Soil suction modelling in weathered gneiss affected by landsliding

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ABSTRACT: The paper presents a numerical procedure to estimate, at a test site, the hydraulic properties and the net rainfall flux across the ground surface, by modelling the suction regime observed by tensiometers. The test site is located in an area affected by landsliding that involves highly heterogenous gneissic soils. Within this area, suction modelling is a fundamental issue as the movements of the landslides are strictly related to transient perched water tables directly linked to rainfall. The numerical procedure adopts an inverse analysis to model the observed suction regime and highlights the role played by the heterogeneity of the soil and by the net flux across the ground surface on the unsaturated flow characteristics at the slope scale.

1 INTRODUCTION

In natural and man-made slopes, soil suction is certainly one of the most important physical variables governing the transfer of energy and water (i.e. infiltration, evaporation and transpiration) between the atmosphere and the soil through the slope surface. Indeed, understanding the mechanisms that control soil suction variations, induced by changes in boundary conditions, and appropriately modelling the soil suction regime are crucial issues for the prediction of the slope behaviour.

In many natural slopes, modelling the soil suction regime may be a quite difficult task, especially when the hydraulic properties of the soils forming the slopes are strongly heterogeneous. In such cases, using the appropriate values of both the hydraulic properties and the boundary condition at the ground surface (i.e. rainfall intensity, evapotranspiration rate) is certainly a crucial point that often calls for experimental and numerical efforts. Among these, non-conventional approaches, analysing the soil suction regime at the slope scale, can be profitably used.

Referring to a particularly complex geolithological context located in Southern Italy, where the landslides movements are strictly related to rainfall, the paper presents an innovative procedure to cope with this issue. Particularly, an inverse numerical analysis is carried out aimed at modelling the suction regime observed by tensiometers at a test site. In the paper, after the description of the geolithological context, the landsliding of the area and the test site, the adopted numerical analysis is illustrated and the obtained results are discussed.

2 GEOLITHOLOGICAL CONTEXT AND LANDSLIDING

The test site is inside a study area of about 7.5 km² in the Western Sila Massif (Southern Italy), where several geological and geotechnical investigations have been developed during the time in order to characterise the landsliding affecting the area and the involved soils (Cascini et al. 1992a, 1992b, 1994). As for the soils, weathered gneiss is largely diffused in the area. The grade of weathering of the gneiss was defined following the procedures developed for Hong Kong (GCO 1988) on similar rocks. A simplified version of the adopted classification system (Cascini et al. 1992a, Gullà & Matano 1997) is shown in Table 1.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
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<tbody>
<tr>
<td>VI</td>
<td>Residual and Colluvial soils</td>
</tr>
<tr>
<td>V</td>
<td>Completely weathered rock (Saprolitic soil)</td>
</tr>
<tr>
<td>IV</td>
<td>Highly weathered rock</td>
</tr>
<tr>
<td>III</td>
<td>Moderately weathered rock</td>
</tr>
<tr>
<td>II</td>
<td>Slightly weathered rock</td>
</tr>
<tr>
<td>I</td>
<td>Fresh rock</td>
</tr>
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Table 1. Weathering grade of gneiss (from Cascini et al. 1992a).
This classification, together with detailed geomorphological analyses, allowed the creation of a landslides inventory map where landslide distribution can be fully interpreted according to morphology, tectonics and weathering grade of the outcropping gneiss. The landslides inventory map reveals that the most widespread types of instability phenomena involve heterogenous residual, colluvial and saprolitic soils (classes VI and V). These are characterised by an impulsive kinematism, with lengthy periods of total inactivity, followed by brief phases of sudden reactivations triggered by remarkable increments in pore water pressures induced by rainfall.

Similarly to landsliding that affects the territories of Brasil and Hong Kong (Lacerda 2004, Brand 1984), in-situ measurements revealed that the pore water pressures in the landslide bodies are strictly related to transient perched water tables. These last are directly linked to the intensity and duration of rainfall events (Cascini et al. 2006).

Therefore, landslides characterisation calls for the definition of relationships among rainfall, pore water pressure increments in the perched water tables and the triggering phases of landsliding movements. To this end, an adequate knowledge of the suction regime and of the unsaturated flow characteristics is absolutely necessary. An innovative approach to achieve this goal is discussed in the following sections.

3 THE TEST SITE

The test site concerns a small landslide, with a maximum depth of 6 m, in a slope which is part of a large ancient landslide (Fig. 1). The small landslide involves gneiss of classes VI and V, resting on a basement formed by less weathered gneiss of class IV and class III-II (Cascini et al. 1992b, Sorbino 1995, Gullà & Sorbino 1996). As for the landslide debris, the particle size distribution with depth (Gullà & Sorbino 1996) reveals an uneven sequence of soils belonging to classes VI and V (Fig. 2).

The conspicuous number of piezometers installed in the test site—in some cases up to five piezometers per borehole—show, in the landslide debris, the presence of a perched water table with a marked transient behaviour related to the seasonal meteoric events. On the other hand, piezometers located in the basement give remarkably lower piezometric heads with annual or multiannual regime (Fig. 1). According to the data acquired in other sites of the study area (Cascini et al. 2006), this circumstance clearly reveals the presence of two different groundwater regimes in the subsoil: the first in the landslide debris, the other in the basement.

As for the relationship between the perched water table and rainfall, soil suction data were collected within the landslide debris by means of five “Jet-fill” tensiometers (Gullà & Sorbino 1996). They were installed, along the same vertical (S6-T6 in Fig. 1), at depths of 0.81 m, 1.45 m, 2.03 m, 2.88 m and 3.58 m below ground surface (Fig. 2). Soil suction measurements from the installation date (May 1993) to May 1995 are shown in Figure 3 together with the daily rainfall (Gullà & Sorbino 1996). Readings at the tensiometers were taken with an average time interval of about one week.

As for the hydraulic properties of the soils forming the landslide debris, they were provided by in-situ and laboratory tests. Saturated hydraulic properties were estimated by means of in-situ piezometer tests.
Figure 2. Location of tensiometers, soil profile and grain-size distribution in the borehole S6 (modified after Gullà & Sorbino 1996).

Figure 3. Daily rainfall and soil suction measured by tensiometers (modified after Gullà & Sorbino 1996).

Figure 4. Experimental soil water characteristic curves, normalized by saturated volumetric water content, and hydraulic functions, normalized by saturated coefficient of permeability, for class VI and V soils (modified after Sorbino 1995).

and by permeameter and oedometric tests in laboratory (Sorbino 1995). As for the unsaturated hydraulic properties, they were determined in laboratory on homogenous undisturbed soil samples collected in the gneiss layers belonging to classes VI and V. Figure 4 shows the obtained experimental values of volumetric water content ($\theta$) and hydraulic conductivity ($K$) against suction, normalized, respectively, by the values of the saturated volumetric water content ($\theta_s$) and of the saturated coefficient of permeability ($K_s$).

4 NUMERICAL ANALYSIS

4.1 Model definition

In order to address the role played, at the slope scale, by the heterogeneity of the soil and by the net flux across the ground surface on the observed suction regime, a transient seepage analysis was performed. The domain of the analysis concerns the vertical column of soil where the 5 tensiometers were installed (Fig. 5).

To this aim, two different schemes were adopted. With Scheme 1 the hydraulic properties of the three different soil layers were determined by best fitting the numerical results with the suction measurements at tensiometers T2 to T4. Scheme 2 was used to estimate a reliable range of evapotranspiration rates (i.e. net rainfall at the ground surface) by best fitting the results of the calibrated model with the measurements at tensiometer T5.

The analyses were carried out using the Finite Element code SEEP/W (GeoSlope 2004), which is able to integrate the well known Richards’ differential equation governing the transient saturated—unsaturated water flow in soils. The one-dimensional domain was discretised using quadrilateral elements with secondary nodes (Fig. 5). Three different soil layers were considered, which refer to the saprolitic (A), residual (B) and upper colluvial (C) layers.

The time-dependent boundary conditions of the two schemes are different. In the first one, pressure boundary conditions were set at the locations of the lowest and uppermost tensiometers (T1 and T5) and were assumed equal to their record of measurements. In the second scheme, the lower pressure boundary condition was set at the location of tensiometer T4; while a transient flux condition, corresponding to estimates of the net daily rainfall intensities based on monthly evapotranspiration rates, was applied at the ground surface (i.e. upper boundary).
For both schemes the transient numerical analysis was carried out with daily time steps covering the two-year long monitoring period of Figure 3. The assumed initial suction distribution was given by a steady-state analysis in which the boundary conditions refer to the first available monitoring data.

For the Scheme 1, the hydraulic properties of the three layers were assumed unknowns, but defined by two analytical relationships. Particularly, the relationship proposed by Van Genuchten (1980) was used for the variation of the volumetric water content against suction, while for the hydraulic conductivity function the relationship proposed by Mualem (1976) was assumed. Both functions are represented by the following:

\[
\theta(s) = \frac{\theta_s}{\left[1 + \left(\frac{s}{s_y}\right)^n\right]^m}, \quad (1)
\]

\[
K(s) = K_s \frac{[1 - (As)^N - 1(1 + (As)^N)^{-M}]}{[1 + (As)^N]^{M/2}}, \quad (2)
\]

where: \(s = \) suction; \(a, n, m, A, N\) and \(M\) = curve fitting parameters. If these last three parameters are assumed dependent from the previous ones through the relations \(A = 1/a; N = n; M = 1 - 1/n\), equations (1) and (2) are completely defined by only five parameters (namely \(a, n, m, \theta_s\) and \(K_s\)).

### 4.2 Scheme 1

Scheme 1 in Figure 5 was used to calibrate the five unknown parameters defining equations (1) and (2) for each of the three soil layers.

The five independent parameters characterizing each soil layer were determined using an inverse analysis algorithm to minimize the error between the measured suctions at tensiometers T2, T3 and T4 and the corresponding computed results. Figure 6 shows a flowchart of the inverse analysis procedure. A regression analysis was performed to minimize an objective function, which quantifies the fit between computed results and observations. The minimization was attained by the optimization of the input parameters needed to perform the numerical model. If the model fit was not “optimal”, the procedure was repeated until the model is optimized. For details on the procedure used and on how to choose the relevant parameters to optimize by inverse analysis see Calvello & Finno (2002, 2004).

Figure 7 shows the model boundary conditions and the comparison between the results of the calibrated model and the measured suction values at tensiometers T2, T3 and T4. The results clearly indicate that the model well reproduces the recorded behaviour both at low and high suction values.
Only 6 parameters were calibrated by the inverse analysis. The results show some significant differences among the initial and final estimates of these parameters. In particular, the values of the calibrated saturated conductivities for soil layers 2 and 3 are not equal as initially assumed and are higher than their initial estimates. The calibration also lead to a differentiation of the shape of the curves for the three soil layers, as indicated by the different values of the first two curve fitting parameters, a and n.

The comparison between the experimental curves of Figure 4 and the calibrated curves for each soil layer is shown in Figure 8. The results indicate that the calibrated hydraulic conductivity functions well compare with the experimental results, while the calibrated volumetric water content curves show a more rapid desaturation of the soils with suction than the measured ones. This could depend by the presence of largest in-situ pore networks that are not adequately represented by the small dimensions of the specimens used in the laboratory tests.

### 4.3 Scheme 2

Scheme 2 defines a domain bounded by the ground surface and the location of tensiometer T4 (Fig. 5). The hydraulic properties of the two soil layers of the model (i.e. layers B and C) were assumed equal to the corresponding calibrated pair of curves in Figure 8. At the lower boundary, a time-dependent pressure condition based on the values measured at T4 was used. At the upper boundary a flux condition was applied,

The calibrated values of the 15 independent model parameters are reported in Table 2 together with their initial estimates. The initial saturated volumetric water content and coefficient of permeability were set equal to the mean values reported by Sorbino (1995). Initial values of the parameters a, n and m were estimated by best fitting each experimental curve (see Figure 4) with the functions defined by equations (1) and (2).
based on daily rainfall measures and on the estimates of the evapotranspiration rate.

To this end, the procedure suggested by Tarantino et al. (2002) was adopted. This is based on a comparison between the potential evapotranspiration ($E_p$) (i.e. the maximum evaporation rate in the case of water availability) and the water limiting evapotranspiration ($E_{lim}$), which is related to the capacity of the soil to transmit water to the atmosphere. The value of daily evaporation rates for the definition of the flux boundary is then fixed, in the numerical analyses, equal to the lowest value between $E_p$ and $E_{lim}$. A detailed description of the procedures used for the evaluation of $E_p$ and $E_{lim}$ is reported in Sorbino (2005).

The estimation of $E_p$ was carried out adopting the Thornthwaite’s empirical equation (Thornthwaite 1954) and using air temperatures recorded at the test site. The limiting evapotranspiration, $E_{lim}$, was estimated using the steady-state flow solution proposed by Gardner (1958) for a homogenous soil, which is a function of the saturated and unsaturated hydraulic properties of the soil and of the depth of the water table.

Figure 9 shows the cumulative total rainfall and the cumulative net flux at the ground surface for two different evapotranspiration (EVT) scenarios. The two scenarios refer to two different estimates of the hydraulic properties of the soil between T4 and the ground surface, assumed as homogeneous in the Gardner solution, leading to two different estimates of the limiting evapotranspiration.

In Figure 10 the measured suction values at tensiometer T5 and the computed results are compared for the two different evapotranspiration scenarios. The Figure clearly shows that, when the soil is highly heterogeneous, the estimation of the evapotranspiration rate can lead to inadequate definition of the boundary conditions at the ground surface. On the contrary, the reliability of its estimation can be highly improved when adequate experimental data on suction are available.

5 CONCLUSIONS

In the paper, the in-situ soil suction regime is modelled at a test site, to be considered representative of the subsoil conditions for landsliding that affects a large area where weathered gneiss prevails.

The comparison between the model results and a two-year long record of in-situ measurements, relative to 5 tensiometers installed along the same vertical, shows that the soil heterogeneity and the net flux across the ground surface play a relevant role in the soil suction regime.

As for the heterogeneity, the laboratory characterization of the hydraulic properties of these soils, albeit accurate, may not be sufficient to define reliable values for the unsaturated flow analysis at the slope scale. To this aim, accurate in-situ tensiometric measures may instead be profitably used. As for the net flux across the ground surface, the results underline how the estimation of the evapotranspiration rate is equally relevant. In this case, the tensiometric measurements may be used to define a range of possible evapotranspiration rates.

Tensiometric measurements and the presented procedure may also be useful to address further goals. Among these, forecasting the recharge of perched water tables at site-scale and/or predicting soil suction regime for the landslides involving class VI and V soils that have been mapped over the whole study area of the Western Sila Massif.

REFERENCES


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