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Long-term investigations on the pore pressure regime in saturated and unsaturated sloping soils

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A B S T R A C T

Pore pressure changes play a major role in the stability of natural slopes, whose safety factor value is usually much smaller than that generally accepted in any other geotechnical problem. Correct assessment of potential seasonal pore pressure distributions is therefore a crucial issue in slope stability analysis. Based on long-term monitoring of some natural slopes, this paper compares the pore pressure distribution recorded in saturated fine-grained deposits and in shallow unsaturated granular covers, both monitored in southern Italy. In spite of the expected differences, the soils display some common features. In particular, from December to mid-May (wet period) in all examined cases the pore water pressures are quite constant over a monthly scale. Thus an essentially steady-state pore pressure condition establishes. It is in this phase, which is characterised by an essentially downward flux, that the safety factor drops to its lowest yearly value. Finally, a simplified method is adopted to model the steady-state pore pressure during the wet period and to calculate the average rain infiltration in equilibrium with the steady-state condition; the results thereby obtained are compared with the findings of an advanced approach, based on the hydrological balance.

1. Foreword

A reliable prediction of the seasonal changes of the groundwater regime is of crucial importance in geotechnical problems, allowing critical design conditions to be identified. During rainy periods, pore pressure experiences a generalised increase. In contrast, during the dry season continuing evapotranspiration causes a pore pressure decrease (Rianna et al., 2014). However, the effects of weather forcing on the groundwater regime are generally delayed and decrease with depth (Pirone et al., 2012).

With regard to fine-grained soils, Kenney and Lau (1984) report the results of pore pressure monitoring in the banks of the Waby Creek, Ontario, over more than 10 years. The large seasonal changes are observed in the shallowest layers while negligible fluctuations are recorded at depths higher than 10 m. Indeed, the lower the coefficient of consolidation, the more the amplitude of pore pressure fluctuations extinguishes with depth.

With regard to partially saturated soils, the hydrological response was numerically investigated by Collins and Znidarcic (2004) who analysed the influence of hydraulic conductivity and the shape of the Soil Water Retention Curve, SWC, of an infinite soil column with an initial hydrostatic suction profile, subjected to repeated rainfalls. Again, it is shown that rainfall effects decrease with depth: the higher the hydraulic conductivity the higher is the rate of suction change in the subsoil as a response to a hydraulic perturbation at ground surface. The SWC also has an important effect: the higher the slope of the SWC (expressed by the variation in saturation degree versus suction), the lower is the rate of suction change.

Slope stability problems typically arise during the rainy season which, in southern Italy, occurs from November/December to mid-May. Henceforth this season will be called the wet period. Generally, the worst pore pressure conditions can be recognized only through careful monitoring. However, at least on a regional scale, some indications can be obtained from accurate interpretation of the results of long-lasting investigations carried out in sites located in the same geological/geomorphological context. This strategy is discussed in the present paper that compares pore pressures measured through monitoring in five sloping areas: three of them are occupied by stiff highly fissured saturated clays and two by essentially granular unsaturated pyroclastic soils (Fig. 1).

The first three sites (in the following indicated as sites A, B and C) are located in landslide-prone areas belonging to the same basin, near the town of Potenza, where flysch formations outcrop. The slopes, that are subject to slow movements, were monitored for about fifteen years (Urciuoli, 1998; Fenelli, 1994). The other two sites (named D and E in Fig. 1), monitored for five and six years respectively, belong to two different basins located in the volcanic context around the town of Naples

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List of symbols

a	about equal to the inverse of air entry pressure
c'	soil cohesion
d	grain diameter
K	hydraulic soil conductivity
K_{sat}	hydraulic saturated soil conductivity
h	total head
i_{ns}	component normal to the slope of head gradient
i_{ts}	component parallel to the slope of head gradient
n	soil porosity
n	empirical parameter of Mualem-Van Genuchten model
n_s	coordinate normal to the slope
$\frac{u}{\gamma_w}$	pore pressure head
q_n	flux from the ground surface normal to the slope
s	matrix suction
S_r	degree of saturation
t_s	coordinate parallel to the slope
u	pore water pressure
w_L	liquid limit
w_N	gravimetric water content
z	depth from the ground surface
z_p	depth of piezometer cell
z_t	depth of tensiometer
z_w	vertical distance from the water table
CF	clay fraction
D	elevation of the water table
ET	real evapotranspiration
I	interception by vegetation
I_L	liquidity index
IP	plasticity index
P	rainfall
Q_{inf}	infiltration flux estimated from in situ measurements
R_{off}	runoff
TDR	Time Domain Reflectometry
WSC	Wet Steady Condition
α	slope angle
β	slope of the streamlines to the horizontal
ω	slope of h profile to the vertical
γ_w	specific water weight
γ_d	soil dry unit weight
γ_s	specific soil weight
θ_s	volumetric soil water content at saturation
θ_r	volumetric residual soil water content
φ'	friction angle
ℓ	empirical parameter of the Mualem-Van Genuchten model
ξ	depth from the ground surface of the water level in the piezometers in clayey slopes/sum of depth of tensiometers, z_t, and suction expressed as a water column in pyroclastic slopes

(Damiano et al., 2012; Pirone et al., 2015a; Pirone et al., 2015c). Elevation, mean slope, mean thickness of soil cover and average annual rainfall recorded in the selected sites are reported in Table 1.

In particular, the paper focuses on pore pressure fluctuations during the hydrological year registered in these very different geological contexts. It is shown that the amplitude of oscillations due to seasonal effects (due to a complex interaction with the atmosphere regulated by many meteorological factors) are higher than those due to single rainfall events, even when the latter may be huge (Pirone et al., 2015c). This is highlighted by the analysis of fluctuations over a daily timescale that shows that the single event is responsible for a small part of the annual pore pressure fluctuations; the remaining part is dependent on factors operating on a long timescale: previous cumulative rainfall and evapotranspiration. Moreover, during the wet season a steady pore pressure regime establishes in the subsoil, representing the predisposing factor to landslide triggering. In this conceptual framework even if the individual event is the trigger, it is not effective in the absence of the predisposing factor. Hence the condition of steady pore pressures occurring during the wet season is a necessary element to comprehend the effect of huge rainfalls on landslide initiation. This issue is covered in depth here and a conceptual framework will be defined to analyse the predisposing role of the wet steady condition in different geological contexts in slope stability problems: this is the main novelty of the paper.

First the soils recognized in situ are briefly characterised and some results of monitoring in saturated stiff fissured clays and in unsaturated pyroclastic slopes are reported and discussed (Sections 2 and 3). However, since the main focus of the paper is seasonal hydraulic slope behaviour, hydraulic soil properties are mainly emphasised. Common features in the slope pore pressure regime among all the sites investigated are then outlined (Section 4). In particular, *(i)* a common steady state condition during the rainy months (mid-December to mid-May) is identified in all the slopes; *(ii)* although the granular soils and fine-grained soils differ greatly in saturated hydraulic conductivity, the hydraulic conductivity of granular unsaturated soils 'operative' in situ is quite similar to that of fine-grained soils at fixed depths. Lastly a simplified approach and an advanced method are applied to model the ground water regime in all the slopes (Sections 5 and 6).

2. Monitoring results in saturated stiff fissured clays

2.1. Geological context

The first three sites (sites A, B and C) are located in the same basin near the town of Potenza, where flysch formations outcrop extensively. Flysch formations are widespread in the southern Apennines. They consist of alternating layers of competent rock and clay shale deposited during the Oligocene - Miocene Age, then subjected to tectonic uplift (Picarelli et al., 1997; Comegna et al., 2004). As a result, they present a highly disturbed structure and the clay shale component is highly fissured (AGI, 1979; Bilotta et al., 1985; Picarelli et al., 2002; Di Maio et al., 2010; Di Maio and Vassallo, 2011; Picarelli et al., 2013). Typically, the uppermost part of the formation is highly softened.

Due to the highly fissured structure of the fine-grained component, the strength of the deposit, as a whole, is rather poor. Indeed, sloping outcrops are subject to widespread movements which have been investigated in depth elsewhere (Iaccarino et al., 1995; Giusti et al., 1996; Picarelli et al., 2005). The three sites are located in an area subject to slow slope movements of the earthflow type that involve the softened cover and that was monitored for about fifteen years from the mid-1980s (Pellegrino et al., 2004; Urciuoli et al., 2016). The three earthflows, whose average slope is only slightly steeper than 10°, present an elongated shape and consist of a source area (depletion zone), a main track (channel) and accumulation zone; the maps are shown in Fig. 2a-c.

The earthflow body soils have lost their original fissured structure due to mechanical and osmotic softening and remoulding induced by slope movements. After triggering, the soil mass is so softened as to behave like a viscous medium. In fact, the unloading of soils close to the back scarp of the slope and mostly the unloading of the soil volumes affected by dislocation and collapse, associated with leaching due to absorption of fresh water (Picarelli and Di Maio, 2010) cause mechanical and osmotic swelling and an increase in the liquidity index from an initial value less than 0 to a value close to or more than 1 (Leroueil, 2016). When the material is highly softened, it flows downward as a new surge, overlapping the old landslide body that can be regarded as the overlapping of various surges formed during different reactivations. The undrained shear strength of the 'material during surges' decreases when the liquidity index increases according to Leroueil et al. (1983),