3D Numerical Modelling and Analysis of the Influence of Forest Structure on Hill Slopes Stability

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Abstract

Stability of a slope covered by vegetation is commonly computed considering root depth zone as soil layer, with associated uniform additional cohesion in Mohr-Coulomb's failure law. Such models of slope reinforced by roots seem to be suitable for grassed slopes stability analysis, where the root distribution is homogeneous. Nevertheless this approach is not suitable in the case of forested slopes, as it does not take into account the non-homogeneous distribution of trees root system parameters (morphology, root area ratio) and the resulting spatial distribution (pattern) of the forest stand. This paper aims to develop a finite element (FE) model in order to analyse the effect of three-dimensional spatial distribution of trees on forested slope stability. Individual tree root plates were modelled according to the root system morphology (heart-, tap- or plate-like root systems), using simple geometrical patterns (half-sphere, cone and cylinder). The soil mechanical behaviour was assumed to obey the Mohr-Coulomb failure criterion. Soil reinforcement due to roots was then modelled using two main parameters, namely additional cohesion and root system morphology. A Python script has been developed in order to perform FE analyses of the stability of such forested slopes. Factor of safety was determined by decreasing soil shearing resistance parameters until failure occurred. Spatial distribution of the resulting plastic strain field and factors of safety were analysed and discussed.

Keywords: Landslides, finite element, soil reinforcement, tree roots, safety factor.

Introduction

Landslides are among natural phenomena which damage environment and lead to economical and human loss. Eco-engineering techniques which consist in using plants for geotechnical engineering purposes are ecologically viable methods to improve long term slopes stability (Stokes *et al.*, 2004). These techniques for slope reinforcement against landslides and erosion are not recent endeavours. Lee (1985) reported works of Pan in 1591 who stabilized banks with willow plantation during Ming dynasty in China. Nowadays attempts are more and more increasing in different parts of the world to better understand how slope stability could be improved by vegetation (Tsukamoto 1987, Operstein and Frydman 2000).

Although numerous experimental works and field investigations have shown that vegetation which growing on a slope may increase slope stability, very few consideration is given to them for geotechnical engineering applications. While analysing effects of vegetation on slope stability, analysis are usually performed in 2D, which seemed to be more suitable for grassed slopes for example. Additional cohesion due to vegetation in the case of grass is usually considered as homogeneous in soil layers (Chok & *al.*, 2004). Numerical techniques appeared, therefore, to be an interesting alternative that can be used to estimate the risk of failure of slopes according to vegetation characteristics. Nevertheless in the case of forested slopes, where different alternative scenarios of plantation can change the root distribution pattern in any directions, there is a lack of appropriate techniques.

Researches that have been carried out in the framework of this project aimed in understanding how forest management scenarios and forest dynamics could affect stability of slopes, through a Finite Element (FE) method. In this paper, we describe how tree root systems have been aggregated in appropriate geometric

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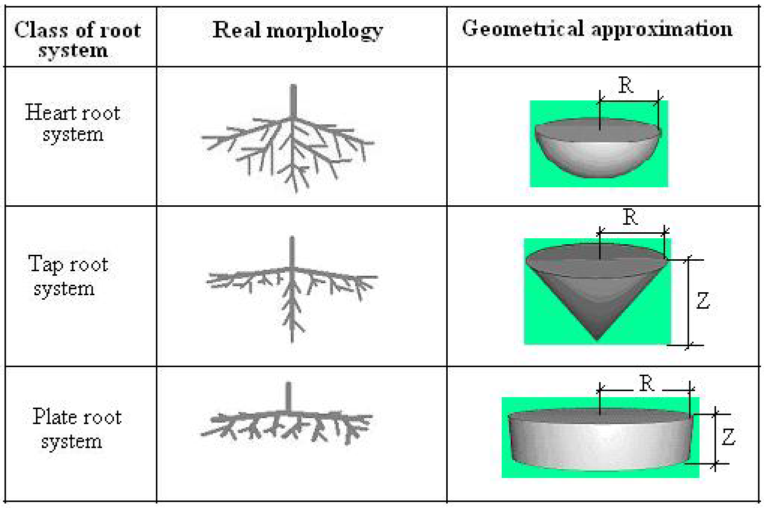

Fig. 1. Morphology and geometrical approximations of roots systems according to Köstler's classification.

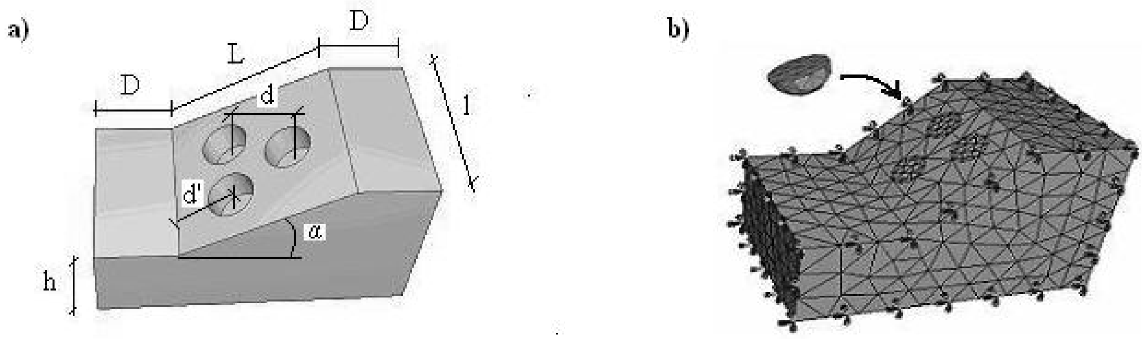

Fig. 2. Geometrical parameters of the slope domain and excavated holes (a). Boundary conditions and meshing of root blocks and slope (b).

patterns and included in the surrounding soil. Analysis techniques used to determine the factor of safety of the reinforced slope are also detailed. Examples of analyses are shown considering a 1:1 slope reinforced by a triangular distribution of tree root blocks where the effect of both additional cohesion and block morphology on the variation of factor of safety has been calculated.

Modelling and methods of analysis

This section explains how reinforced blocks of soil and their associated mechanical properties have been built according to tree root systems morphologies. These soil blocks were distributed on the slope according to the planting scenario to be investigated.

Modelling parameters

Geometry of reinforced block and slope

Three main types of root morphology have been considered according to Köstler & *al* (1968), namely heart-, plate-, and tap-like root systems. Geometrical shapes which were considered for the reinforced blocks were based on this classification. The chosen geometrical patterns were a semi-sphere, a cylinder and a cone for heart, tap and plate root system models respectively (Figure 1).

The slope was modelled as a limited domain with a rectilinear profile. The domain parameters are slope angle α slope length L, depth h at down-slope, slope width l, distance d between blocks, distance d' between block's center and the lowest part of the slope inclined plate and distance D between inclined plate and the up and down limits of the domain (Figure 2a).

Soil properties of reinforced root blocks The mechanisms involve in the reinforcement of soil by plant roots are well known. Soil fixation by plants is due in particular to an increasing in soil shear resistance when roots are held in tension (Wu & *al*, 1979). This increasing is in fact considered as an augmentation of the soil cohesion, the additional cohesion C_r of the reinforced soil being expressed by:

$$C_r = t_r(\cos\theta \tan\Phi + \sin\theta) \tag{1}$$

where t_r is the average tensile strength of roots per unit area of soil, θ is the angle of the roots with regards to the slip surface and Φ is the soil friction angle.

It could be noticed that this additional cohesion C_r is mainly dependent on soil and roots parameters. Many C_r values can be found in the literature. These values come from laboratory tests, field experiments or model calibrations, ranging from 1.00 to 17.5 kPa (Coppins & Richards, 1990).

The whole slope is finally assumed to be composed of two types of soil: the surrounding soil whose properties are not disturbed by roots, and the reinforced soil which is associated to the rooted blocks. The soil mechanical behaviour was chosen as an elasto-plastic material associated to a Mohr-Coulomb's failure criterion. Reinforced soil in the root blocks was obtained adding the additional cohesion C_r to the effective cohesion C_s of the root free soil.

Root blocks distribution and connection with the slope As a first stage of the domain definition, preliminary holes were made on the slope surface according to the stand structure to be analysed. For instance, the triangular pattern that was considered in this study was generated giving the constant distance d between trees (Figure 2). Each hole was then associated to a complementary root block. Slope and reinforced blocks were modelled and meshed as different parts or domains. In order to obtain a continuum media formed by both reinforced blocks and slope and to perform analysis as a whole, block surface mesh and mesh of the holes surfaces were tied together.

Finite element model

For each model, boundary conditions were defined. They were applied to simulate surrounding infinite earth. These kinematic conditions were imposed on lateral and underside faces of the slope (Figure 2b). Nodes of the underside face of the slope were embedded in order to avoid translations and rotations. Only translation in the direction k was blocked for nodes of the lateral faces perpendicular to direction $k (k \in \{1, 3\})$. Gravity load was also applied to the whole domain in order to generate geostatic stress field prior to the mechanical calculation.

The mechanical analyses were performed with ABAQUS (HKS©) FE software. The whole domain, including soil blocks, was meshed with 3D tetrahedral elements. Equivalent plastic strains were computed during mechanical calculations. In ABAQUS, the "plastic equivalent strains" identifier is a variable which tells whether the material is currently yielding or not. This field of plastic equivalent strains thus allowed the failure mechanism of the slope to be analysed both qualitatively and quantitatively. Moreover nodal displacements ui were computed and used to determine the global factor of safety of the slope.

Stability analysis of 3D reinforced slope

Several modes can occur in the failure mechanism of a slope. While analysing the stability of a given slope with the FE method, the more commonly used technique consists in decreasing step by step the soil shear resistance parameters (cohesion, internal angle of friction) until the soil reaches the ultimate state of plasticity, i.e. until failure (Rocscience Inc., 2001). Gravity load remained equal to its initial value while decreasing soil resistance parameters.

This stepwise technique is usually implemented in FE codes devoted to soil and rocks analysis, but is not available in ABAQUS. In the framework of this work, the method was implemented writing a dedicated Python script. This script used ABAQUS as a subprogram and allowed the stability analysis of the reinforced slope to be performed. The main steps of the script algorithm were defined as follow:

Step 1: Developing of a FE model of a reinforced slope with ABAQUS. This model is considered as a template.

Step 2: Parameterizing cohesion C and internal angle Φ of friction of the material. For the parameterization, n couples (C, Φ) are computed with initial values C_1 and Φ_1 from an incremental procedure:

$$C_{i+1} = C_i - \Delta C, \Phi_{i+1} = \Phi_i - \Delta\Phi, i \in \{1, .., n\} \tag{2}$$

where C_i is the computed cohesion value for increment i, Φ_i is the computed angle of friction value for increment i, ΔC and $\Delta\Phi$ are the angle of friction and cohesion increments respectively for the current step.

Table 1. Root systems geometrical parameters chosen for the trees planted on the slope.

Root morphology	Radius R [m]	Depth Z [m]
Heart	0.78	non-defined
Plate	0.68	0.68
Tap root	0.86	0.86

n different configurations of the slope were generated based on the template and the n couples (C_i, Φ_i) of strength properties.

Step 3: Computing nodal displacements for each of the n slopes configurations by using ABAQUS as a sub-program.

Step 4: Gathering displacements of given nodes located near the expected slip surface.

Step 5: Determining the cohesion variation as a function of total nodal displacements and computing the factor of safety FS. FS was computed as the ratio of cohesion just before failure (big jump in nodal displacement) to the initial cohesion C_1 as follow:

$$\mathrm{FS} = \frac{C_1}{C_{ult}} \tag{3}$$

where C_1 is the initial cohesion value and C_{ult} is the cohesion value at the ultimate state of plasticity.

Influence of parameters on slope stability

In a preliminary study, a slope reinforced by 3 root blocks was analysed in order to assess the sensitivity of slope stability to block's morphology (heart, plate, and tap roots) and additional cohesion ($C_r \in \{0, 10\text{kPa}\}$). Firstly, slope was considered and analysed without additional cohesion ($C_r = 0$ kPa) and for a given morphology of root blocks. A stability analysis of the same slope was then carried out with additional cohesion ($C_r = 10$ kPa). Distance between trees was set to 5m (equilateral triangle of edge $d = 5$m, Figure 2). In order to avoid the soil block volumes to influence the results, geometrical parameters (radius R and depth Z, Figure 1) were chosen in such a way that the volume of the block remained constant for all types of block (Table 1).

For the study, a 1:1 homogeneous slope with an angle = 45, a height H of 5 m, a width l of 10m a slope length L of 8.8 m and distance D of 5m was considered. The soil properties were as follow:

Soil density $\gamma_s = 16$ kN/m^3
Soil Young's modulus $E_s = 10$ MPa
Friction angle $\Phi_s = 30°$
Effective soil cohesion $C_s = 1$ kPa.

Results and discussion

Reinforced blocks models

Stresses and strains in root blocks (heart, plate, and tap root system), were analysed after applying gravity load to the whole slope. Observation of plastic strains contours showed that blocks were deformed as well as the slope. Not only slope was deformed (plastic strains) but also the blocks (Figure 3). Stresses seemed to be well transmitted to the blocks via connection between slope holes surfaces and blocks lateral surfaces. This was mainly due the nodes of the surfaces which were adjusted during mechanical calculations in order to be the same. Displacements of a given node on the "master surface" (hole surface) were automatically imposed to its neighbour on the "slave surface" (block lateral surface) to which it was tied.

Stability analysis

Using the algorithm written in Python in addition with ABAQUS models for the analysis of slope stability, a result of FS = 1.21 was obtained (curve of cohesion-nodal displacement, Figure 5) for the slope without reinforcement elements. Analysis of the 2D model of the same slope with Abaqus and Plaxis (Brinkgreve & Vermeer, 1998) gave higher FS values (Table 2). Furthermore, the slope was generally more stable in the 2D analyses than in 3D (increase > 8 %, Table 2).

Difference between the results of 3D and 2D slope models was mainly due to the 3D effect which takes into account transversal plastic flow. In 2D the slope width is infinite, which is not the case in 3D (width $l = 10$m). Moreover the difference could also be due to the type of elements used to model the slope.

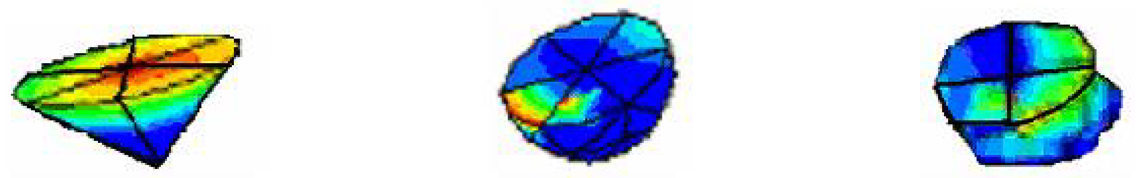

Fig. 3. Equivalent plastic strains contours in root blocks of reinforced soil (example of tap, heart and plate block roots). The blue colour corresponds to elements which were not deformed. Highest values of plastic strains are represented by the red colour.

Table 2. Computed values of FS for different models. Differences between FS values are given with regard to those obtained with the 3D model.

Analysis	FS	Difference (%)
3D model	1.21	-
Abaqus 2D model	1.31	8.2
Plaxis 2D model	1.37	13.22

Table 3. Computed values of FS for different root models and differences with reference to the non-reinforced slope.

Root morphology	FS	Difference (%)
Heart root	1.45	19.8
Tap root	1.57	29.7
Plate root	1.46	20.7

Indeed infinite elements were generally the most suitable elements to model in a more realistically way soil. Nevertheless, this type of element was not available in the library of ABAQUS Environment (Complete Abaqus Environment CAE) used for the modelling. In 2D, very slight difference was observed between the results of stability obtained with Plaxis and ABAQUS (1.37 and 1.31). Divergence of the numerical solutions was noticed after the point which corresponds to the ultimate state of plasticity, during mechanical calculations.

Effects of root block morphologies and additional cohesion on slope stability Regardless of root block morphologies, the stability of reinforced slope was always improved regardless to non-reinforced slope, i.e. factor of safety increased, whatever the root types that were considered (Table 3). The FS of non reinforced slope (1.21) increased more than 19 % in the less favourable case. This result showed that an additional cohesion (C_r = 10 kPa) due to the presence of tree roots in the three blocks had a significant effect on the stability of the whole slope. This positive effect of tree root systems on slope stability was shown by several other studies (Greenway 1987, Chok & *al*, 2004).

Among all the three types of rooted blocks, it could be remarked that slope reinforced with heart- and plate-like root morphologies were less stable than slope reinforced by tap-like morphology (Table 3). Plastic strain field was more uniform in the tap root block than in the two others (Figure 4). In this case, it appeared that stresses in both slope and root blocks increased in the same way during mechanical calculations. This similar behaviour between the whole slope and the root blocks was not observed anymore in the case of heart- and plate-like root systems. The better performance of the slope reinforcement by tap-like root systems could be explained by a deeper block pattern (depth = 0.86m, Table 1) if compared with the others root block types. Failure generally extended beyond the root zone and consequently the critical slip surface shifted deeper in the case of slopes reinforced by tap root systems.

Conclusion and perspectives

A preliminary study has been presented, which aim was to develop numerical models and tools dedicated to 3D analyses of forested hill slope stability. First results showed the significant influence of tree roots on slope stability, even if the spatial distribution of these roots is not homogeneous. Similar conclusions were

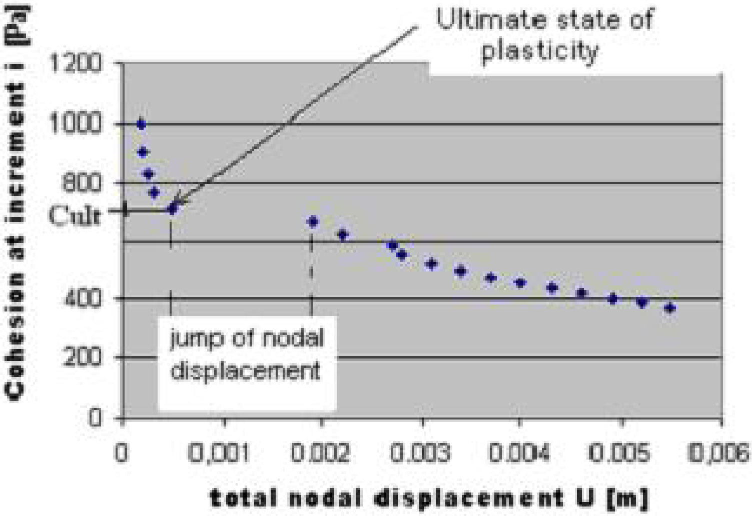

Fig. 4. Cohesion vs. nodal displacement. The total nodal displacement was computed at a given node close to the slip surface for each cohesion value.

found in the literature, but for homogeneous root distributions (Wu & *al* 1979; Wu 1984). It was also pointed out that tap root systems are more efficient than heart or plate patterns in reinforcing slope against landslides. This is mainly due to the deeper rooting of such root structures.

In further studies, this FE approach will be used in order to perform numerical design of experiments. This work will allow the influence of parameters such as spatial structure of forest stand, root system's morphology and additional cohesion, to be quantified.

These tools will be extended to applications in the field of eco-engineering, in particular to study the influence of forest management scenarios on a long term period. Such an application project is already being carried out in Togo and includes the following studies:

- testing root in tension for some tropical plantation tree species in Togo (*Tectona grandis, Terminalia ivorensis, Terminalia superba, Khaya grandifoliola*) in order to compute additional cohesion due to roots;
- measuring variation of root area ratio according to depth and distance from the stem.
- computing the stability of real forested hill slopes in Togo (West Africa) using realistic spatial distribution of trees.

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