Journal of Hydrology 510 (2014) 480–492

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Investigation of soil–atmosphere interaction in pyroclastic soils

Guido Rianna [a], Luca Pagano [b,*], Gianfranco Urciuoli [b]

[a] *Centro Euromediterraneo sui Cambiamenti Climatici (CMCC), Divisione Impatti al suolo e sulle coste (ISC), via Maiorise, Capua, Italy*
[b] *Dipartimento di Ingegneria Civile, Edile e Ambientale (DICEA), Università di Napoli Federico II, via Claudio 21, Napoli, Italy*

ARTICLE INFO

Article history:
Received 26 July 2013
Received in revised form 19 December 2013
Accepted 24 December 2013
Available online 9 January 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Fritz Stauffer, Associate Editor

Keywords:
Soil–atmosphere interaction
Soil suction
Unsaturated soils
Lysimeter
Pyroclastic soil
Evaporation

SUMMARY

This paper investigates the interaction between soil and atmosphere in pyroclastic soils with a view to understanding whether and to what extent the prediction of the hydraulic (and mechanical) behaviour of geotechnical problems (cuts, slope stabilities, embankments, foundation, retaining structures) regulated by rainfall-induced fluctuations of matric suction is influenced by evaporation phenomena. Evaporation fluxes are quantified and compared with other fluxes (precipitation, run-off, deep drainage) affecting soil water content and matric suction. This work is based on the data collected through a physical model over 2 years of experimental tests. The model consisted of a 1 m^3 tank, filled in this case with pyroclastic soil and exposed to natural weather elements. The system was extensively monitored to record atmospheric and soil variables. The results provided by the experiments highlight the importance of the top-soil state in determining the intensities of infiltrating rainfall and actual evaporation. The results also bring to light the significance of evaporation which, during the dry season, largely prevails over infiltration, raising suction to very high values. Also during the wet season, evaporation gives rise to a non-negligible flux with respect to the infiltrated precipitation. The reliability of two pre-existing empirical models to estimate evaporation flux is also investigated and appraised within this paper.

1. Introduction

Infiltration and evapotranspiration flows across the ground surface are different aspects of soil–atmosphere interaction and are responsible for matric suction (referred to as "suction" throughout the paper) within the vadose zone. Due to the dependency of soil mechanical and hydraulic properties of unsaturated soils upon suction, the behaviour of geotechnical systems interacting with shallow soil layers is strongly affected by soil–atmosphere interaction. This is the case of cuts, slopes (e.g. Toll et al., 2011; Sorbino and Nicotera, 2013; Cascini et al., in press), retaining walls (Aversa et al., 2013) and shallow foundations (Russo, 2004). Earthworks may also experience considerable influence from climate conditions, especially if the boundary surface exposed to weather elements is significant with respect to the fill volume (e.g. Calabresi et al., 2013).

In the above applications soil suction distribution and its evolution are usually obtained through the solution of a boundary value problem. Suction computations are required, in principle, not only for cases in which suction is fully unknown (in the absence of a suction monitoring system), but also for cases supported by suction measurements, when extrapolation of a continuous distribution from suction measurements is required. In all these cases, hydraulic boundary conditions at ground level should be accurately defined, accounting for all influencing factors (e.g. Blight, 1997; Rahardjo et al., 2013).

Soil–atmosphere interaction is too often converted into excessively simplified boundary conditions which do not consider evapotranspiration. Indeed, it is widely held that evaporation flow is much smaller than rainfall infiltration, especially in winter, the period most affected by failures and instabilities of geotechnical systems. This assumption completely neglects, however, the possible effects relating to evapotranspiration persistency, that may result over long periods in significant amounts of cumulative water loss from the soil. Over recent years this increasing awareness about the importance of evapotranspiration has led researchers to investigate factors affecting evapotranspiration and establish approaches suitable for quantification in geotechnical contexts.

Recent contributions in the geotechnical literature have dealt with the interaction of silty sands (e.g., Cui et al., 2005; Cui and Zornberg, 2008; Pirone et al., 2012; Papa et al., 2013) and clays (e.g. Cui and Zornberg, 2008; Ridley, 2012; Smethurst et al., 2012) with the atmosphere. Studies involving clay soils have often concerned the additional application field of waste covers, which require upward flows generated by evaporation to tackle deep infiltration of contaminants (e.g. Cui and Zornberg, 2008; Blight, 2009).

---

* Corresponding author. Tel.: +39 0817683478.
E-mail addresses: guido.rianna@cmcc.it (G. Rianna), lupagano@unina.it (L. Pagano), gianurci@unina.it (G. Urciuoli).

0022-1694/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.12.042

In this context the present work investigates the soil–atmosphere interaction for non-plastic silty pyroclastic soils. Depending on weather conditions, suction in these soils typically ranges from 100 kPa and more during the dry season to 5–30 kPa during the wet season (Pirone et al., 2012; Papa et al., 2013). Exceptionally, suction may drop to nearly null levels (saturated conditions) causing (Aversa et al., 2013) settlements in shallow foundations, instabilities in retaining walls whose stable condition is based on thrust reduced by suction, or instabilities in natural slopes often turning into rapid flow-like landslides (Cascini and Sorbino, 2004; Pagano et al., 2008, 2010; Greco et al., 2010; Damiano et al., 2012).

The paper investigates the issue in one-dimensional conditions, interpreting the experimental data provided by a physical model, testing a silty layer subject to weather elements, completely neglecting transpiration, which is in any case traditionally derived from evaporation flows. The tested soil was placed at a porosity typical of pyroclastic soils covering steep slopes in Campania (Italy), often involved in rainfall-induced landslides and at times forming deposits on lowlands. The results illustrated herein, in terms of evaporation and infiltration flows, are hence particularly suitable to support overall slope stability analyses and to interpret landslides caused by rainfall infiltration. That said, the results may also be qualitatively used in the other geotechnical fields listed above.

The paper initially illustrates the geographical, geological and hydrological context involved. The physical model and all procedures adopted to interpret monitoring data are then described. Measurements collected over 2 years of monitoring are subsequently illustrated. Estimations of water exchanges between soil and atmosphere obtained from theoretical interpretation of monitoring data are finally presented and discussed.

2. Geographical, geological and hydrological context

Pyroclastic soils mantle a large part of the Campania region (e.g., Pagano et al., 2010). They consist mostly of volcanic ash and pumice produced in the last 10,000 years by different volcanic centres (Roccamonfina, Phlegraean Fields and Somma-Vesuvius). Air-fall deposits have also formed at large distances from the eruptive centres, with alternating layers of pumice (gravelly sands) and ash (silty sands).

The finest component of ash soils (silt with some clay) is generally non-plastic due to the absence of active minerals. The grain size of air-fall ashes is very uniform throughout the areas since it has the same geological origin (air-fall deposition); their porosity can be as high as 70% with peaks attaining 80%. A large amount of rainwater is generally trapped within the material in the form of water menisci, due to large void volumes consisting of small pores resulting from the silty fraction. Due to the unstable structure of the soil skeleton at high porosities, soil volumetric collapse upon wetting is possible, as shown by tests conducted by physical models of slopes (e.g., Pagano et al., 2008). On steep slopes, most volcanic outcropping ashes are undisturbed and maintain the original structure due to air-fall deposition, for which they are affected by the described properties. At the foot of the slopes, alluvial soils often outcrop (originating from the ash cover deposited on the slopes, eroded and transported downslope by run-off), with properties differing greatly from the original ones. In other zones, undisturbed ashes outcrop, with greater thickness than those remaining on the slopes. In general, these soils are cohesionless, exhibiting an effective friction angle ranging between 35° and 39° and ductile behaviour.

In situ, slopes consisting of non-altered silty pyroclastic covers may reach angles up to 60°, with thickness decreasing as the slope angle increases, up to a few decimetres for the steepest slopes. Such high angles of natural and artificial fronts are possible due to the high shear strength of the material induced by suction. Silty pyroclastic layers may lie over pumices, clay layers or calcareous bedrocks which are very often intensely fractured.

As regards landslide triggering, suction drops have been found to be induced by significant rainfall, when a main event, consisting of 80 mm of water heights over a day at least, merges with a prior prolonged wet period, with cumulative rainfall over the preceding 2 months exceeding 400 mm (Pagano et al., 2010).

3. Methods

3.1. Experimental apparatus and procedures

A wooden tank filled with about 1 m^3 of reconstituted silty pyroclastic soil, placed on a metallic base, constitutes the core of the physical model (Fig. 1). To study the soil–atmosphere interaction experienced by the soil under the effects of actual atmospheric variables, the physical model was exposed to the atmosphere at a site in Napoli (Lat. = 40°49′46.61N; Long. = 14°11′21.01E). The aim was to reproduce realistic soil–atmosphere water exchanges under fully controlled and widely monitored conditions without the burden and difficulty of field monitoring, typically related to undetectable random inhomogeneities of soils and/or uncertainties in hydraulic conditions acting at lateral and lowermost boundaries (Pagano et al., 2006).

The square horizontal section of the soil layer, 1.15 × 1.15 m, is wider than the vertical rectangular section, 1.15 × 0.75 m. The layer shape is halfway between those of a lysimeter and an infiltration column. The purpose of a lysimeter is to characterise the soil–atmosphere interaction by monitoring both the weight changes of the soil layer and the meteorological variables. For a given soil volume, its markedly flattened shape maximises the weight changes with respect to the whole sample weight, allowing accuracy in their measurements (e.g., Howell et al., 1991). On the other hand, an infiltration column aims to characterize an infiltration process by monitoring seepage flows, pore water pressures and water contents. Its columnar shape makes flow paths long enough to observe the progress and features of the infiltration process in the best possible way (e.g., Yang et al., 2004). The soil layer shape was designed to be slightly flattened in an attempt to preserve sufficient accuracy in the observation of both the layer weight changes and infiltration processes.

The sides of the tank contained large holes (hole diameter = 100 mm) equipped with screw plugs ensuring water-

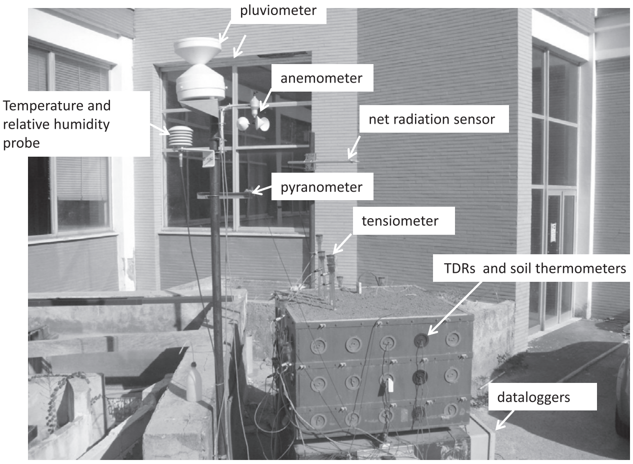

Fig. 1. Illustration of the physical model at work.