Numerical modelling of rainfall effects on the slow movement of slopes

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ABSTRACT. *This paper concerns the assessment of rainfall-induced slow movement of slopes. The effects of the rainfall intensity and the geometric slope conditions on the induced displacements are studied via a parametric finite element simulation. For some given initial slope conditions, a model assessing the expected displacement due to a rainfall intensity level is proposed.*

RÉSUMÉ. *Ce travail concerne l'évaluation du mouvement lent d'une pente soumise aux précipitations régulières par la modélisation numérique. Utilisant la méthode des éléments finis avec une formulation couplée qui relie les déplacements du milieu aux pressions interstitielles et/ou succions, on étudie l'influence des conditions hydriques in-situ, les propriétés hydrauliques du massif et le taux de la précipitation sur le mouvement lent du massif non saturés. Ainsi des modèles pour analyser le rôle du rapport entre la capacité d'infiltration du sol et le taux de précipitation sur le déplacement de la pente et l'avancement du front de saturation sont montrés.*

KEYWORDS: *Landslide, Unsaturated soil, Rainfall infiltration, Numerical simulation.*

MOTS-CLÉS : *Glissement de terrain, Sol non saturé, Infiltration de la pluie, Simulation numérique.*

1. Introduction

Slope instability due to rainfall is a common geotechnical problem in several regions around the world where residual soils are abundant. A large number of steep, natural and engineered slopes remain stable for a long time and then fail during heavy rainstorms. Many field studies have confirmed that rainfall-induced slope failures are mainly caused by infiltration of rainwater. Parameters such as pore pressure propagation, perched water table formation by rainwater infiltration, antecedent rainfall, geological features, topography, vegetation or a combination of these factors can have a major effect on slope instability (Rahardjo *et al*., 2001; Li *et al*., 2005; Lindenmaier *et al*., 2005; Rahardjo *et al*., 2008).

Numerical simulation of rainwater infiltration in slopes and hillslopes is needed for the analysis of slope failure induced by heavy rainfall. Numerical models have been used previously in many studies. Usually, two types of approaches are employed. The first produces a factor of safety against the slope failure for an unsaturated slope suffering from rainfall infiltration (Ng *et al*., 1998; Cho *et al*., 2001; Huat *et al*., 2006; Rahardjo *et al*., 2008). The second approach evaluates the permanent displacements induced by the rainfall in order to predict the slope failure and/or debris flow runoff (Angeli *et al*., 1998; Mukhlisin *et al*., 2006).

The objective of this paper is to evaluate the displacements induced on an infinite unsaturated slope due to steady infiltration. This paper focuses on using numerical methods to examine the mechanism of slope failures and slow-moving landslide within an unsaturated soil mass during rainfall infiltration. A typical process of rainfall infiltration is illustrated through a finite element analysis. Changes in wetting zones and distribution of pore pressures and stresses can be calculated by using the finite element method. Thus a 2D coupled finite element modelling with *GEFDyn* Code is carried out using an elastoplastic multi-mechanism model to represent the soil behaviour (Aubry *et al*., 1982; Hujeux, 1985).

In this paper, three assumptions have been made. (i) Evaporation was not taken into consideration. As the focus of this work is the changes in pore-water pressures during a rainfall event (i.e. evaporation can not occur) this is not a major limitation to the analyses presented below. (ii) It is assumed that the hysteresis of the soil water characteristic curve between the wetting and the drying phases can be neglected. (iii) The effects of capillary hardening as well as the concept of capillary stress proposed by (Kohgo *et al*., 1993; Abou-Bekr, 1995) among others are not included in the adopted stress framework.

2. Numerical model

Figure 1 shows the finite element mesh of the idealized infinite slope for the parametric study. The ground conditions at the site comprise a slope with three inclination angles, 27°, 31° and 33° at the bedrock. The slope consists of a residual soil with a 10m thick layer at downstream and at upstream. In order to simplify the problem it is assumed that the slope is composed of a homogenous and isotropic residual soil. The left and right edges are located at a distance of 20m and 10m from the toe and the crest respectively in order to avoid any influence of the boundary conditions on both the mechanical behaviour and the seepage process within the slope area. The two-dimensional finite element mesh used in the analysis, as a plane strain problem is composed of 1400 four-node quadrilateral continuum two-phase porous elements and 1565 nodes.

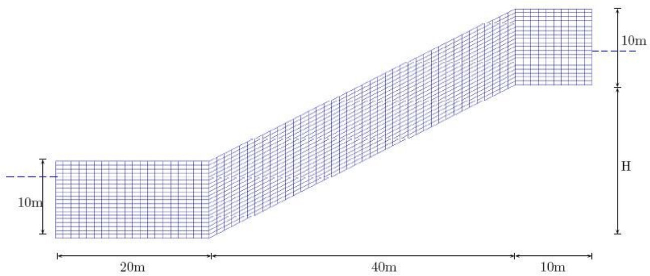


Figure 1. *Used finite element mesh in the numerical model*

The calculations are performed in two steps. In the first step, since soil behaviour is a function of the stress state for nonlinear elastoplastic models, initial in situ stress state due to gravity loads are computed. After this initialization, the displacements and deformations are initiated and the initial effective stresses, pore-water pressures and model internal variables are stored to be used as an initial state for the second computation step. In this latter, the infiltration load is applied as a prescribed nodal flux time history at the exposed sloping surface. The initial position of the ground water table at the middle of the slope (GWT40m) is 10m below the surface. A hydrostatic condition is imposed at initial time and the negative pore-water pressure generated is based on the initial depth of water table on the slope. In all computations the horizontal displacements on the lateral boundaries of the model are blocked and only vertical displacements are allowed. The nodes at the bottom of the model are fixed. Concerning the hydraulic conditions, in the initialization phase, all the nodes are pressure free. The bedrock is assumed to be impervious. The position of the ground water table as well as both the initial pore water pressure and saturation level is defined by a seepage analysis using seepage elements at the mesh border. These kinds of elements give a solution of transient flow through unsaturated porous media.

Concerning the infiltration levels, several rainfall intensities (*Ir*) from 36 to 180mm/h (i.e. from $1x10^{-5}$ to $1x10^{-4}$m/s) for 4h duration were used. These *Ir* are applied as a boundary flux at the exposed sloping surface. As a consequence, soil in the wetted zone remains partially saturated at any point of the slope. In the infiltration computation, it is assumed that ponding of water into the soil slope cannot occur.

2.1. *Elastoplastic model*

The ECP's elastoplastic multi-mechanism model (Aubry *et al*., 1982; Hujeux, 1985), commonly called as Hujeux model, is used to represent the soil behaviour. This model can take into account the soil behaviour in a large range of deformations. The model is written in terms of effective stress. The representation of all irreversible phenomena is made by four coupled elementary plastic mechanisms: three plane strain deviatoric plastic deformation mechanisms in three orthogonal planes and an isotropic one. The model uses a Coulomb type failure criterion and the critical state concept. The evolution of hardening is based on the plastic strain (deviatoric and volumetric strain for the deviatoric mechanisms and volumetric strain for the isotropic one). To take into account the cyclic behaviour a kinematical hardening based on the state variables at the last load reversal is used. The soil behaviour is decomposed into pseudo-elastic, hysteretic and mobilized domains. Refer to Aubry *et al*. (1982) and Hujeux (1985), among others, for further details about the ECP model. Concerning the unsaturated behaviour, the suction stress formulation is based within the context of Terzaghi's classical effective stress theory as modified for unsaturated soils by Bishop *et al*. (1963). Assuming that the air pressure *ua* can be neglected (Griffiths *et al*., 2005), the total stress tensor ($\underline{\sigma}$) is split in two components:

$$\underline{\underline{\sigma}} = \underline{\underline{\sigma}}' - \underline{\underline{\sigma}}_f \quad [1]$$

$$\underline{\underline{\sigma}}_f = S(p_{\text{int}}) \cdot p_{\text{int}} \cdot \underline{\underline{I}} \quad [2]$$

where ($\underline{\sigma}$') is the effective stress tensor, (p_{int}) is the pore-water pressure, $S(p_{int})$ is the degree of saturation and $\underline{I}$ is the identity second order tensor. No specific hardening mechanism is especially necessary to model phenomena such as the collapse encountered in unsaturated soil during imbibition. However, the behaviour is modelled by an adapted choice of the model parameters. Interested reader can find information on this specific hardening in literature on the enhanced Hujeux model (Abou-Bekr, 1995). In order to describe the soil water characteristic curve (SWCC), the governing equation implanted in the ECP model is that proposed by van Genuchten (1980):

$$S(p_{\text{int}}) = S_{res} + \frac{1 - S_{res}}{\left(1 + \left(\frac{\alpha_s \cdot p_{\text{int}}}{\rho_w \cdot g}\right)^{n_s}\right)^{ms}} \qquad [3]$$

where S_{res} is the residual saturation, p_{int} is the negative pore-water pressure and α_s, m_s and n_s are curve fitting parameters. The evolution of permeability k as a function of porosity (n) and degree of saturation (S) is given by:

$$k(S, n) = k_{sat}(n) \cdot k_r(S) \qquad [4]$$

$$k_r(S) = \left(\frac{S - S_{res}}{1 - S_{res}}\right)^3 \qquad [5]$$

$$k_{sat}(n) = k_{sat}(n_0) \cdot \frac{n^3}{n_0^3} \cdot \frac{(1 - n_0)^2}{(1 - n)^2} \qquad [6]$$

where $k_{sat}(n_0)$ is the saturated permeability at initial porosity (n_0).

2.2. *Soil properties*

The selected mechanical elastoplastic model parameters represent a residual soil behaviour. For the sake of convenience and brevity, only the friction angle of the soil (ϕ_{pp}) at the critical state is given in Table 1. Concerning the unsaturated behaviour, the soil parameters used to derive the soil-water characteristic curve are summarized in Table 1. The derived SWCC function is illustrated in Figure 2.

	SWCC				Critical State	Permeability
Soil type	α_s	S_{res}	m_s	n_s	ϕ_{pp} [°]	k_s [m/s]
S1	2.2	0.424	0.5	2	31	$1x10^{-3}$

Table 1. *Parameters of soil for parametric study*

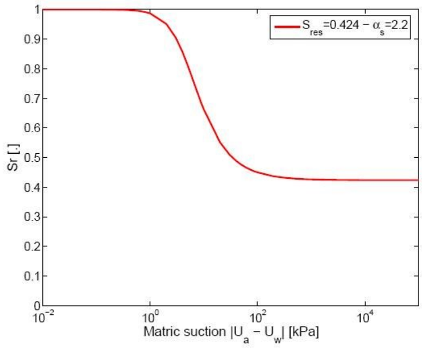


Figure 2. *Soil-water characteristic curve of soil used in study.*

3. Parametric study

In order to study the numerical simulation of the infiltration phenomena and to identify the role of several parameters a parametric study was performed. This parametric study concerns the rainfall intensity and the slope inclination. Other parameters such as the location of initial ground water table and the soil-water properties are not considered in this paper. They will be studied in further works. The effect of altering each of the parameters is highlighted below, through a series of steady-state and transient analyses where only one parameter is changed at a time to clearly evaluate the influence of each parameter. The results of the parametric studies are presented in this section with attention drawn to the effects of each factor on the displacement, the pore water pressure and saturation evolution on the slope.

Figure 3 shows the position of the wetting front at several times of infiltration into a cut profile at the middle of the slope (i.e. 40m). It can be noted that soil profile is not fully saturated within the wetted zone. Moreover, even if the slope surface is continuously supplied with water, the saturation degree is not 100% (i.e. $p_w \leq 0$). This behaviour agrees with the results given by Ng *et al*. (1998), Fourie *et al*. (1999), Springman et al. (2003) and Gavin *et al*. (2008) among others. In this computation the rainfall intensity is *Ir* = 180mm/h and the slope inclination (θ) is 31°. As far as it concerns the total displacements (u_t) induced in the slope by the rainfall (Figure 4), it is noted that after 4h of rainfall the maximum displacement is obtained near the surface. According to the performed computation this displacement is equal to 0.2cm at the middle of the slope. Furthermore, it may be seen that the displacement at the middle of the slope can be compared to the movement of the soil as a rigid block.

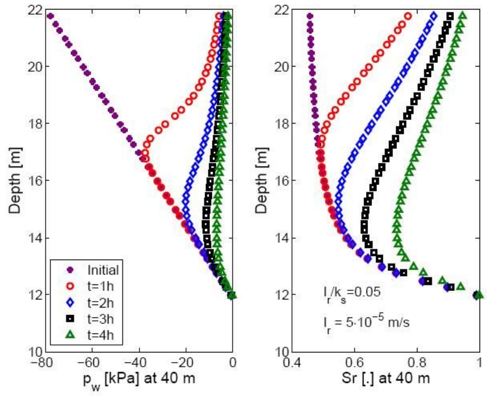


Figure 3. *Evolution of the pore-water pressure and the degree of saturation with time. Section profile at 40m.*

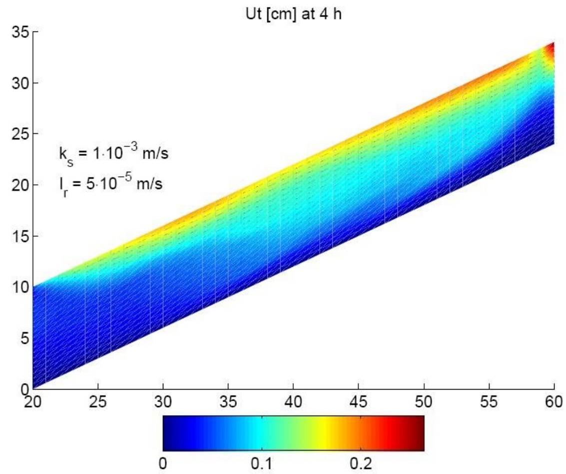


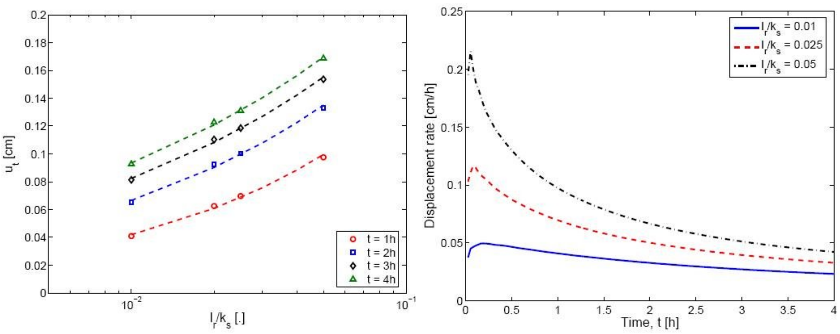
Figure 4. *Distribution of total displacement on the slope after 4h of rainfall.*

3.1. *Effect of rainfall intensity*

During rainfall, water infiltrates the soil from the surface and redistributes in the unsaturated zone. It leads to the development of perched water table or rise of the main groundwater level, resulting in an increase in pore water pressure and thus a reduction in soil matric suction (Ng *et al*., 1998; Gavin *et al*., 2008). In this section are presented the results with θ = 31° subjected to several rainfall intensities *Ir* According to figure 5a, for a given saturated permeability coefficient of the soil (k_s), the higher is the rainfall intensity *Ir* the higher is the displacement u_t. In order to explain the effects of the infiltration problems several authors propose to use the ratio *Ir/ks* or the relative rainfall intensity, which describes the ratio between the actual rainfall intensity and the permeability of the soil. A comparison of the variation of displacement rate with time (Figure 5b) indicates that in all cases, the rate increases fastest at the beginning of rainfall, then it reaches a peak value and finally it decreases regardless of the *Ir/ks* value. In addition, contrarily to the case with *Ir/ks* = 0.01, the obtained displacement rate for the case with *Ir/ks* = 0.05 decreases fastest after the peak.

3.2. *Effect of slope inclination*

Figure 6a gives the variation of total displacement (u_t) with the *Ir/ks* value after 4h of rainfall for the three slope inclinations (θ). As expected, for a given *Ir/ks*, where the lower the θ is, the lower the displacements on the slope will be. Furthermore, it is noted that for all Ir/ks values, the maximum displacement is obtained when θ is higher than the friction angle of the soil (ϕ_{pp}) (Figure 6b).



(a) (b)

Figure 5. *a) Effect of rainfall intensity (Ir) on slope displacements for several rainfall durations and b) Displacement rate at several Ir/ks ratios.*

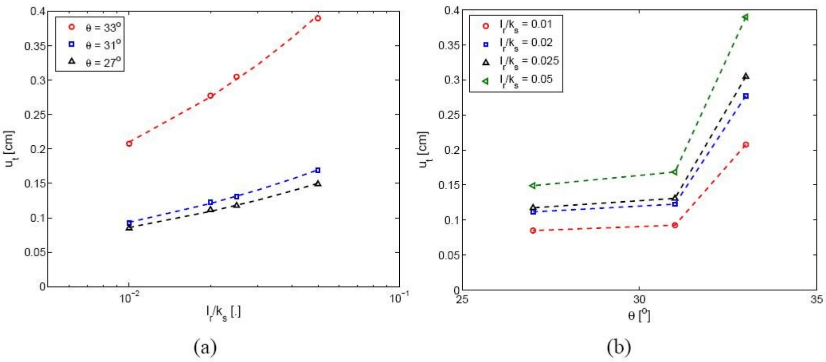


Figure 6. *a) Effect of rainfall intensity (Ir) on slope displacements at several rainfall durations and b) Displacement rate at several Ir/ks ratios.*

Finally, for the purpose of assessing the induced slope displacement taking into account simultaneously the geometrical and the hydrological conditions, a "yield surface" could be constructed (Figure 7). This surface provides for a given slope inclination, rainfall duration and soil type, the expected displacement due to a rainfall intensity level.

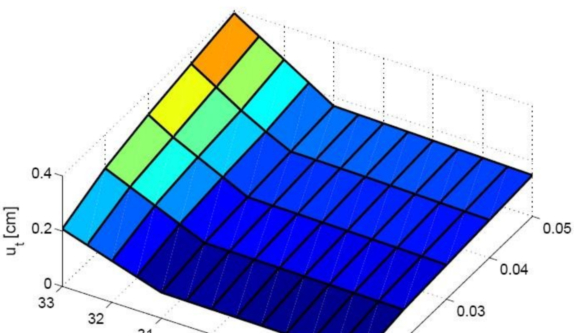


Figure 7. *Effect of slope inclinations (θ) and Ir/ks ratio on slope displacements.*

4. Conclusions

The main conclusions drawn from this study are as follows:

– According to the responses obtained with the model, it can be concluded that the ratio Ir/ks remains the most subtle parameter in order to define the slope displacement.

– A "yield surface" could be constructed, assessing for a given slope inclination, rainfall duration and soil type, the expected displacement due to a rainfall intensity level.

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