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A new approach to integrate effects of changes in vegetation cover in slope stability assessment.

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ABSTRACT: Global changes would have direct impacts on landslide activities through the modifications of the triggering events with the evolutions of climate forcing. However, some predisposing factors would also evolve, like, for example, the vegetation covers. Indeed, forests are likely to be modified, either by anthropogenic interventions, natural ageing or adapting to climate change. And this evolution is likely to result in changes of the susceptibilities of slopes to landslides. In order to propose adequate solutions for current and future forestry management, it is therefore necessary to properly estimate the influences of the vegetation on slope stabilities.

In the present study, we are developing a complementary module to our slope stability assessment tool to take into account the effects of vegetation on the soil mechanical properties (cohesion and over-load), but also in a future second step, on the slope hydrology (change in interceptions, run-off, and infiltration). Hence the proposed methodology will combine a mechanical stability analysis using finite slope analysis, with a hydrological model, and with a vegetation module which interfere with both aspects. All these elements are interfaced within a GIS–based solution. The method will be applied to a Pyrenean Valley, in Laruns, a site which is part of the Observatoire Pyrénéen du Changement Climatique (OPCC).

1 INTRODUCTION

1.1 Parameters governing slope stability

Slopes’ stability is controlled by the equilibrium between the moving forces and the resisting forces. The disequilibrium of this ratio will induce landslides. In a natural context (i.e. with no human intervention), the moving forces correspond mostly to the weight of the soil, whereas the resisting strength are only dependent on the shear characteristics.

One of the main factors controlling the evolution of this equilibrium is the soil water content. Indeed, when this parameter increases, the moving momentum increases (due to an increase in the weight) while the resisting momentum decreases (due to a reduction of the shear strengths of the soil or at the interface between soil layers).

In the saturated zone, the shear stress (τ) is given by the Mohr Coulomb criteria:

$$\tau = c' + (\sigma - u_w) \cdot \tan\varphi' \qquad (1)$$

where $\sigma =$ total stress; c'= internal cohesion; φ'= internal friction angle; and u_w= the pore water pressure.

In the unsaturated zone, where the effect of vegetation would be exacerbated, the effective stress is described by Bishop and Morgenstern (1960) according to Equation 2:

$$\sigma' = \sigma - u_a + (u_a - u_w) \cdot \chi \qquad (2)$$

where u_a= air pressure; u_w= pore water pressure, $u_a - u_w$= suction; and χ= parameter dependent of the degree of soil saturation.

Combining equations 1 and 2, in equation 3, the suction effect can be seen as an apparent cohesion ($c_{app} = (u_a - u_w) \cdot \chi \cdot \tan\varphi'$), increasing the shear strength of the soil.

$$\tau = c' + c_{app} + (\sigma - u_a) \cdot \tan\varphi' \qquad (3)$$

Hence, the parameters potentially modifying the equilibrium are from two types: those modifying the constraints and those modifying the soil properties (c_{app}, c' and φ').

1.2 Potential effects of the vegetation on the shear strength

It is commonly considered that roots' presence increases shear strength, but the ways to take their effects into account are still discussed. A lot of authors introduce an artificial additional cohesion in Mohr Coulomb criterion, but without taking into account the heterogeneity of the roots system at the scale of a slope. The range of possible value for this additional cohesion is between 2 kPa and 20 kPa (O'Loughlon and Ziemer, 1982). If a large number of factors are involved in this mechanical reinforcement, the resistance of the roots to traction is largely concerned: if the roots are assumed to be perpendicular to the surface of the slide, the roots are mostly mobilized in traction. However, the distribution of the roots in the soil has more influence on the safety factor than on the resistance to traction. (Genet et al., 2010)

One of the first quantitative relationships to estimate the additional cohesion due the resistance to traction of the roots and their spatial repartition has been introduced by Wu et al. (1979). Then, Pollen and Simon (2005) improved this model, which originally overestimated the stabilizing effect of the vegetation.

A list of values for the resistance to traction for 67 species is provided by Stokes at al. (2008), while Gennet et al. (2008) provide an equation linking by a power law the resistance to traction to the inverse of the diameters of the roots.

1.3 Influence of the vegetation on the suction

In unsaturated soils, the natural evaporation, increased by the action of roots which uptake water from the soil, induces the apparition of negative pore pressure, also called suction phenomena.

This suction phenomenon increases the effective stress in the unsaturated layer of the soil, and therefore stabilizes the slopes against shallow landslides. The suction can be quantified based on the length of existing roots per unit of volume or surface (ratio called Root length density – RLD) (Stokes et al., 2009).

The influence of the vegetation on slope stability, via the modification of suction, is therefore variable according to the period of the year and to the saturation of the soils. In temperate areas, the shallow landslides take mostly place in saturated soil, when evapotranspiration are low and vegetation have low effect through suction effects. This influence becomes more significant in tropical areas, where evapotranspiration is high, all along the year (Stokes et al., 2009).

There are only few studies taking into account both mechanical and hydrological effects of vegetation on landslides, to compare their effects. Schwarz et al. (2010), demonstrate that the relative importance of both effects is dependent of the size of the deformation. For small deformation, (up to few millimetres), stability reinforcement is mostly the result of suction, whereas for centimetric deformations, the mechanical reinforcement is predominant.

1.4 Influence of the vegetation on infiltration

The presence of vegetation creates preferential drains which facilitate local vertical infiltration, and could, during high precipitation events, contributes to the rapid increase in pore water pressure at the interface between the soil and the substratum or in existing discontinuities (Sidle and Ochiai, 2006).

However, there is no general proof that the vegetation cover increases globally the in-depth water supply. Inside the soil, the modification of permeability is likely to be localized, diffuse and restrained to the vicinity of the roots system.

1.5 Influence of the vegetation on weight

According to Ladier et al. (2012), the vegetal mass of a forest would only correspond to a 5cm-litter and could therefore be negligible for deep-seated landslides. Except this assessment, very few quantitative studies exist on the influence of the induced weight of vegetation at a slope scale. In all cases, the influence of the weight cannot be evaluated alone, because the stabilizing influence of roots on shear stress reinforcement could not be omitted.

1.6 Synthesis on the influence of the vegetation on slope stability

Vegetation influences very poorly the deep-seated landslides. However, this influence exists for shallow landslides, but remains difficult to address. In the same time, the vegetation cover increases ground weights, and so it would tend to decrease the safety factor, but it also increases the shear strength. Some comparisons between these two effects are performed according to the localization of the forest on the slope. The stability would be increased if the vegetation is present on the toe of the slope (Greenwood, 2004, Genet et al. 2010, Ji et al., 2012) but this stabilizing effect would be reduced if the vegetation is located on the upper part of the slope (Norris, 2008, Genet et al., 2010). In this last situation, the influence of the weight would overpass the mechanical reinforcement. However, the beneficial effect of vegetation would be dependent on the size of the landslides (Schwarz et al. 2010).

2 SLOPE STABILITY MODEL

The aforementioned characteristics of the interactions between landslides and vegetation, and their variable effects according to the hydrological regime, the properties of soil, the types of landslides and the localization and species of forest, encouraged us to integrate their effects directly inside our physically-based model for slope stability assessment ALICE.

2.1 Principle

ALICE (Assessment of Landslides Induced by Climatic Events) is a software designed to support landslide hazard mapping for areas ranging from slopes to department (Sedan 2011). The model is based on a mechanical and geotechnical approach for which the main physical characteristics of the soils and surfaces are quantified. These parameters are integrated in a mathematical model to calculate a safety factor for each pixel of the profiles (Aleotti & Chowdhury 1999). In this model, the spatial variability of the parameters (e.g. mechanical characteristics of the different soil layers) has to be known and is handled through GIS solution. The probabilistic approach used allows us taking into account uncertainties by giving probabilistic distributions to some of the parameters of the model such as the soil characteristics: cohesion (c), angle of friction (φ) and unit weight (γ).

The 2D profiles on which the stability is assessed are automatically generated using four input raster maps derived from the Digital Elevation Model (DEM), to cover the whole area. Pedological and geological characteristics, and their spatial variability, are taken into account thanks to the altitude maps of the interfaces between each soil layer, the highest limit corresponding to the topographic surface (DEM).

2.2 Hydrological Modelling

Water table level is set by determining two constant piezometric maps: one for the maximal water table level and the other one for the minimal water table. The current water table is then automatically generated between these piezometric levels by setting a global filling ratio. This filling ratio, corresponding to the level of the present water table compared to the maximal water table level, is computed thanks to a global lumped hydrological model, GARDENIA (Thiery, 2003). The hydrological system is modeled by a system of 3 tanks, which reproduces the 3 layers characteristics of the hydrological behavior of the soil:

- the top zone, the first tens centimeters, where the evapotranspiration occurs
- the unsaturated zone, where runoff occurs
- the saturated zone

The model allows estimating the relationships between the piezometric levels and the meteorological parameters, such as precipitation, temperature (to distinguish between snow and rain fall) or the potential evaporation. These relationships, after being calibrated using past records, allow estimations of future series of soil water content.

2.3 Safety factor calculation

The software uses the Morgenstern and Price method (1967), which is a finite slope stability model based on the equilibrium calculation between slices subdividing the landslide volume. This method is used on the regularly spaced topographic 2D profiles. The principle consists in analyzing the forces applied on a sliding body along a potential slip surface and assessing an overall measure of its stability through a safety factor. More precisely, the sliding body is divided into slices and the forces exerted on each slice (weight, resultant water force, shear and normal forces on the base, interslice forces, external force and seismic force) are taken into account. The safety factor (SF), calculated for the whole sliding body, can be expressed as:

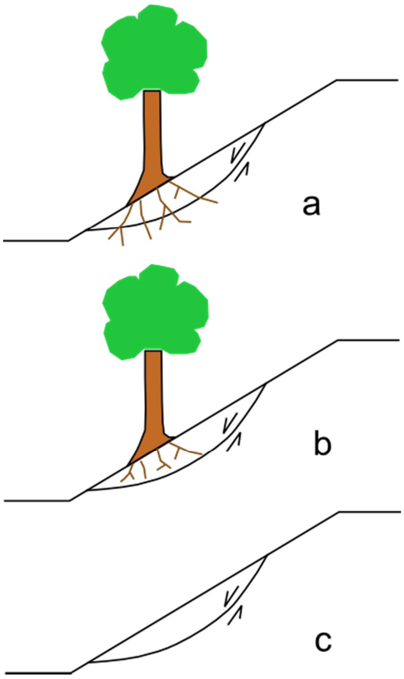
$$SF = \frac{soil\ shear\ strength}{shear\ strength\ required\ \ for\ equilibrium} \qquad (4)$$

Theoretically, a sliding body for which the value of the safety factor is less than unity is unstable. Unless the slip surface is previously known, the safety factors should be calculated for every potential slip surface of a hill slope. The slip surface for which the safety factor is the smallest is the critical slip surface, along which sliding is the most likely to occur.

The software calculates safety factors on each profile of the studied area. The probability of having the safety factor below one represents the probability of landslide occurrence for a given triggering scenario (i.e. landslide geometry and water table level). The dispersion of the distribution gives the uncertainty associated to the result. Finally, a map is created, displaying the highest calculated probability of occurrence for each pixel of the studied area.

2.4 Integration of vegetation

So far, the vegetation has been integrated in the model in two ways, with an additional apparent cohesion of the soil due to root reinforcement of the resistance to shear and additional weights on the slices according to the vegetation cover. The vegetation cover is an additional layer of the model, with 3 characteristics, the additional cohesion due to the roots (c_{forest}), the average depth of the roots (d_{roots}) and the average weight of the forest indicated as a surface force (W_{forest}). These modifications affect mostly shallow landslides, where the potential slip surfaces would be situated inside the root layer (Fig 1.a) and for which the additional weight will be significant compared to the weight of the soil above the slip surface (Fig 1a and 1b). The soil characteristic would be modified as described in Equation 5:



$$\begin{cases} c' = c_{soil} + c_{forest} \\ W = W_{soil} + W_{forest} \end{cases} \quad (5a)$$

$$\begin{cases} c' = c_{soil} \\ W = W_{soil} + W_{forest} \end{cases} \quad (5b)$$

$$\begin{cases} c' = c_{soil} \\ W = W_{soil} \end{cases} \quad (5c)$$

Figure 1: Description of the different potential situations of mechanical effects of vegetation on slope stability.

3 APPLICATION TO THE LARUNS TEST SITE

The above method is being applied to the Laruns test site, which is located in the Pyrénées Atlantique region, in the South of France. The studied area is located in a mountainous valley with altitudes ranging from 506 m to 2613 m, and with high slopes (the median slope is above 40%). It covers 4758 ha, amongst which 2164 ha are covered by beech, fir, or mixed beech-fir forests (Fig. 2a). A simplified 3D geotechnical model has been constructed based on the geological map and contains four zones called respectively “colluvium”, “pelite”, “limestone” and “granite” (Fig 2b). The characteristics of the soils for the four zones have been calibrated based on an inverse method and on punctual data (Table 1). The model considers so far only one upper layer susceptible to slide, over the bedrock, and the parameters are considered homogenous (and therefore constant) inside a zone.

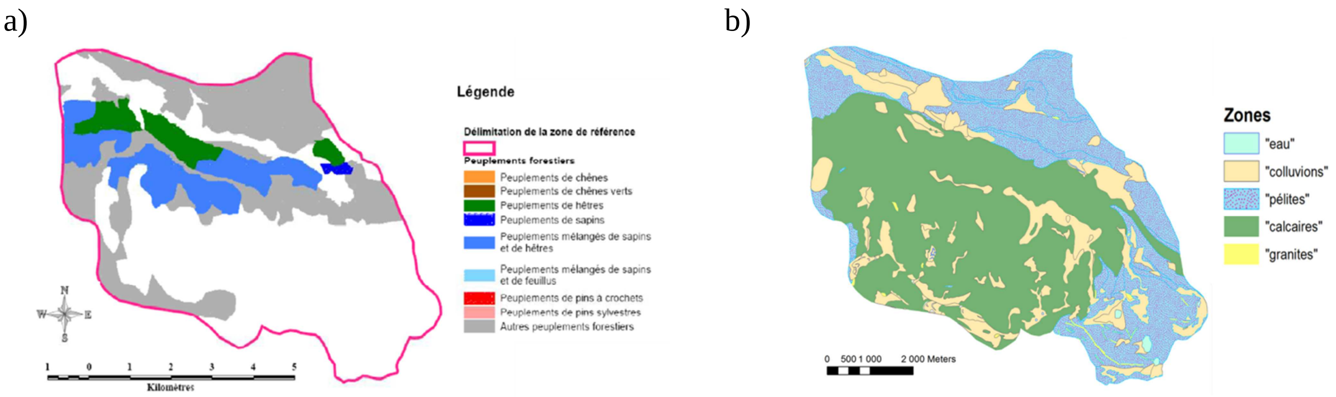


Figure 2: Description of the studied area: a) forest cover (source: CRPF) and b) geotechnical model.

The first simulations are run for different levels of water table, for different lengths, for rotational landslides with slip surfaces located between 1 and 5 m below the surface, and, as no distributions are introduced yet, safety factors are returned. (Fig.3). Further simulations have to be performed to consider heterogeneity in soil properties, the vegetation cover and the evolution of the hydrological context.

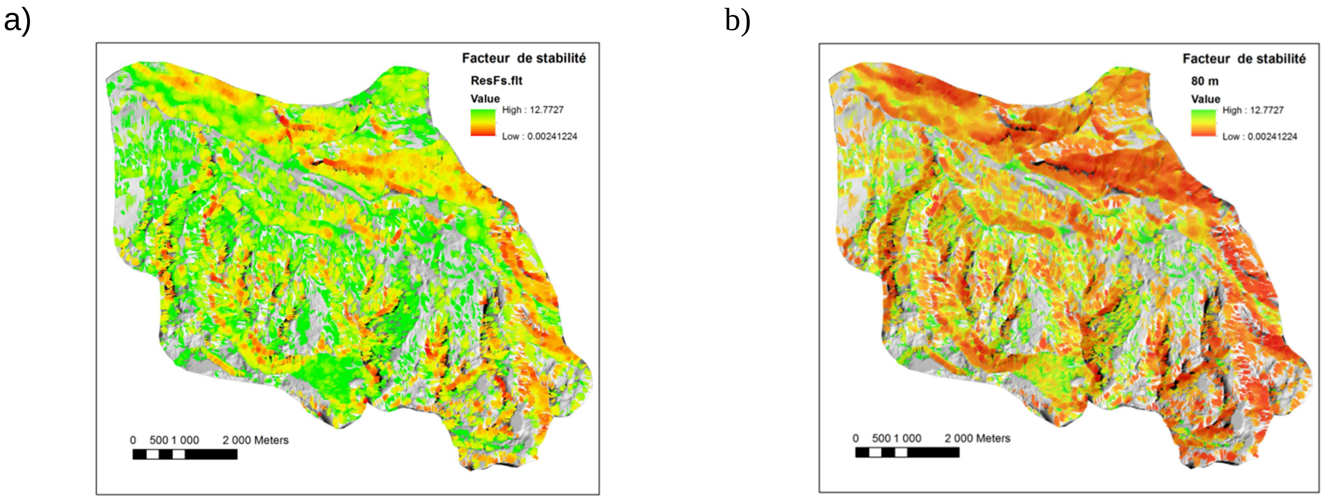


Figure 3: Results of the spatial distributions of the safety factors for different water table levels (a, water table = DEM; b, water table = DEM-5m)

Table 1. Characteristics of the 4 zones of the geotechnical model

Zone	Cohesion (kPa)	frictional angle (°)	Gamma (kN.m^{-3})	Depth (m)
1-colluvium	5	30	18	25
2-pelite	2	30	17	5
3-linestome	2	35	18	1
4-granite	80	40	19	100

4 DISCUSSIONS

The ALICE software has been further developed to be able to integrate the effects of the evolution of the vegetation cover on the stability of the slopes, and therefore to be able to provide insights for forestry management. So far, the influence of the vegetation on the mechanical properties has been integrated, but the related uncertainties on depth of influence and on quantitative effects should still be considered. Furthermore, the effects of vegetation on the hydrological cycle would have to be analysed, through our hydrological modelling, with variations of evapotranspiration, but also on its effect on the spatial repartition of the water table level. All these development will be applied to the Laruns test sites, to simulate different scenarios of global changes (climate and land-cover). The results shown here are only preliminary results, which will be used as support for the comparison and the sensitivity analysis of the different upgrades of the model.

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