stability. The effect of spatial patchiness of vegetation on slope stability has been considered in recent studies (Abernethy and Rutherfurd, 2000; Roering et al., 2003; van Beek et al., 2005; Genet et al., 2008; Ji et al., 2012). Abernethy and Rutherfurd (2000), focusing on riparian vegetation on riverbanks in Australia, found that the distance between the spatial position of vegetation with regard to the head of the bank, significantly influenced bank stability. Similarly, van Beek et al. (2005) found that patchy vegetation had a significant effect on mass wasting processes in abandoned Mediterranean orchard terraces. In separate studies in China (Genet et al., 2010; Ji et al., 2012), vegetation positioned at the toe of a slope was more efficient at stabilizing a slope compared to vegetation at the middle or head of a slope. However, for temperate montane forests, current forest management scenarios seldom take into consideration (but see Genet et al., 2010), or even totally ignore, the impacts of different types of ecological patches and their spatial position on overall slope stability.

Most slope stability models analyze the likelihood that a slope will fail in only two-dimensions (2D). These 2D models are based on either limit equilibrium methods (Bishop, 1955; Abernethy and Rutherfurd, 2000; Docker, 2003; Greenwood, 2006; Pollen, 2007; Pollen-Bankhead and Simon, 2009; Genet et al., 2010; Thomas and Pollen-Bankhead, 2010), or finite element (FE) analysis (e.g. Genet et al., 2008; Ji et al., 2012). Because of their simple model design, user-friendly platforms and short computing time, 2D models are widely used in both engineering and scientific research studies. Nevertheless, three-dimensional (3D) or four-dimensional (4D), i.e. 3D plus a time scale, models would provide a more refined description of the spatial variability of output parameters, and therefore a more exhaustive estimation of landslide hazard. However, incorporating 3D heterogeneity of soil and root data into slope stability models (Kokutse et al., 2006; Lin et al., 2010; Fan and Lai, 2013), is challenging with regard to computation time and numerical convergence.

We explore the use of numerical modelling in three dimensions (3D), to determine how variability in forest structure affects slope stability. We designed five data-based scenarios and three virtual scenarios of forest landscapes on steep hillslopes that differ in terms of ecological patches and vegetation position, as well as soil reinforcement due to roots. Using a numerical modelling approach based on the FE method, we aimed to quantify and evaluate the effect of each forest landscape on slope stability. Using this 3D model, we also showed the pertinence of using refined spatial distributions of both input and output data. This paper therefore provides a baseline for future 3D numerical studies of forest management on unstable slopes, taking into account the spatial and temporal variability typical of forest ecosystems.

2. Materials and methods

2.1. Site description

Ground truth data were obtained from a forested slope located at an altitude of 1400 m a.s.l. in Isère, French Alps, France (Prémol forest, 45°07′ N, 5°51′ E, see Mao et al. (2013) for figures). The slope was covered by a mixed, mature, naturally regenerated forest. The stem basal area was >40 m^2 ha^{-1} and Silver fir (*Abies alba* Mill., 56–72%) was the dominant species, followed by Norway spruce (*Picea abies* (L.) Karst., 9–28%) and European beech (*Fagus sylvatica* L., 14–18%). The soil was acid brown colluvium to mull (i.e. well decomposed organic matter in humus) above green schist with an abundant water supply due to precipitation and snow melting and a high content of rock blocks (Joud, 2006). The mean annual precipitation was approximately 1250 mm. The highest and lowest mean daily air temperature occurred in July–August (approximately 20 °C) and January–February (approximately −5 °C), respectively. More details about the climate are available in Mao et al. (2012, 2013).

2.2. Forest management scenarios

Despite the presence of gaps, the study area was one of the densest montane forests at Prémol (basal area >40 m^2 ha^{-1}) and prone to disturbance by natural hazards. For both safety (the forest is a hiking zone in the summer and used for hunting in the autumn) and commercial reasons, the forest was thinned from 2005 to 2007 resulting in gaps throughout the forest. In order to test the effect of several different forest management methods (such as thinning, clearcutting and regeneration) on slope stability, five scenarios were chosen for study (Fig. 1):

[A] Bare soil (Fig. 1a): this situation represents a slope without vegetation.
[B] Tree island on bare soil (shortened to "tree island," Fig. 1b): this situation refers to a tree island as an embedded patch in the model that is surrounded by bare soil. Transitional boundaries may exist between the embedded patch and surrounding landscape. This pattern can be used to describe "mosaic cutting" of tree islands in the Alps, utilized to ensure the continued existence of forest on a slope for both productivity and substrate protection (Gauquelin and Courbaud, 2006).
[C] New gap in homogeneous forest (shortened to "new gap," Fig. 1c): this situation refers to a gap (bare soil) as an embedded patch in the model that is surrounded by forest. Transitional boundaries may exist between the embedded patch and surrounding landscape. This pattern is formed after thinning or natural tree falls that create "new gaps." New gaps can provide little soil reinforcement due to roots because understorey species are scanty and root mortality is high because of soil disturbance or water stress.
[D] Old gap in homogeneous forest (shortened to "old gap," Fig. 1d): this landscape is a stage successive to [C]. Several years after thinning or tree fall, the gap ages through the colonization of pioneer understorey species and regeneration. The understorey and regeneration in gaps can provide significant soil reinforcement due to roots. However, this reinforcement is much lower than that in the surrounding tree islands forest (Mao et al., 2012).
[E] Homogeneous forest (shortened to "forest," Fig. 1e): this landscape could either be a consequence of plantation and maturation with natural regeneration, or a stage of closure in a forest with gaps.

From scenarios [A] to [E], root density along the whole slope increases (Fig. 1). Scenario [D] old gap is the actual state of the forest site at 1400 m a.s.l., but all the other scenarios are data based and can be commonly found on mountain slopes in the region (Gauquelin and Courbaud, 2006). The data based forest scenarios can be considered as the consequence of different management decisions.

2.3. Numerical slope stability model "Ecosfix 1.0"

To determine the effect of scenarios [A] to [E] on slope stability, we developed a 3D slope stability model with the FE software ABAQUS 6.9 (SIMULIA, www.simulia.com). The FE method allowed us to calculate the strains and displacements of all points of different modelled slopes with different soil and root properties under gravity loading only. For that purpose, the modelled slopes were meshed, i.e. divided into assemblies of 3D sub-volumes, called elements. A material stress–strain relationship was associated with each element. The gravity loading, considered as an