SOIL-ATMOSPHERE INTERACTIONS. COMPREHENSIVE MODELLING AND PRACTICAL RULES

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The paper presents a framework to model the response of slopes under climatic actions, based on the consideration of a non-linear, time variable boundary condition which retrieves the different thermo-hydraulic fluxes crossing soil-atmosphere interface. Model is validated on several cases of slopes in soils and rocks and hints provided for an effective use of the model.

Keywords: Climatic action, Natural slope, Numerical modelling, Finite Elements, Field cases

INTRODUCTION

The interactions between the ground and the atmosphere play a central role in the analysis of natural risks associated to slope movements. As pointed by Leroueil (2002), slopes respond often to changes in pore pressure whose relationship to rainfall is complex. It depends, on the one hand, on material properties such as permeability and consolidation coefficients and, on the other hand, on the interactions with atmosphere, including infiltration, runoff, evaporation and evapotranspiration. Vegetation plays often a non-negligible role by intercepting part of the rainfall, limiting the runoff, releasing back vapour to the atmosphere and providing the soil with root reinforcement, when not creating settlements or increasing soil permeability by desiccation. Details in stratigraphy and three-dimensional slope geometry are moreover important factors that determine zones of run-off concentration and preferential infiltration.

The objective of the paper is to present a modelling framework suitable to be implemented in numerical tools for geotechnical analysis and aiming at simulating the effect of climate on slopes. After a brief description of the physical processes acting at the interface between ground and atmosphere and of the equations used to model them, emphasis is put on the practical use of this kind of models through the analysis of several real cases.

PHYSICAL PROCESSES AND MODELLING FRAMEWORK

The processes controlling atmosphere conditions include solar radiation, heat and moist exchange (controlling clouds and precipitation), air mass motion as well as their interactions with earth surface, including outcropping soils and rocks, free water surfaces and vegetation canopies. All these processes are coupled and form complex, turbulent and instable systems whose modelling is far beyond the scope of the geomechanical modelling of slope response under climatic actions. A suitable alternative consists in representing the effect of the atmosphere by a special boundary condition prescribed at soil surface. This condition retrieves all the fluxes crossing the surface (solar short wave and long wave radiation, sensible heat, water infiltration, evaporation) and the state of the atmosphere above the ground (temperature, relative humidity and air pressure) (Blight, 1997). In the same spirit, vegetation effect can be simplified into nonlinear sink terms of water mass applied in the root zone (Noilhan & Mahfouf, 1996).

The atmosphere/vegetation boundary condition defined in that way must be consistent with the continuum formulation considered to model the underlying ground. Particularly, all the fluxes crossing the boundary must be balanced by ground internal fluxes of the same nature (see Tab. 1). Their modelling in deformation problems like slope analysis requires the consideration of fully coupled thermo-hydro-mechanical models. The THM formulation used is based on the work by Olivella et al. (1996) and includes the solution of the mass balance of water and air, the energy balance and the stress equilibrium, supplemented by constitutive laws and restrictions. Thermo-hydraulic laws are summarized in Tab. 2 in case in which local thermal equilibrium is considered between air, water and solid phase. They are completed by the stress-strain-temperature-suction law of the soil matrix.

Tab. 1 Soil-atmosphere fluxes and their counterpart within the ground.

Fluxes at ground-atmosphere interface	**Fluxes within the ground**
Infiltration and ponding	Liquid water filtration (Darcy’s law)
Sensible heat	Heat conduction (Fourier’s law)
Evaporation	Vapour diffusion (Fick’s law)
Heat convected by liquid and gas fluxes	Heat convection by liquid and gas fluxes
Vapour convection by gas flow	Vapour convection by gas flow

Tab. 2 Constitutive laws and restrictions used in thermo-hydro-mechanical models.

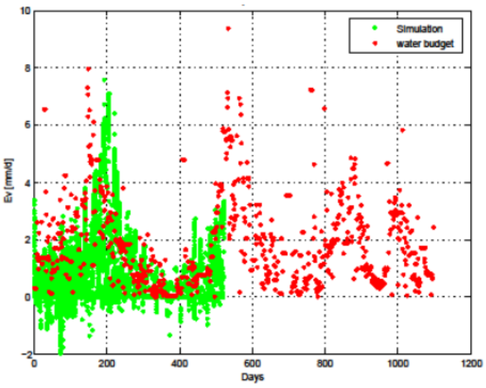
Terms	**Hydraulic laws and restrictions**	**Thermal laws and restrictions**
Storage term	Soil-water retention curve	Heat capacity for water, air and solid phase
	State equations of liquid water and vapour	State equation for solid phase
	Psychrometric law	Latent heat for water vaporization
Flow term	Darcy’s law	Fourier’s law
	Variation of hydraulic conductivity with degree of saturation, temperature and porosity	Variation of thermal conductivity with degree of saturation, temperature and porosity

The numerical analysis of slope response under climatic action would thus ideally require solving thermo-hydro-mechanical boundary value problems where a time-variable atmospheric condition is applied at ground-atmosphere interface. Variation period must be generally small in order to include daily atmospheric variations and short events rainfall. On the other hand, the need for a realistic representation of infiltration and run-off would often induce to consider three-dimensional geometry. These aspects generally lead to models requiring large computational resources and the identification of a significant number of parameters. In this context, model validation and reduction are essential issues for the effective use of numerical models in the study of soil and rock slopes under climatic actions.

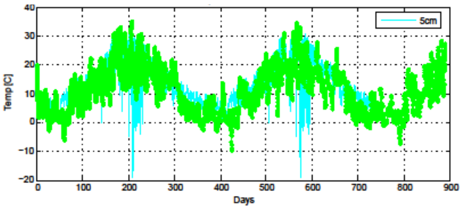
MODEL VALIDATION

The strategy used to model soil-atmosphere interactions has been validated by benchmarking numerical results with measurements obtained in several experimental fields. The case reported here corresponds to an experimental field located at “Le Fauga”, France (Calvet et al., 2007). It is a flat ground composed by quaternary deposits of gravels relying on a substratum of yellow marl and topped with 0.5 m thick layer of silt. Precipitation, atmospheric pressure, incoming solar (short wave) and atmospheric (long wave) radiation, air temperature, relative humidity, wind speed and direction were monitored on a half-hour basis. Sensible and latent heat have been also estimated using both the eddy-covariant and the aerodymanic methods. Vegetation parameters (height, biomass, dry matter, water content and Leaf Area Index) were measured weekly on samples of size 25 x 25 cm2 randomly taken in the fallow area. Soil moisture and temperature profiles are automatically measured each 30 minutes by impedance sensors installed at depths: 5, 10, 20, 30, 50, 60, 70, 80 and 90 cm.

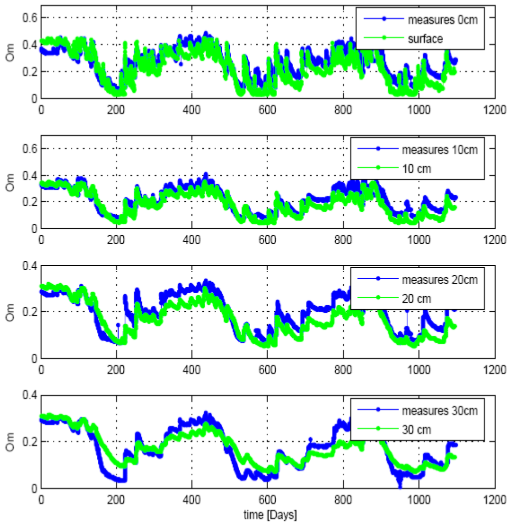
Fig. 1 shows the comparison between computed values and measurements for several variables: surface evapotranspiration flux, temperature below the surface and volumetric water contents at different depths. They evidence on the one hand an acceptable representativeness and accuracy of the model. On the other hand, they highlight typical patterns of water content variations in soils. At ground surface, fluctuations respond both to daily and seasonal atmospheric actions. In depth, the amplitude of variations decreases progressively and the daily signature gradually borrowed. This response is consistent with the diffusive character of the water mass balance equation and provides hints to reduce computational costs by removing part of the frequency spectrum of meteorological records according to the depth at which pore pressure variations are relevant for the mechanical problem.



a) Surface evapotranspiration



b) Temperature at 5 cm depth



c) Water content at 0, 10, 20 and 30 cm

Fig. 1 Comparison between numerical results and measurements at “Le Fauga” experimental field.

APPLICATION TO SLOPES

Model has been applied to different cases of slopes in slope and rocks. A first case corresponds to a rock fall what occurred in a calcareous cliff above the village of La Roque Gageac, France (see Fig. 2.a). To estimate the risk of a larger failure, several extensometers have been installed to monitor displacements (and temperatures) in the massif. Numerical model evidences the strong relationship existing between strain and temperature variations in the massif, in turn controlled by atmosphere temperature and incoming solar radiation, which allows defining scenarios of rock falls. Sensitivity analysis highlights moreover the robustness of the model against parameters controlling soil-atmosphere heat exchanges.

Two other cases (Fig. 2) refer to shallow landslides in essentially granular materials (Cervinara, Italy; Damiano et al., 2017; and Senet, Spain; Oorthuis et al, this issue). In both cases, failure is clearly related to suction and pore pressure values, whose variations are strongly controlled by the retention curve of the materials and the presence of preferential water paths at some depths. Monitoring should thus ideally include measurements of both water contents and suctions at close points in depth, in order to correctly identify the retention curve in the field. Numerical model appears to exhibit a good predictability of hydraulic changes in the slope, provided that the ratio between run-off and infiltration is well-estimated. In order to capture it, a special layer has been introduced in the model on top of the ground surface. Discussion on the estimation of the initial state in the slope is also reported.

a) Rock fall at La Roque Gageac, France

b) Debris flows and floods at Senet, Spain

Fig. 2 Two cases of slope failure induced by atmospheric actions and modelled within the present framework

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