TOWARDS A NUMERICAL SIMULATION MODEL OF SHORT-TERM IMPACT OF FORESTED HILLSLOPE STABILITY UNDER RAINFALL CONDITION

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ABSTRACT

Eco-engineering has been recently recognized as producing effective and environmental friendly techniques to prevent shallow landslides (Stokes *et al.*, 2007). Modelling and predicting slope stability reinforcement by vegetation at a rainfall time scale for different stand ages is essential for the development of eco-engineering practices in various geographical conditions. This paper presents the basics of an integrative numerical approach that is currently being developed in order to simulate and investigate impacts of soil root reinforcement on forested hillslopes under rainfall conditions. The numerical model is an extension of ForSLOPE3 (Kokutse *et al.*, 2006), a Finite Element model developed under SIMULIA software (www.simulia.com), which considered the coupling between soil mechanics, trees distribution and unsaturated soil. The extended model introduces hydrological effects. In this paper, a simple case study is presented.

Key Words: Landslides, Hydrology, Finite element model, Stand, Root reinforcement, Factor of safety

INTRODUCTION

The use of forest plantations to reinforce soil and to stabilise slopes against shallow landslides are more and more increasing as a practice worldwide. These so-called eco-engineering techniques are ecologically viable methods to improve long term slopes stability (Stokes *et al.*, 2004). To understand slope stabilization process, interactions between soil, roots and water should be taken into consideration in research projects. The particular stabilizing effects of tree roots are supported by several studies (Wu *et al.*, 1979; Waldron and Dakessain, 1981; Genet et *al*, 2007). Investigating impacts of forest stands on slope stability and therefore understand how failure processes can occur in reinforced soil under rainfall conditions, needs to take into consideration the three major components of the system: soil, stand and water.

Analysing effects of soil reinforcement on slope stability needs to carry out field investigations and laboratory tests. Nevertheless, based only on field investigations and

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rainfall events, etc.

laboratory tests, it is often difficult to extrapolate to the landslide process which may occur at the scale of the whole slope, because results are highly variable within sites, species, stands rainfall event, etc.

There is a real need to develop models as a decision support tool that can incorporate different knowledge in order to help eco-engineers and other end-users. While considering models in the field of eco-engineering, there are few models that deal with three-dimensional slope stability modelling with different forest stand scenarios (Kokutse, 2008) and slope stability modelling with hydrological effects due to rainfall events (Sidle, 1991). Very few eco-engineering models take into consideration combined effects of stand structure and rainfall events on slope stability. There is therefore a need to develop such types of models. Studies that have been carried out in the framework of this research project aimed to understand how rainfall events can have impacts at the short time scale on the stability of a slope covered by a given forest stand. This paper presents an integrative numerical approach that was developed in order to simulate mechanism involved in soil reinforcement by a stand and impacts of rainfall events. A part of the model was developed as an extension of a mechanistic 3D forested slope model (Kokutse, 2008; Kokutse *et al.*, 2009), a finite element model which can be run under ABAQUS software (www.simulia.com). Coupling between soil mechanics and tree root systems morphologies and distribution have been considered in the forested slope model. Hydrological components had been introduced in this version of the model to take into consideration rainfall impacts. Modelling techniques, hypothesis and equations that governed the extended simulation model of the impacts of rainfall events are detailed. Basis of the forested slope mechanistic model were also presented. A case study with a slope covered by a random distributed stand of trees of given characteristics (root system morphology, root systems depth and lateral extent), impact of a rainfall event has been simulated and factor of safety of the slope has been calculated.

THE MODEL AND METHODS OF ANALYSIS

The model developed in the framework of the present study is composed of two main parts. The first part is the mechanistic model which enables to build the forested slope domain and to integrate the mechanical effects due to root systems reinforcement. The second part is presented as an extended module of the first part. It takes into consideration hydrological components in the reinforced slope domain, due to rainfall event. This section presents the basis of the two main parts of the model.

Basis of the mechanistic and mechanical reinforced slope model

To build the mechanistic reinforced slope model, several parameters are required for the model.

Geometry of the slope and soil properties

The slope geometry was modelled as a limited domain with a shape that can be of planar, concave or convex surfaces. In the case of planar surface, slope angle is considered as the main parameter. For the purpose of simplification of the simulations, it assumed that the slope is composed of a homogeneous and isotropic soil.

Roots mechanical reinforcement model

In the field of eco-engineering of slope stability, mechanisms which involved in soil reinforcement by tree fine roots are well known. According to these reinforcement mechanisms developed by Wu *et al.* (1979) and validated by Waldron and Dakessian (1981), effects of tree fine roots can be considered as additional cohesion in the soil matrix. In conventional reinforced slope design, roots reinforcement can be taken into consideration by adding this additional cohesion C_r that simulates root presence to the classical Mohr-Coulomb failure criterion:

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

Where τ is the total soil shear strength and $C'_s + \sigma'_n \tan\phi'$ 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 angle ϕ'.

Values of additional cohesion C_r can be found in the literature (Genet *et al.*, 2005; Coppins and Richards, 1990) or can derive from field investigations and laboratory tests. A high variability can be found for the values of additional cohesion mainly due to differences within species and site conditions.

Stand structure, individual trees description and distribution

Different types of parameters are needed at two scales to describe a forest plantation that covers a slope, stand parameters and trees parameters. At a given age, stand can be described with a regular or random distributed stand and a plantation density. At the level of the tree, root systems morphology, maximum depth Z and lateral extent R were considered as description parameters. The geometry of the domains that corresponds to roots systems morphologies can be modelled according to chosen tree species root systems morphology. Morphologies can be therefore of different shapes: semi-sphere shape heart family root system, cylinder for plate root system and conical for tap root systems family (Kokutse, 2008).

Hydrological and mechanical parameters

The whole slope domain model can be assumed to be divided into two parts, the hydrological part and the mechanical part of the model. Hydrological parameters allow integrating into the whole model hydrological conditions due to a rainfall event, outcoming groundwater flow and seepage conditions, etc.,. Pore fluid–stress step of calculations can allow taking into consideration both pore flow and mechanical stress conditions in the model. Pore fluid conditions were therefore coupled with mechanical stress due to gravity load.

Water flow through the soil: Introduction and basic equations

Ground water flow can be transient or steady-state. In steady-state conditions, the hydraulic head at any point of the flow is constant with time. In transient flow the hydraulic head changes as a function of time. The governing equation in either case combines Darcy’s law and the continuity equation. The governing equation for steady-state flow, called Poisson’s equation can be presented for three-dimensional flow as follow within a domain composed of heterogeneous and anisotropic soil:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) + q = 0 \qquad (2)$$

Where h is the hydraulic head, k_x, k_y, k_z are the coefficients of permeability of the soil with respect to water along the *x, y, z* axis and q is the applied flux in the domain.
In the case of transient flow conditions where hydraulic head is dependent on time, volumetric water content is a function of time. Therefore continuity equation can not be satisfied unless the change with time of the volumetric water content at a point is included. Poisson's equation can be adapted for unsteady-state flow. The final equation is known as Richard's equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right)+q=\frac{\partial \theta w}{\partial t} \tag{3}$$

Where θ_w is the volumetric water content.

Coupled pore fluid stress analysis

A coupled pore fluid-stress analysis allows to take into consideration in a model single phase (solid phase) and partially or saturated fluid flow through porous media.

In order to take into consideration realistic hydrological conditions due to rainfall in the domain delineated by the forested hillslope, a coupled pore fluid-stress analysis was performed. Effects of reinforcement due to tree roots were assumed to be relevant only in the case of unsaturated soil. The analyses were therefore performed in the case of unsaturated soil. This analysis uses the continuity equation for the mass of fluid in the medium which were previously exposed.

The mechanical part of the simulation model involved in defining a geostatic stress step of calculations. This step of simulation is necessary to generate geostatic stress field due to application of gravity load.

Other parameters needed for the finite elements model

Finite elements analysis (FEA) was performed using SIMULIA software (www.simulia.com). For the purpose of the analysis, boundary conditions were defined to simulate action of the surrounding infinite earth. These kinematic conditions were imposed to all lateral and underside faces of the slope. The domain was discretized into elements. Discretization technique consists in breaking the domain into small elements and to compute displacement of each discretization node under given loads (Zienkienwicz, 1977). Pore pressure elements were chosen for the finite elements model. These elements are suitable for coupled pore fluid stress analysis. The boundary flux q was also required.

The finite element code SIMULIA enabled to define directly boundary flux condition in a coupled pore fluid diffusion and stress analysis. The boundary flux condition was specified by defining the total pore pressure in the geometrical domain.

Stability analysis of the slope

Stability of a slope, even reinforced can be expressed with a number which is the factor of safety. According to Duncan (1996), factor of safety FoS can be defined as the factor by which the shear strength of the soil would have to be divided to bring the slope into a state of barely equilibrium. FoS can therefore be determined by reducing the soil shear strength parameters until failure occurs. Shear strength parameters are cohesion *C* and internal angle of friction Φ of the material. This strength reduction technique is the approach which is implemented in many commercial finite elements codes dedicated to geotechnical analysis. This approach is used in the present study to determine the stability of the slope in two configurations, namely by taking into considerations (1) hydrological effects and (2) hydrological effects and root systems reinforcement. Comparison between slopes in the two configurations enables to estimate effects of the reinforcement on the slope. Details of the implementation of the technique of strength reduction approach for SIMULIA finite elements model may be found in Kokutse (2008) and Kokutse *et al.* (2009).

A CASE STUDY

A first configuration of a given slope was analyzed, i.e. by taking into consideration hydrological effects (unsaturated soil). Factor of safety was determined based on strength reduction approach. The same slope was analysed with a plantation scenario in order to assess global impact of the plantation on the overall stability. The plantation scenario analysed in the present was composed of a random distribution with different root morphology families. For the study, a slope with angle of 35° was chosen. The other parameters needed for the model simulation model were summarized (Table 1).

Table 1 Parameter and values chosen for the reinforced slope analysis with hydrological effects.

Parameter description	***Values or defined***
Slope length (m)	100
Slope angle (°)	35
Root systems morphology	Tap, plate
Roots additional cohesion (kPa)	1-17
Soil cohesion (kPa)	1.2
Internal angle of friction (°)	35
Plantation scenario	Random distribution
Boundary flux	defined
Void ratio	defined

RESULTS AND DISCUSSION OF THE STABILITY OF THE SIMULATED SLOPE

Based of slope stability analysis a factor of safety, a result of **FoS = 1.15** was obtained for the slope without reinforcement but in the configuration of unsaturated soil. Analysis of the same slope with reinforcement derived from a random distributed plantation showed **FoS = 1.37** stability, which corresponds to **13.91%** of stability increase. Difference or increase of the slope stability due to the reinforcement that was included in the analysis at the second step of the analysis. The slope in the second configuration (with reinforcement) was therefore more stable than slope without reinforcement, but with only unsaturated soil. Field of plastic strains which was obtained showed performance of the approach and the model developed in the present study (Fig. 1). It was noticed that stand structure through additional cohesion provided by the root systems network, can have positive effects on slope stability in configuration of unsaturated soil. Stand structure, i.e. the way trees are distributed on the slope, is not taken into consideration in the present study. This aspect should be analyzed with regards to soil degree of saturation. Roots effect on soil behaviour was not explicitly modelled in terms of roots water uptake. This phenomenon can be interesting to be included into the model by implementing an approach like the one developed by Feddes *et al.* (1978). The way stand distributed on the slope was not also taken into consideration. Difference patterns of stand distribution can have different impacts on slope stability (Kokutse, 2008). The way trees are distributed on the slope, combined with the degree of saturation of the soil can lead to different slope factor of safety and failure mechanisms.

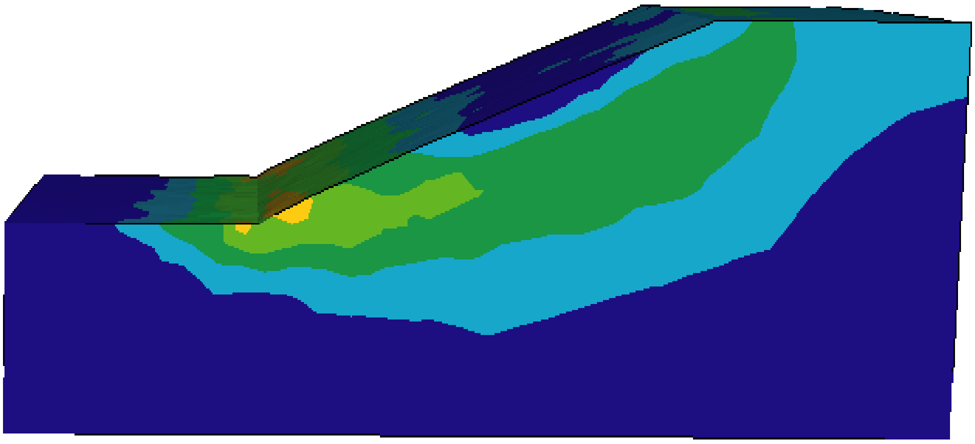

Fig 1. Configuration of the slope after application of the strength reduction approach. Contours of plastic strains after application of reinforcement and hydrological parameters.

CONCLUSION AND PERSPECTIVES

This project presents a preliminary aspect of a generic integrative approach to develop a 3D numerical model that can take into consideration impacts on slope stability of the reinforcement provided by a forest stand by including hydrological short term impacts due to rainfall scenario. First results showed that there is a positive and significant influence of reinforcement provided by roots systems of tree roots on slope stability for an unsaturated soil. Similar conclusion, with slopes without rainfall scenario based on limit equilibrium modelling approach can be found in the literature (Sidle, 1992).

In further studies, the model will explicitly integrate root water uptake in order to investigate and analyse how combined effects of rainfall patterns, stand patterns and reinforcement provided by roots systems can have influence on slope stability. This influence will be quantified based on numerical experimental investigation. The study will also include effects of unsaturated soil in the slope stability analysis. The use of seepage will allow investigating how seepage will occur in a reinforced slope under different hydrological conditions.

These numerical tools will be extended to applications in the field of eco-engineering, especially to investigate different forest management scenarios on slope stability. These applications will be done based on data provided by different environmental conditions field studies, semi-arid region in Shanxi province (China) and tropical environment in Agou (Togo, West Africa).

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