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Discussions

Landslide susceptibility from mathematical model in Sarno area

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Abstract

Rainfall is accepted as a major precursor for many types of slope movements (rapid, shallow soil slips and deeper landslides) and the technical literature is rich in examples of study cases and analysis models, related to landslides induced by rainfall.

In general, the developed model can be regrouped in two categories: hydrological and complete. The first ones involve simple empirical relationships linking antecedent precipitation to the time that the landslide occurs; the latter consist of more complex expressions that take several components into account, including specific site conditions, mechanical, hydraulic and physical soil properties, local seepage conditions, and the contribution of these to soil strength.

In this study, the analysis was carried out by using a model belonging to the second category for a landslide-prone area in Campania region (Southern Italy), were disastrous mud-flows occurred on 5 May 1998.

In details, the model named SUSHI (Saturated Unsaturated Simulation for Hillslope Instability) was used and the obtained results made possible to better define the triggering conditions and differentiate the scenarios leading to instability of those slopes.

1 Introduction

The problems and the damage caused by landslides become increasingly complex and worrisome. Among the factors which contribute to the occurrence of these phenomena, rainfall is one of the most important. As a result of rainfall events and subsequent infiltration into the subsoil, the regime of pore pressures can be profoundly altered: decrease of capillary tension in the unsaturated soil layers, increase in pore pressure in the layers already saturated, saturation of initially unsaturated layers before rainfall event. The direct consequence of this variation for the stability of a slope is, in any case, the reduction of the resistance forces.

The occurrence of the phenomena is also influenced by heterogeneity of hydraulic and geotechnical properties, soil moisture and water interaction.

In this context, the technical literature reports many approaches that are different for: (a) the spatial scale range adopted that varies from wide area, up to ten of thousands kilometers, to small area, that can be reduced to a single landslide; (b) the quality and quantity of hydrologic, hydraulic and geotechnical available data; (c) the adopted detail for describing the hydrological and geotechnical mechanisms in slope. Concerning the type of modelling, two categories can be identified: hydrological and complete. The first category comprises all the models that are based on historical landslides data and related antecedent rainfall heights, and do not require field instrumentations and measurements (Campbell, 1975; Caine, 1980; Cannon and Ellen 1985; Wieczoreck 1987; UNDRO, 1991; Sirangelo and Versace, 1992; Wilson and Wieczorek, 1995; Guzzetti, 2008; Cepeda et al., 2010; Capparelli and Versace, 2011). However, this kind of analysis does not give any information about the hydrological processes involved in a landslide area and thus it does not improve our understanding of landslide dynamics. On the contrary, complete models can help in understanding triggering mechanism since they attempt to reproduce the physical behaviour of the processes involved at hillslope scale, employing detailed hydrological, hydraulic and geotechnical information (Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Pack et al., 1998; Gasmo et al., 2000; Iverson, 2000; Tsaparas et al., 2000; Baum et al., 2002, 2010; Tsai and Yang, 2006; Qui et al., 2007; Simoni et al., 2007; Tsai et al., 2008). Referred to complete models, it is possible to make a general distinction between regional and local models. The former develop analysis over wide areas and usually produce a susceptibility map characterizing the landslide prone zones according to a stability index. The latter are in general much more accurate for analyzing the slope stability based on detailed hydraulic and geotechnical characteristics; they can reproduce the spatial and temporal pattern of water flows in domains very well detailed, and to take account of hydrological phenomena that interfere with the groundwater flow such as the meteorological forcing, the sliding surface, evapotranspiration (Arnone et al., 2011).

In this work a local model named SUSHI (Simulation for Saturated unsaturated Hill-slope Instability, Capparelli, 2006; Capparelli and Versace, 2011) is applied. SUSHI takes into account several components, as specific site conditions, mechanical, hydraulic and physical soil properties, locale seepage conditions and the contribution of these to soil strength. The model was developed in order to be suitable for the cases of strongly heterogeneous soils, irregular domains, boundary conditions variable in space and time. It is composed by a hydraulic module, to analyse the water circulation in saturated and unsaturated layers, in non-stationary conditions, caused by rainfall infiltration, and by a geotechnical module, which provides indications regarding the slope stability starting from limited equilibrium methods. After a brief description of the model, the paper describes some applications to some very complex cases such as the pyroclastic cover of Sarno (Campania region – Southern Italy), where terrible and dangerous mud flows occurred on 5 May 1998, during which 159 people died and life lines and villages were destroyed.

2 General description of the study area

The study area is located in Campania region (Southern Italy), where catastrophic flowslides and debris flows in pyroclastic soils are very usual. A brief list of some recent events is reported in Table 1 (Versace et al., 2009), which includes also information about the size of the landslide. The area where the landslides occurred includes the Pizzo d'Alvano massif, a NW-SE oriented morphological structure, consisting of a sequence of limestone, dolomitic limestone and, subordinately, marly limestone dating from the Lower to Upper Cretaceous age and characterized by a thickness of several hundred meters. The Pizzo d'Alvano slopes are mantled by very loose pyroclastic soils, produced from the explosive phases of the Somma-Vesuvius volcanic activity, both as primary air-fall deposits and volcanoclastic deposits. Air-fail deposits were dispersed from N-NE to S-SE, according to prevailing wind direction and covered a wide area reaching distances up to 50 km. Pumiceous and ashy deposits belonging to at least

5 different eruptions were recognized. From the oldest to the youngest, they are: Ottaviano Pumice (8000 yr BP), Avellino Pumice (3800 yr BP), 79 AD Pumice, 472 AD Pumice, 1631 AD Pumice. The deposits are affected by pedogenetic processes determining paleosoil horizons during rest phases of the volcanic activity. The total thickness of the pyroclastic covers in these areas ranges between few decimetres to 10 m, near to the uppermost flat areas. The general structure of the soil progressively adapts itself to the morphology of the calcareous substratum showing, therefore, complex and variable geometries.

On 5 May 1998, 40 mud flows were triggered in almost all the basins of the slopes of Pizzo d'Alvano (Fig. 1), involving an extension area of around 60 km^2 and causing immense damages to urban centres (Sarno, Quindici, Siano and Bracigliano). These landslides, classified as very rapid to extremely rapid soil slip/debris flows, were analyzed in several papers, in which the most significant geomorphological, hydrological and geotechnical aspects of slope failure and post-failure evolution were described and several models for the triggering and channelization of flow-like landslides were developed (Cascini et al., 2000; Olivares and Picarelli, 2003).

Applications of SUSHI model involved the trigger zone of the mudslide occurred in the Tuostolo basin, represented in Fig. 1.

3 Framework of SUSHI model

The model named SUSHI (Saturated Unsaturated Simulation for Hillslope Instability, Capparelli, 2006; Capparelli and Versace, 2011) is based on the combined use of two modules: HydroSUSHI, aimed at studying subsoil water circulation, and GeoSUSHI, suited for evaluating the degree of slope stability.

Infiltration analysis is carried out by using Richards' equation, expressed as a function of the suction to enable applications for layered soils and transient flow regime in both saturated and unsaturated conditions. Stability analysis is performed with limit

equilibrium methods, adapted for the unsaturated soils as suggested by Fredlund and Rahardjo (1993).

HydroSUSHI analyses subsoil water circulation in a spatial 2-D domain which can be characterized by irregular soil stratigraphy with different hydrogeological properties. By adopting a Cartesian orthogonal reference system Oxz, with z axis positive downwards, the governing differential equation is:

$$\frac{\partial}{\partial x}\left[K(\psi)\frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right)\right] = C_{\mathrm{SU}}(\psi)\frac{\partial \psi}{\partial t} \tag{1}$$

where $K(\psi)$ is the hydraulic conductivity which depends on suction ψ for unsaturated soils. Soil anisotropy was ignored, so $K_x(\psi) = K_z(\psi) = K(\psi)$ is assumed. The $C_{\mathrm{SU}}(\psi)$ coefficient was introduced to simulate water flow in both unsaturated and saturated zones, so avoiding the use of different algorithms for the resolution of parabolic and elliptical equations respectively (Capparelli and Versace, 2011; Paniconi et al., 1991). Since Richards' equation does not allow analytical solutions unless in cases where simplifying hypotheses and /or particular boundary conditions are introduced (Iverson, 2000), the finite differences scheme and the fully implicit method are adopted for numerical simulations of SUSHI (Capparelli and Versace, 2011). Moreover, was upgraded through the integration of a method for the evapotranspiration process description, even if this component usually produces secondary effects when slope mobilizations occur in very rainy periods. Validation tests were carried out by comparing HydroSUSHI outputs with solutions proposed in literature (Capparelli, 2006), and with the suction data collected by the jet fill tensiometers located in a pilote site (Capparelli and Versace, 2011). The comparison of results for both applications was satisfactory and confirmed the capability of the model to simulate groundwater circulation.

Concerning GeoSUSHI module, it is based on well-known General Limit Equilibrium methods, and it used the slope failure equation proposed by Fredlund and Rahardjo (1993) for unsaturated soils:

$$\tau = c' + (\sigma - u_{\mathrm{a}})\tan\phi' + (u_{\mathrm{a}} - u_{\mathrm{w}})\tan\phi_{\mathrm{b}} \tag{2}$$

where τ is shear strength; c' is effective cohesion; σ is total normal stress; u_a is pore air pressure due to surface tension; u_w is pore water pressure; ϕ' is the effective friction angle; ϕ_b is the angle expressing the rate of strength increase related to matric suction. In practical applications, this last term is evaluated using the expression proposed by
5   Vanapalli et al. (1996).

4   Modelling of flowslide triggering and results

To define the dynamics of the water circulation in the subsoil, the solution process re-quires the definition of the investigated domain, the soil water characteristic curves, the permeability functions, the mechanical properties of the involved soils, the bound-
10   ary and initial conditions. With reference to the geological characteristics, the surveys and studies carried out by using the information available in the literature indicated the presence of alternating layers of pumice with a composition and thickness related to the characteristics of the eruptions and to the distance from the eruptive centers. As already mentioned in Sect. 2, this sequence comprises both primary air-fall and volcan-
15   oclastic deposits. The primary deposits are composed by alternating layers of pumice, with interbedded paleosoils. At the basis of this sequence, above the bedrock, there is a layer of red-dark clayey ashy soil ("regolite") with rare limestone fragments. The modelled slope and the stratigraphic details are illustrated in Fig. 2.

In order to determine the mechanical properties of the involved cover, soil samples
20   were collected, both in the investigated area and in other triggering areas belong to Pizzo d'Alvano slopes. Physical and mechanical properties were determined for all the samples through laboratory tests, and the soil layers were assumed as isotropic.

For hydraulic properties in unsaturated conditions, the best fit of laboratory data was obtained with the retention curves proposed by Van Genuchten and Nielsen (1985).
25   The values of the bubbling pressure, or air-entry tension, ψ_b, were determined through the graphic method proposed by Fredlund and Xing (1994). In summary, the parameter values are listed in Table 2.

The variable boundary conditions have been provided by using both Dirichlet and Neumann conditions. In details, on the basis of domain side:

  – on the top (i.e. on the ground surface) flux boundary condition equal to rainfall infiltration capacity was performed; the runs allow to define step by step the infiltration rate for each node of the domain;

  – on the bottom (i.e. at the contact between the pyroclastic cover and the bedrock) no flux was imposed, since the bedrock was assumed impervious;

  – similarly for the upslope left side, a Neumann condition of no water flow was fixed, since the morphology of the area under analysis makes plausible the hypothesis that there is coincidence between the superficial and the deep watershed so that contributions of water coming from upstream may be assumed equal to zero;

  – for the downslope right side, along the morphological frames, two different boundary conditions were imposed by using a Neumann or a Dirichlet condition if saturation occurs or not respectively.

The initial conditions were defined in a non-arbitrary way, due to the use of data provided by some tensiometers installed after the landslide occurrence near the study area. The measurements were performed at different depths from the ground level: at 20–40–60–80–100–120–140 cm. This information has been of great use to set the initial conditions. Constant distribution suction throughout the domain was firstly hypothesized by selecting, in particular, the following values:

$$\psi(x, z; t = 0) = -0,3; -0,4; -0,6; -0,8; -1; -1,4 \ [\text{m}] \tag{3}$$

A warm-up was performed for each of these values, by starting a simulation with no rain in order to allow the redistribution of water content among the nodes of the domain and, therefore, between the layers, based on their hydraulic characteristics. The equilibrium condition was reached when the standard deviation of the suction values of each node,

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is less than 10^{-5}. The obtained distribution was compared with the ψ values measured by tensiometers at the end of summer periods. By comparing these profiles, a strong similarity was evident with the ψ values obtained from the condition $\psi_0 = -0.6$ m, as shown in Fig. 3. This distribution was set as the initial condition for the simulation of the period 1 October 1997–5 May 1998.

The defined elements just make possible the application of the hydraulic model to reconstruct the events of May 1998 and, in particular, the identification of the pore water pressure. This application was developed with the aim of establishing an interpretative model of the triggering phase of the mudflow and its relations with the infiltration of rainwater in the pyroclastic covers.

The considered period was characterized by a total rainfall of 891 mm with greater values of rainfall intensity occurred between the end of October and December 1997.

Given the domain size under investigation and the number of involved variables, some diagrams were prepared to provide an example of results (Figs. 4–5). The diagrams concerns the conditions reached in two areas, considered as representative of the selected domain: one in the upslope part (hereafter referred to as "section A"), the other at the bottom of the slope, almost at the right boundary of the domain ("section B"). For each of these sections, the temporal evolution of suction profile is represented (Fig. 4a and b). From Fig. 4a it is evident that water table is not present at the top of the slope, since the values of the pressure head in the section are always lower than zero. This situation is fully congruent with the morphological characteristics of the zone, where steep slopes do not allow any form of accumulation. The situation is different for the Section B (Fig. 4b), where the lower layers reach saturated conditions, and the upper ones present higher values close to saturation on 5 May. These results confirm the hypothesis that the saturation of the underlying layers was not the only cause of the instability of the slopes, even if it contributes to this phenomenon.

In fact, the suction levels seem to have played an important role for the mudflows occurred in May 1998. The values of rainfall heights during those days were not so extreme, but certainly unusual for a late spring period. In addition, the rainfall measured

by the active station during that time is certainly lower than rainfall recorded on a slope. The station is, in fact, located at an altitude much lower than the triggering-areas. The simulated ground effects are likely underestimated.

The values of ψ achieved on May 1998 in the lower layers are not singular values: on the contrary, in previous periods the model provided quite similar distributions. The main difference lies in the fact that on 5 May 1998, the vertical profiles of ψ present conditions close to saturation of the shallow layers.

This result is still more evident if we compare the distribution of the pore water pressure at different depths from the top soil with the obtained FS values (Fig. 5a and b). In details, for each considered depth (0.3 m, 0.7 m, 0.85 m, 1.8 m, 2.15 m, in Fig. 5a, and 2.9 m, 3.1 m, 3.45 m and 3.8 m in Fig. 5b) the average value of pore pressure was calculated, and then the correspondent value of FS was estimated using the method of infinite slope. The plots in Fig. 5 show relevant results and can help to understand the evolution of the slope stability conditions. It is clear that further analyses should be carried out in order to better evaluate the influence of the bedrock, of the road cuts located in the upper zone of the triggering areas, and other factors that could have influenced the evolution of events.

5 Conclusions

The proposed SUSHI model is able to represent, with sufficient details, the phenomena induced by rainfall events that occur in soils characterized by complex stratigraphy and hydraulic properties, and represents a complete model for water circulation analysis. The application in the selected slope of Sarno area (Southern Italy) has enabled the reconstruction of the full development of pore pressures in colluvial blankets and to distinguish the conditions occurred on May 1998 from the previous ones, thus providing important information to identify the possible critical conditions of these slopes. In particular, by analyzing the results, the role of the suction appears to have been decisive for the triggering of landslide movements, consistently with the most reliable theories

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that attribute to the dynamics of water circulation in the surface soils a primer role either for the triggering phase and the subsequent propagation phase.

The results could be even more significant if more realistic rainfall data were available. The simulations certainly would provide greater distinction in the performed period, providing an index of stability, here represented by the safety factor, much less than 1.

Further applications to cases recorded on 5 May 1998 and periods without landslides could certainly better delineate the critical conditions and provide useful information for a possible early warning system.

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Table 1. Features of some recent flowslides in Campania Region (Versace et al., 2009).

Site	Date	Length (m)	Volume (m^3)
Ischia	2006	450	3×10^4
Cervinara	1999	2×10^3	4×10^4
Avella	1998	15×10^2	2×10^4
S. Felice a C.	1998	8×10^2	3×10^4
Sarno	1998	$2–4 \times 10^3$	5×10^5
Bracigliano	1998	$1–2 \times 10^3$	15×10^4
Siano	1998	14×10^2	4×10^4
Quindici	1998	$1–4 \times 10^3$	5×10^5
Maiori	1954	10^3	5×10^4
Avellino	2005	4×10^2	2×10^4
Montoro Inf.	1997	2×10^3	3×10^4

Table 2. Properties of the involved soils.

	Top Soil	Pumice 1631	Paleosoil	Pumice 472	Paleosoil	Regolite
Soil properties						
Dry unit weight [$kN\,m^{-3}$]	10.99	6	7	6	9	10.75
Saturated unit weight [$kN\,m^{-3}$]	17.2	13	13	13	15	15.3
Saturated soil water content θ_s	0.55	0.82	0.61	0.68	0.61	0.60
Residual soil water content θ_r	0.14	0.23	0.18	0.05	0.18	0.10
Saturated hydraulic conductivity K_s [$m\,s^{-1}$]	3.2E-05	1.0E-03	1.0E-06	1.0E-02	4.0E-06	7.6E-07
Effective coesion c' [kPa]	2	0	4.5	0	4.7	15
Friction angle φ' [°]	15	30	24	32	28	21

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Fig. 1. Localization of Sarno (Southern Italy) and investigated area with SUSHI model.
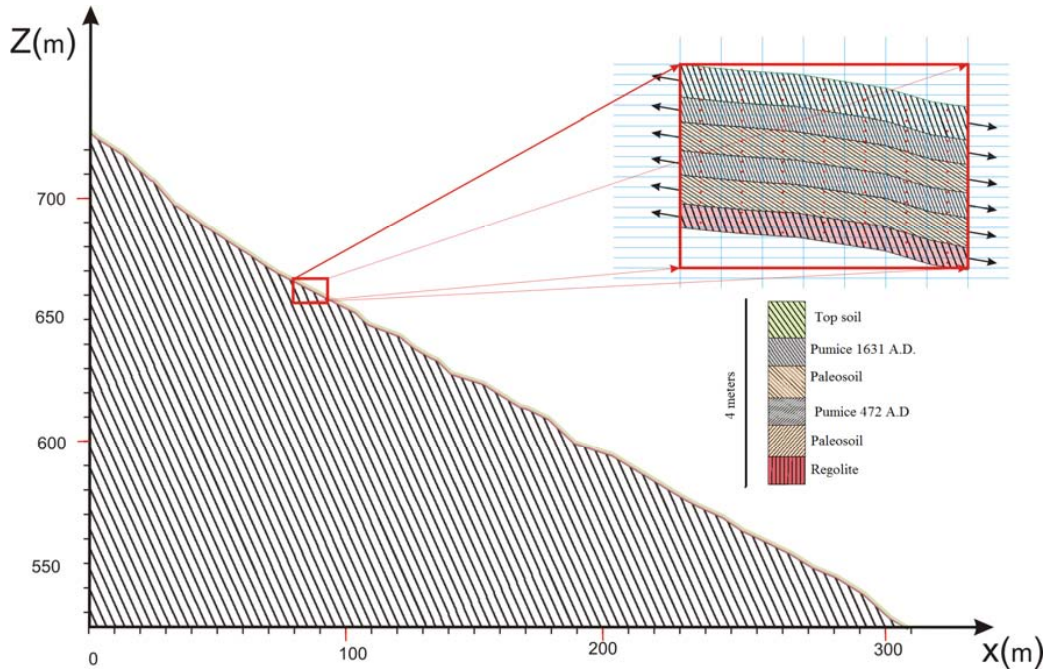
Fig. 2. Geometric and stratigraphic characterization of the investigated slope.

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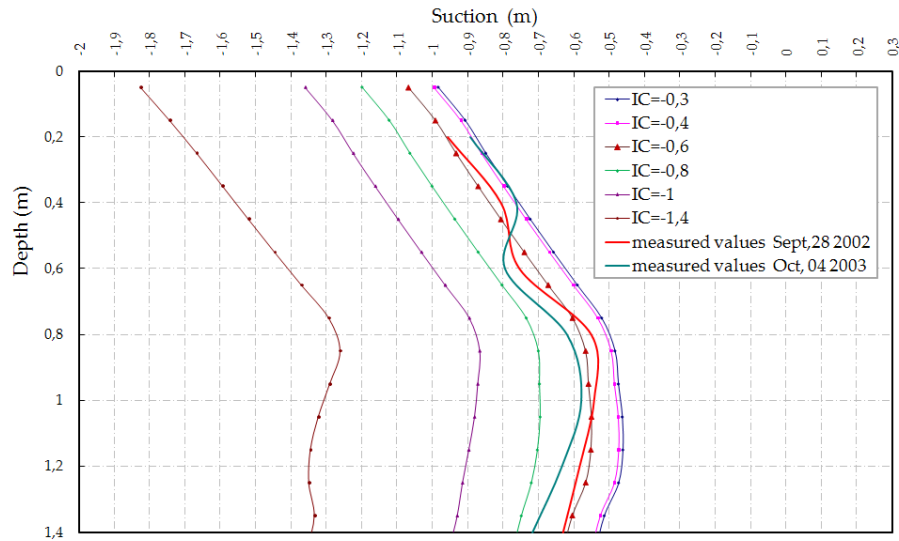
Fig. 3. Comparison between the suction values measured (red and green lines) and simulated for each initial condition (lines with dots).
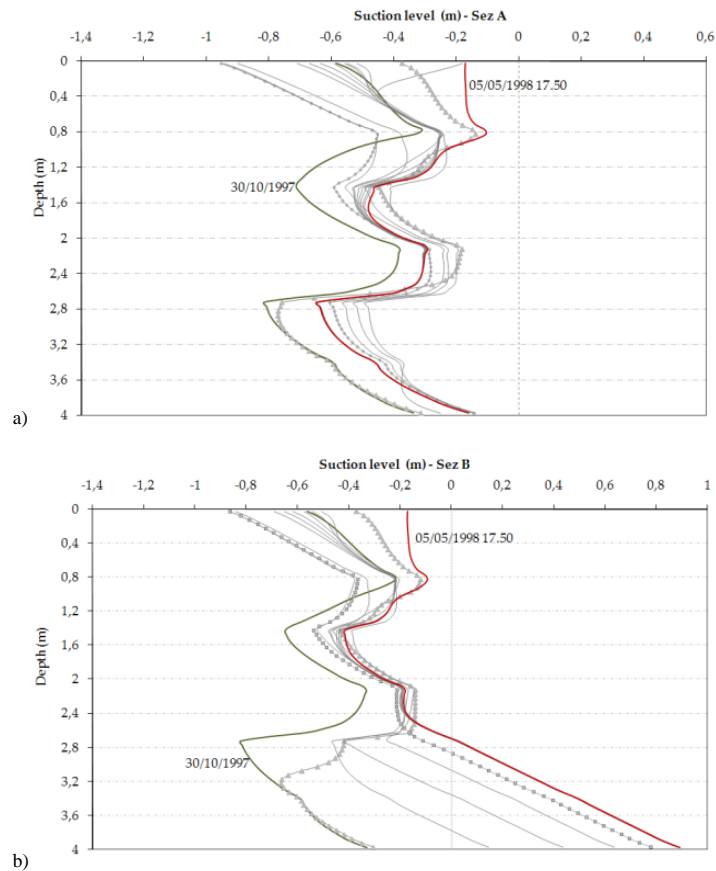
Fig. 4. Suction profile for **(a)** the upslope section (Sez A) and **(b)** the downslope section (Sez B).

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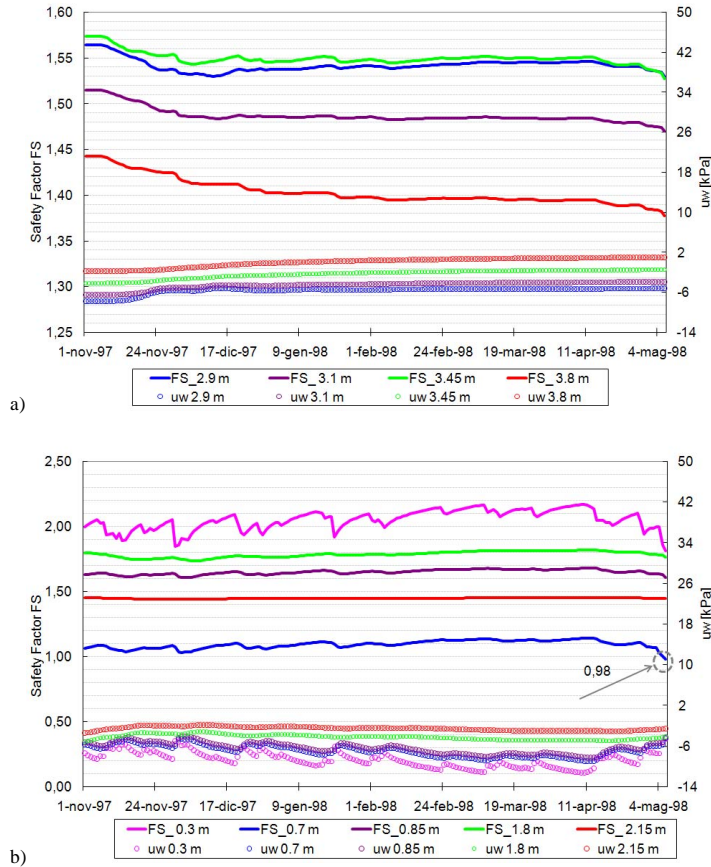
Fig. 5. Pore water pressure distribution and FS values at different depths.