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Effects of anisotropy ofpreferential flow on the hydrology and stability of landslides

Elena Cristiano[a]*, Thom Bogaard[a], Stefano Barontini[b]

[a]*Delft University of Technology, Faculty of Civil Engineering and Geosciences, Water Management Department, Stevinweg 1, 2600 GA Delft, the Netherlands*
[b]*Università degli Studi di Brescia, Dipartimento di Ingegneria Civile, Architettura, Territorio e Ambiente, e di Matematica, Via Branze, 42, 25123 Brescia (BS), Italy*

Abstract

Infiltration is one of the most important landslides triggering mechanisms and it is controlled by the hydraulic characteristics of the soil, which depend on degree of saturation, existence of preferential flow paths and anisotropy. In order to account for preferential flow that can have place in macro-pores and fissures, it is common to represent the soil matrix by means of the superimposition of two different domains: a soil matrix domain, which mainly accounts for the flow in the porous matrix, and preferential flow domainrepresentingthe flow through macro-pores and fissures. There have been recentinvestigations on the influences of preferential flow on slope stability;however, the combined effects of anisotropy and preferential flow on infiltration processes and on rainfall induced landslide mechanisms havenot been studied yet, at our knowledge.Aiming at better understanding the effects that anisotropy combined with preferential flow has on the infiltration process, we investigated the stability of a hillslope using a numerical modelling approach. Results indicate that anisotropy affects the slope stability and its failure area.

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*Keywords:*Anisotropy, Hydraulic conductivity, Dual permwability model, slope stability

1. Introduction

Infiltration is recognized as one of the most important landslides triggering mechanisms. In fact, during the infiltration process a perched water table can onset and the positive pressure head reduces the effective stresses.

* Corresponding author. Tel.: +31 (0)15 2788578.
E-mail address: e.cristiano@tudelft.nl

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Both infiltration and soil water dynamics are strongly influenced by the profile of soil hydraulicconductivity[1,2]and by the anisotropy of the conductivity tensor.[3]Many soils,in nature, exhibit a certain degree of anisotropy due to stratification associated with sedimentation processes and consecutive soil forming process, such as illuviation and compaction. Recently, various authors investigated the effects of rainfall on layered soilsand on rainfall-triggered landslides, by means of experimental, theoretical, numerical and conceptual approaches,[4,5,6,7] but the combined influence of anisotropy and preferential flow on slope stability is still poorly investigated.

Shao and coauthors[7] studied the influence ofpreferential flow on slope stability using a numerical modelling approach. They showed that for a low intensity rainfall event, modelling a hillslope using a dual permeability model results in a smaller failure area compared to using the single permeability model. This is due to the fact that preferential flow facilitates the drainage of the hillslope. For great rainfall intensity, the preferential flow domain of the slope facilitated the infiltration and reduced significantly the stability. In that work the authors simulated low intensity and high intensity rainfall events, using a hypothetical hillslope modelled by means ofboth a single and a dual permeability model.

The aim of this research is to contribute to better understand the combined effects of anisotropy and preferential flow oninfiltration process and on landslide triggeringand failure size.In this work, we started from the approach proposed by Shao and coauthors[7]and on their presented numerical model.The paper is organized as follows: section (2) presents the theoretical background, focusing on the definition of anisotropy and on the interaction between soil water flow and slope stability; model, methodology and investigated scenarios are subsequently described in Section (3); section (4) presents the discussion of the results, considering both the hydrological results and the stability analysis.

2. Theory

2.1. Dual permeability model

A single permeability model consists in only one domain, made of soil, where the water can flow through it. A dual permeability model, instead, supposes that the soil is split into two overlapping flowing domains: a soil matrix domain (indicated by subscript *m*) and a preferential flow domain(indicated by subscript *f*), which represents the ensemble of preferential flow paths such as macro-pores and fractures in the soil.[8] The fractures and the matrix blocks have their own characteristic and properties (i.e. porosity, hydraulic conductivity function and soil water retention relationship), and water flow is allowed in both the domains.[7,9,10]These two domains co-exist in the same total volume V. The sum of the preferential flow domain and the soil matrix domain gives the total domain:

$$V_f + V_m = V \tag{1}$$

or in terms of ratios v between the partial and the total volumes:

$$v_f + v_m = 1. \tag{2}$$

This model does not need a pre-defined fracture network, but it considers only the fraction of fractures over the total volume V.

In the dual permeability model, the water flow is represented by two coupled Richards equations, one for each domain:

$$C_m(h_m)\frac{\partial h_m}{\partial t} = \nabla[\boldsymbol{K_m}(h_m)(\nabla h_m + 1)] + \frac{\Gamma_w}{v_m} \tag{3}$$

$$C_f(h_f)\frac{\partial h_f}{\partial t} = \nabla[\boldsymbol{K_f}(h_f)(\nabla h_f + 1)] - \frac{\Gamma_w}{v_f} \tag{4}$$

where C is the specific water capacity function,h is the tensiometerpressure head, t is the time, $\boldsymbol{K}$is the hydraulic conductivity tensor and Γ_w is the water exchange term. The tensiometerpressure potential is defined according to USS-ISSS[11]convention and accounting for all the interactions between the soil matrix, the water and the environmental pressure. The exchange of water between the matrix and the fracture pore systems is assumed to be proportional to thedifference between the tensiometerpressure head of the two systems.[8,12]

$$\Gamma_w = \alpha_w(h_f - h_m)K_a; \tag{5}$$

where α_w is the first order water transfer coefficient, and K_a is the apparent conductivity that is defined as:[7]

$$K_a = \frac{(K_m + K_f)}{2} \tag{6}$$

2.2. Anisotropy of the hydraulic conductivity

If a soil consists only of spherical grains, hydraulic conductivity at saturation K_{sat}would be the same in all directions and flow rates would be isotropic. However, in natural soils, sediments are commonly deposited in such a way that their hydraulic conductivity in one direction is greater than in the other direction. The stratification may results from the shape of the particles. Sedimentological and pedological processes and soil consolidation cause particles to be oriented with their longest direction parallel to the plane on which they settle. Later, this produces flow channels parallel to the bedding plane, thus making the medium anisotropic.[13]

The horizontal hydraulic conductivity at saturation $K_{sat,x}$ is assumed to be directly proportional to the vertical one $K_{sat,y}$, and this anisotropy factor r [−] is defined as the ratio between the vertical component and the horizontal one:

$$r = K_{sat,y}/K_{sat,x} \tag{7}$$

This is the simplest anisotropic hydraulic conductivity's conceptual model and it assumes that the anisotropic factor r is uniform and consistent and it does not depend on the soil saturation degree. Other conceptual models were proposed to describe the relationship between the anisotropy's factor and the saturation degree.[3]

On a slope it can be assumed that the preferential flow occurs along the bedding plane as well, thus with regards to the horizontal and vertical directions (x, y), the hydraulic conductivity at saturation is expressed by a tensor. The hydraulic conductivity can be written as:

$$\boldsymbol{K} = \boldsymbol{K_{sat}} k_r = \begin{bmatrix} K_{sat,xx} & K_{sat,xy} \\ K_{sat,yx} & K_{sat,yy} \end{bmatrix} k_r \tag{8}$$

where $k_r(h)$is the relative hydraulic conductivity.Due to the fact that the tensor is symmetric and with positive values it is always possible to identify two principal directions (x^*, y^*). The conductivity tensor can be rewritten as diagonal in the directions (x^*, y^*) and the hydraulic conductivity becomes:

$$\boldsymbol{K} = \boldsymbol{K_{sat}} k_r = \begin{bmatrix} 1 & 0 \\ 0 & r \end{bmatrix} K_{sat,x*} k_r \tag{9}$$

2.3. Slope stability

The slope stability analysis is developed using the local factor of safety F_{LFS}, which is determined at each point within a hillslope. To calculate the stress and displacement in the slope, a linear elasticity model, governed by the momentum balance equation is used:

$$\nabla \boldsymbol{\sigma} + \gamma(\theta)\boldsymbol{b} = \boldsymbol{0} \tag{10}$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{b}$ is the unit vector body stress and γ is the bulk unit weight, which is a function of the water content θ. Once solved the stress field $\boldsymbol{\sigma}$, in an unsaturated soil, the effective stress $\sigma'$is described by Bishop's equation:

$$\sigma' = (\sigma - \psi_a) + \chi(\psi_a - \psi_u) \tag{11}$$

where ψ_a is the air pressure potential, $\psi_u$is the water pressure potential and χ is the effective stress parameter.The difference$\psi_a - \psi_u$is the matrix suction, and it correspond to the opposite of the tensiometer pressure head h:

$$h = -(\psi_a - \psi_u).$$

The effective stress parameter χ is strongly dependent on the effective degree of pore water saturation $s(\theta)$:

$$\chi = \chi(s) \tag{12}$$

Different empirical formulations of this relationship are presented in the literature, but we will refer to the approach proposed by Lu and coauthors,[18]in which:

$$\chi(h) = s(h) \tag{13}$$

The local factor of safety F_{LFS} is defined, for a non-swelling soil, as the ratio between the potential Coulomb stress τ^* and the current state of Coulomb stress τ .[18]If the Mohr-Coulomb failure criterion is used, the local factor of safety results:

$$F_{LFS} = \frac{\tau^*}{\tau} = \frac{2\cos\varphi'}{\sigma_1' - \sigma_3'}\left[c' + \frac{\sigma_1' + \sigma_3'}{2}\tan\varphi'\right] \tag{14}$$

where the c' is the drained cohesion of the slope material, φ' is the drained friction angle of the slope material, and σ'_1 and σ'_3 are the first and the third effective stress for the variable saturated soil.[7,18]

2.4. Soil water flow and slope stability

The dual permeability model is a coupled system: the soil matrix domain and the preferential flow influence each other through the water exchange. Each domain is governed by its Richards equation, but it depends on the water exchange ratio Γ_w, which is a function of both domains.

However, there is not a real coupling between hydrological and mechanical approach and the slope stability is evaluated with a single domain approach by means of considering the body load:

$$\gamma(\theta) = \gamma_{dry} + [\theta_m v_m + \theta_f v_f]\gamma_w \quad (15)$$

where γ_{dry} is the dry unit weight, θ is the volumetric water contentand γ_w is the water unit weight.

In this equation, the unit weight γ_{dry}, which is a soil propriety of mechanical interest, is influenced by the volumetric water content of soil matrix domain θ_m and preferential flow domainθ_f, which arethe output of the hydrological model. The tensiometer pressure head of the preferential flow domain is used for the slope stability analysis, because the preferential flow domain seems to have a bigger impact on the slope stability.[4]The hydrological results are sequentially coupled with the soil mechanics model without considering the feedback of soil deformation on hydrological process. The stability analysis are conducted with a field theory approach in a Mohr-Coulomb framework.

3. Model and methodology

3.1. Model geometry and boundary conditions

The model set-up is described in detail by Shaoand coauthors.[14] Only a short summary will be presented here. For more details the reader is referred to the original paper. The analyzed slope is 6 meters high and 15 meters wide. It has two different layers: an upper layer, that consists of sandy loam, composed by 60% sand, 10% clay and 30% silt, and a lower layer, which is made up of clay. Sandy loam particles are larger than clay particles, andfor this reason, hydraulic conductivity is usually higher in sandy loam layer. The sandy loam layer's depth is 2 meters. Both layers present a constant thickness and are parallel to the ground surface. A large computational area was added in order to reduce the influence of boundary conditions on the hydrological and slope stability results. The total computational area is 57m wide and 33m high (Fig.1a). Preferential flow domain was chosen equal to 10% of the total volume, in both the layers. The hydrological and mechanical parameterizationof the model is given in Table 1.The geometry was modelled using COMSOL Multiphysics.

Table 1. Hydrological and mechanical parametrization. The soil-water constitutive laws for this numerical study were assumed to be in the Brooks and Corey[15] and Burdine[16] founds. $\theta_r$and$\theta_s$are the residual and saturated water content respectively , $h_b$is the bubbling pressure, λ is pore size distribution index *and* $K_{sat}$is the hydraulic conductivity at saturation.

Hydrological parameter	Sandy loam	Clay
θ_r(cm^3 cm^{-3})	0.041	0.09
θ_s(cm^3 cm^{-3})	0.41	0.39
h_b (m)	14.7	37
λ (-)	0.32	0.13
l (-)	1	1
$K_{sat,m}$ (cmd^{-1})	5.7024	570.24
$K_{sat,f}$ (cmd^{-1})	1.032	5.136

Mechanical parameter	Value
Young's Modulus (kPa)	10000
Poisson's ratio(-)	0.35
Friction angle (°)	35
Dry unit weight (kN m^{-3})	15.5
Drained cohesion clay (kPa)	6
Drained cohesion sandy loam (kPa)	3

In order to prepare a framework with steady initial conditions, we performed a long preliminary simulation at very small infiltration rate until the steady state was reached. Details are reported in Section 3.2.

To solve the Richards equations, hydraulic boundary conditions are applied on the soil matrix and preferential flow domain (Fig. 1b). On the upper boundary was applied a rainfall-infiltration condition, which involves switching between Neumann'sandDirichlet'sboundary conditions, depending on the solution at the soil surface.[17]The right boundary of the sandy loam layer is a seepage boundary condition, while the clay layer has a hydrostatic pressure head boundary condition. The pressure along the seepage is atmospheric and the ground surface above a seepage face is typically no flow or it is subjected to a specific evaporative or infiltration flux. No flow boundary condition is set on the left boundary of the domain and on the bottom of the clay layer. Over the all domain is set a mass source condition. This condition characterizes the dual permeability model, because it connects the two domains.

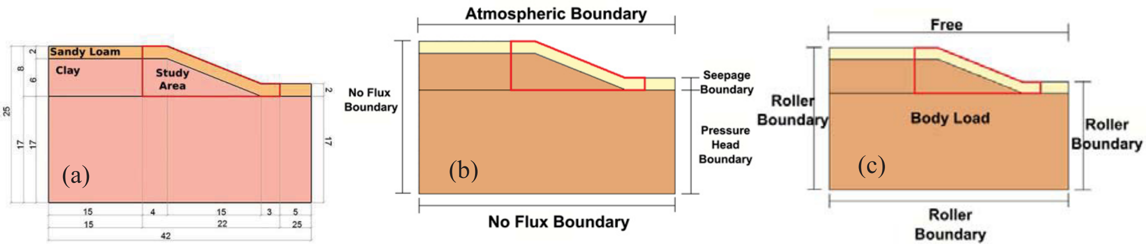

Fig. 1. Geometry of the model (a) and boundary condition for the hydrological (b) and slope stability (c) analysis

For the soil mechanic model, the following boundary condition are imposed (Fig. 1c). For sandy loam layer upper surface no restraint is set, thus the upper surface is free to move.Lateral boundaries are supposed to behave like a roller, which means that the displacement can only happen in the horizontal direction. Even the bottom of the clay layer behaves like a roller, but in this case the displacement can only happen in the vertical direction. This boundary condition is only a numerical condition, and it has no physical meaning. In fact, there is no displacement and the roller is set there only to simulate the horizontal and vertical force, due to the symmetry. The roller is set far from the study area, and it does not influence the slope. Over the whole domain, the body load condition is set. The horizontal component of the body load is null, while the vertical component is given by Eq. 15.

3.2. Step of the study

The numerical studyis divided into three steps:modelling the initial conditions, modelling the hydrological response of the slope to a rainfall event and consequently the slope stability analysis.

The first step isa "warming up period", which is neededto get the steady initial condition for the rainfall event study. To obtain this situation a daily average rainfall was applied for a long period before the rainy event, starting from a condition where the tensiometer pressure head*h* is equal to zero all over the domain. The average daily rainfall intensity applied for all the scenarios is equal to 1.8 mmd^{-1}, until the water storage becomes steady.During the second step a uniform rainfall event with low intensity and long duration (2mmh^{-1} for 150h) was applied to the model.At the end, the stability of the slope was analyzed. For this step,the time-varying soil moisture and tensiometer pressure headobtained during the rainfall event were used as an input.

3.3. Overview of study scenarios

In this work, one isotropic and two anisotropic scenarios wereinvestigated. Hydraulic conductivity at saturation for the soil matrix domain was maintained isotropic in all scenarios, while it was changed for the preferential flow domain, in both sandy loam and clay layers. In the basic or reference geometry, isotropic hydraulic conductivity at saturation(henceforth called ISO)was imposed. In this case, hydraulic conductivity at saturation is equal in both directions.

$$K_{sat,x} = K_{sat,y} = K_{sat} \tag{16}$$

In the first scenario (henceforth called ANI1) an anisotropic hydraulic conductivity of the preferential flow domain at saturation, with saturated hydraulic conductivity in the vertical direction five times smaller than the saturated hydraulic conductivity in the horizontal direction, is applied:

$$\boldsymbol{K_{sat}} = \begin{bmatrix} 1 & 0 \\ 0 & 0.2 \end{bmatrix} K_{sat,x} \quad (17)$$

The second scenario (henceforth called ANI2) considers the effects of an anisotropic hydraulic conductivity of the preferential flow domain at saturation, with horizontal saturated hydraulic conductivity five times smaller than the vertical one.

$$\boldsymbol{K_{sat}} = \begin{bmatrix} 0.2 & 0 \\ 0 & 1 \end{bmatrix} K_{sat,y} \quad (18)$$

For the interpretation of the hydrological results,the distribution of the soil water content θ and the tensiometer pressure head$h$ were considered. Total water storage and water exchange between soil matrix domain and preferential flow domain are presented and analyzed. The total water storage W_S[L^2] is defined as the integration over the whole study area $A$of the water content:

$$W_S = \int_A \theta dA \quad (19)$$

4. Results and discussion

4.1. Hydrological results

In this section the main results of the simulations of the uniform rainfall event with low intensity (2 mm h^{-1}) and long duration (150 h)are presented and discussed. In Fig.2 water content θ distribution of the three scenarios is plotted. It is worth noting that the field of water content θ is not the same after the preliminary simulation, as consequence of the different conductivity scenarios.

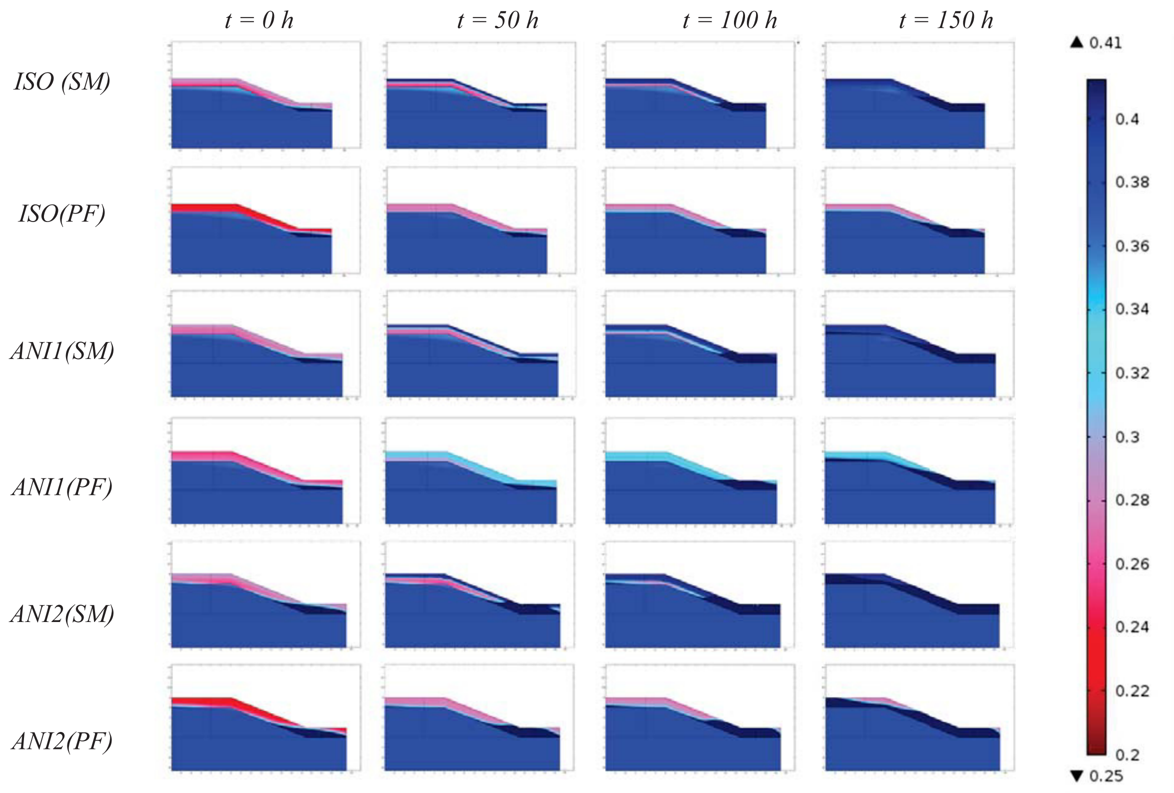

Fig. 2 Water content (θ) distribution in the of preferential flow domain (PF) and soil matrix domain (SM) for the three scenarios analyzed. It varies from 0.2 (dark red) and 0.45 (dark blue).

Particularly, in ANI2 the level of the water table is greater. This behavior can be related with the fact that $K_{sat,x}$ is in this scenario smaller than in the other two cases, due to the anisotropy. Soil water content θ increases in all the scenarios, but the soil does not reach full saturation during the rainfall event studied. In the soil matrix domainthe water content is greater than in the preferential flow domain. In the preferential flow domain the water table rises and tends towards the sandy loam surface, while in the soil matrix domain the water content increases starting from the free surfaces. At the end of the rainfall event, the water content in the soil matrix domain is greaterin ANI2 than in ANI1 and ISO. In the preferential flow domain, anisotropy in both directions largely influences the water content, that is generally greater, especially in the anisotropic ANI2 scenario.Fig. 3showsdistribution of the tensiometer pressure head during the rainfall event.The groundwater table, represented by the blue line, is generally higher in the anisotropic scenario ANI2, and the hillslope reaches full saturation at the beginning of the rainfall event. This means that the seepage flow is greater in this condition and it plays an important role in the water balance.In Fig.4the total water storage during the rainfall event is plotted for both domains. Water storage in preferential flow is smaller than in soil matrix domain, and it is generally less for the isotropicscenario than for the anisotropic scenario ANI1, which is smaller than in ANI2. In the soil matrix domain water storage increases in similar ways in all three scenarios, and it seems to reach stationarity at the end of the rainfall event. Conversely, in preferential flow domain, water storage increases with different timing in the different scenarios.

Fig. 5and Fig. 6 showthe distribution over the hillslope and the magnitude of water exchange between soil matrix and preferential flow domains. Negative values represent flow from the soil matrix domain to the preferential flow domain, while positive values characterize flow from preferential flow domain to soil matrix. Looking in detail to the sandy loam top layer, a clear vertical distribution exists in direction of water exchange. In all three scenarios, water flows from the soil matrix domain to the preferential flow domain at the soil-atmosphere interface (light blue color). On the contrary, water flows from the preferential flow domain to the soil matrix domain at the interface of the top sandy loam and clay layer (red color). At the soil-atmosphere interface water pressure is raising in the soil matrix during the rain infiltration, whereas after some time at the bottom of the sandy loam layer water pressure is raising in the preferential flow domain (as also visible in Fig. 2).The results also show a temporal evolution of the water exchange (Fig.6). Water exchange from the soil matrix domain to the preferential flow domain, is larger at the end ($t= 150$ h) of the rainfall event than half way ($t= 75$ h). The total water exchange in ISO and ANI1 is always less than zero, meaning that water flows from the soil matrix domain to the preferential flow domain. Contrarily, in ANI2, water flows more to the preferential flow domain between $t = 35h$ and $t = 115h$, which is located in the perched water table at the bottom of the sandy loam layer (Fig.5).Hereafter, the preferential flow domain is exchanging water to the matrix domain at the top of the perched water table in the surface layer (see Fig.3 for water table and dark blue in Fig.5).

4.2. Stability analysis

The local factor of safety F_{LFS} (defined by Eq.14) was used in this work to analyze the stability of the slope and its development, from the initial condition to the end of the rainfall event, is shown in Fig.7 for the three scenarios.

At the start of the simulation the shape of the failure is already identifiable, but it is very small and it increases in all the scenarios during the rainfall event. The failure zones in ISO and in ANI1 are very similar, as is to be expected as the hydrological behavior was similar in these two scenarios (Fig. 2 and Fig. 3). In ANI2 the failure area is somewhat bigger, especially in the toe area, where water content (Fig. 2) is bigger and where the groundwater table is very close to the surface of the slope (Fig. 3). After 75 h of low intensity rainfall, the local factor of safety decreases in all the scenarios.In ISO the failure area increases at the toe of the slope, where water content is greater. In ANI1 the failure area increases less than in the others scenarios. In ANI2 it increases especially in the toe area. At the end of the rainfall ($t= 150$ h), in the ISO and ANI1 scenario, the increase of the failure area sets off especially from the toe of the slope, while in ANI2 it is located in the middle of the slope.

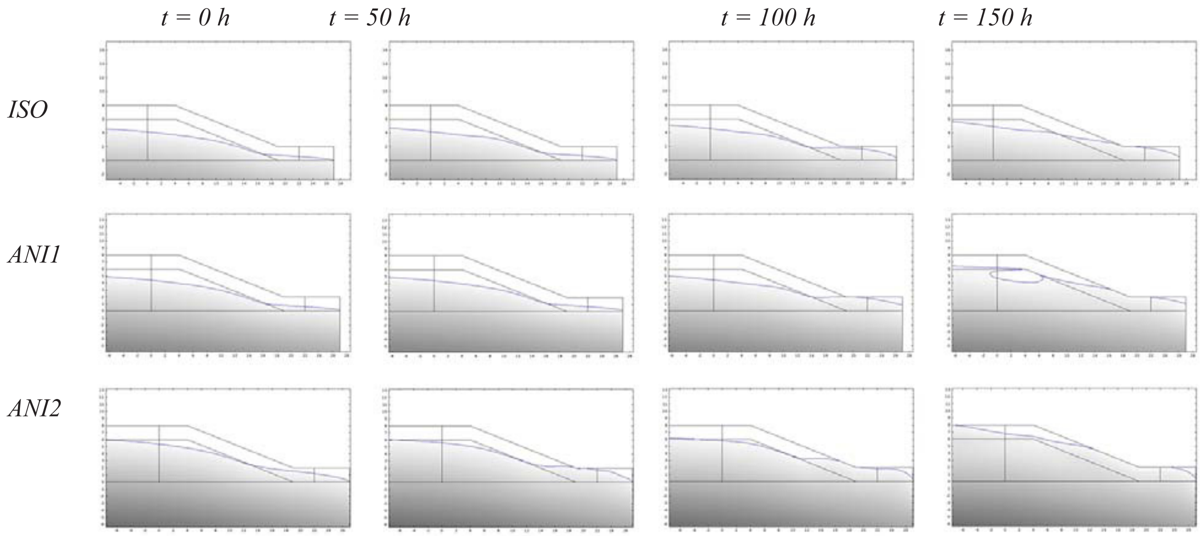

Fig.3 The tensiometer pressure head(h) distribution for the three scenarios analyzed. It varies between *-0.5m* (white) and *21m* (black), and the blue line represents $h = 0m$.

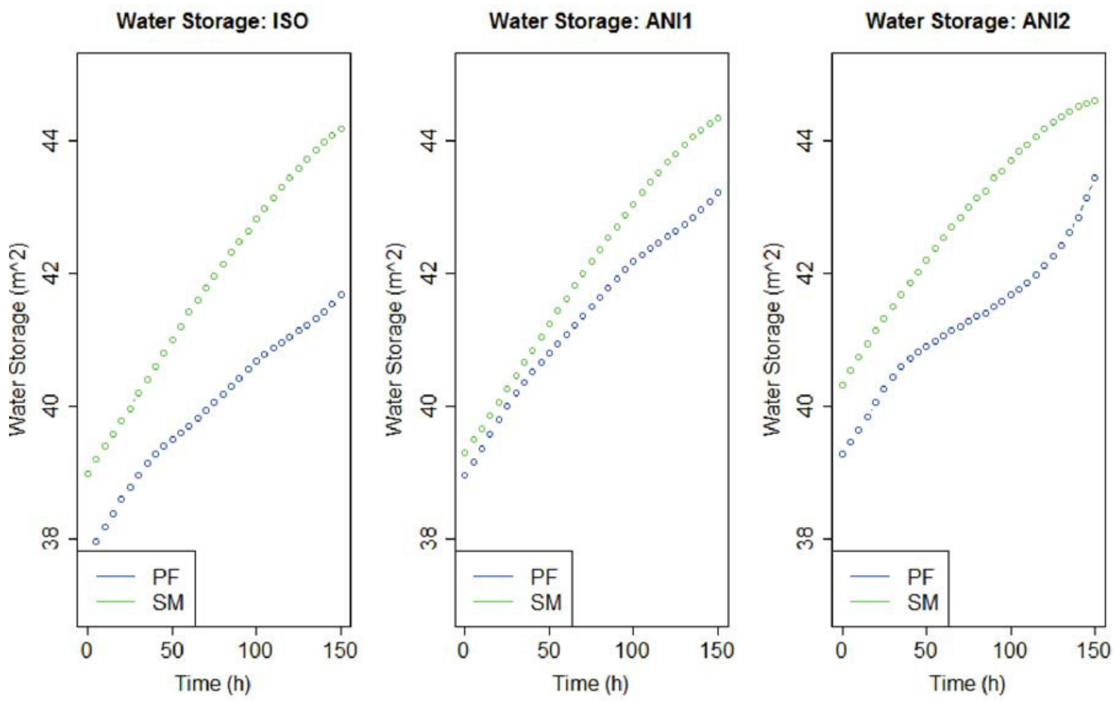

Fig. 4 Water storage (m^2) of preferential flow domain (PF) and soil matrix domain, for the three scenarios analyzed.

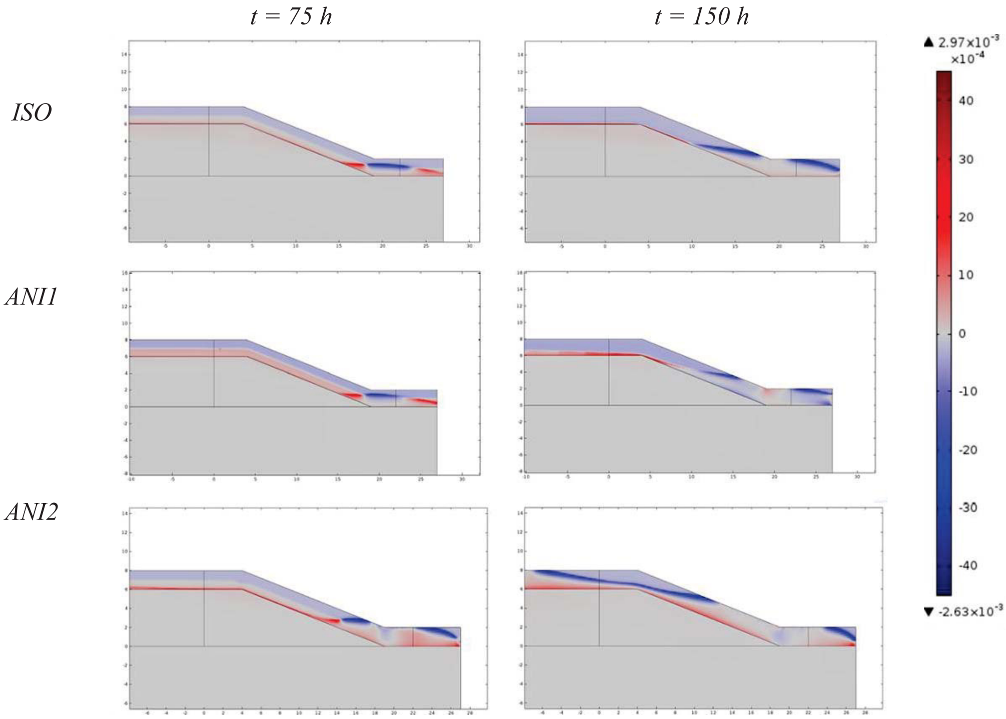

Fig. 5 Water exchangedistribution:from preferential flow domain (red) and from soil matrix domain (blue), for the three scenarios analyzed.

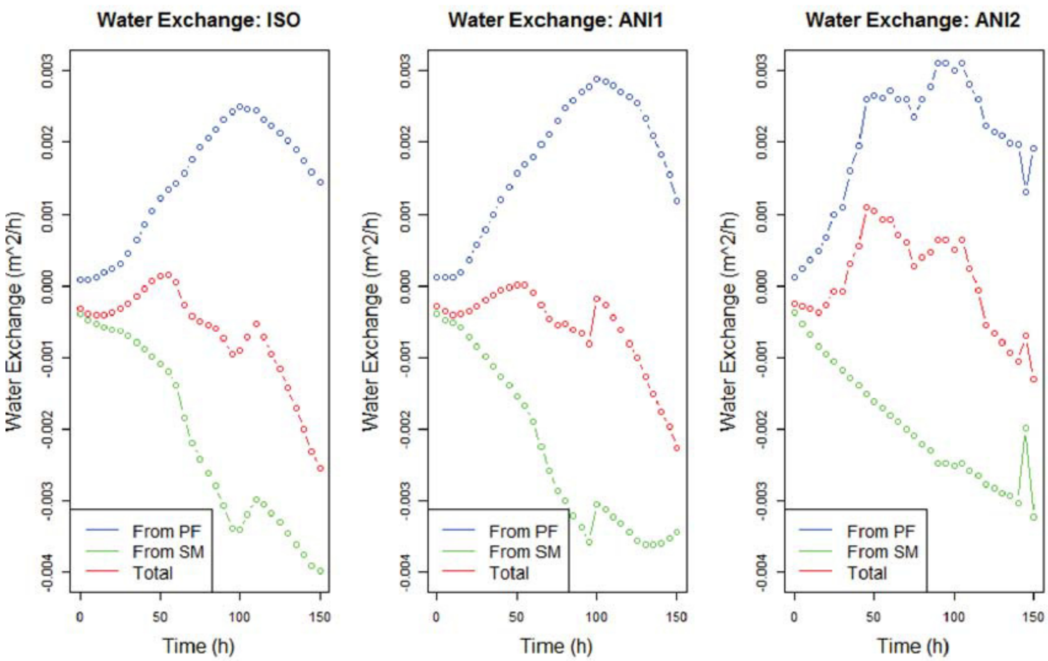

Fig.6 Water exchange ($m^2 h^{-1}$) from the preferential flow domain (PF), from the soil matrix domain (SM) and total, for the three scenarios analyzed.

The results show that the failure area is influenced by the anisotropy in the preferential flow domain and, compared to the isotropic scenario a hydraulic conductivity at saturation in the slope parallel direction can increase the slope stability, which is reduced in the case of bigger vertical hydraulic conductivity at saturation. When the anisotropy is greater in the horizontal direction (ANI1), the failure area is smaller, while it is larger in the case when the hydraulic conductivity at saturation is greater in the vertical direction (ANI2).

Below the groundwater table the LFS is not represented because it spontaneously decreases at increasing depth, thus leading to assess potential instabilities which are not realistic for the investigated geometry.[14,18]

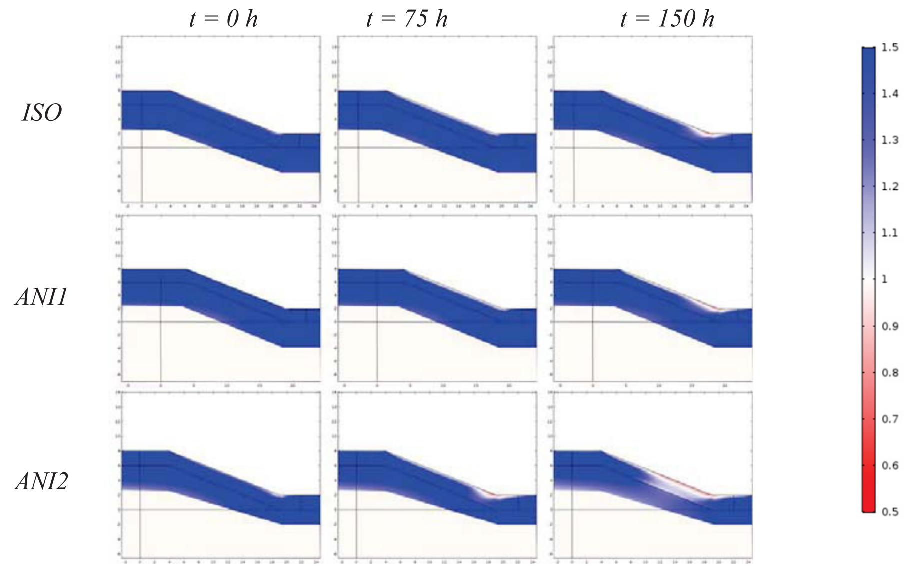

Fig.7Local safety factor (F_{LFS}) distribution, for the three scenarios analyzed. It varies from 0.5 (red) and 1.5 (blue).

5. **Summary and conclusions**

This work presents an analysis of the influence of anisotropy of the preferential flow domain within a dual permeability model,on hillslope hydrology and slope stability. In this synthetic study, a low intensity, long duration rainfall event was applied on a hillslope conceptualized with a dual permeability soil.We presented two different scenarios with anisotropic hydraulic conductivity at saturation in order to investigate how the anisotropy in the preferential flow domain influences landslides triggering, location and size. The first scenario was a reduction of the vertical (slope transverse) permeabilitycompared to the isotropic reference model to get an anisotropic hydraulic conductivity tensor of a factor 5. In the second case the horizontal (slope lateral) component of the hydraulic conductivity was reduced by a factor of 5.

Hydrological results show that the anisotropy in the preferential flow domain influences the hydrologicalbehavior andthe tensiometer pressure head distribution and, consequently it affects the slope stability. Water content and tensiometer pressure head generally increase more in the anisotropic scenarios than in the isotropic scenario. The water exchange between the preferential flow and the soil matrix domain shows that when the hydraulic conductivity at saturation is isotropic or greater in the horizontal direction the water mainly flows from the soil matrix domain to the preferential flow domain, while when the hydraulic conductivity is greater in the vertical direction the water moves from the preferential flow domain to the soil matrix. The water exchange between the preferential flow and the soil matrix domain shows that when the hydraulic conductivity as saturation is isotropic or bigger in the horizontal direction the water mainly flows from the soil matrix domain to the preferential flow domain, while when the anisotropy is greater in the vertical direction the water moves from the preferential flow domain to the soil matrix. Both water content and tensiometer pressure head increase in the hillslope due to the anisotropy, combined with the water exchange between the two domains,strongly influences the slope stability, which in this analysis resulted in a larger failure area in the case where the hydraulic conductivity at saturation is bigger in the vertical direction, compared to the isotropic scenario. In the case where the horizontal component of the hydraulic conductivity at saturation is greater,the failure area is slightly reduced, and the anisotropy in the preferential flowdomain ends to stabilize the slope.

In the scenario with bigger vertical than horizontal conductivity in the preferential flow domain, the patterns of the water content suggest the possibility of the onset of a perched water table. This phenomenon might be caused by the fast water infiltration in the preferential domain and by the water exchange from this domain into the soil matrix.

Therefore, this research aims at contributing to show that the influence of anisotropy in dual permeability soils can be significant and should be considered when analyzing hillslopes for slope stability.

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