

Field investigation of soil-atmosphere interaction on a slope prone to shallow landslides

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Abstract – Long-term field monitoring of slopes prone to shallow landslides can be a fundamental tool for the identification of failure conditions. The aim of this work was the development of a field monitoring system able to integrate different meteorological and hydrological tools, in order to enhance both frequency and quality of measurements. The equipment was installed on a slope susceptible to shallow landslides in north-eastern Oltrepò Pavese (Northern Italy). Some expedients were established to improve the interpretation of field data. This allowed for checking the accuracy of the data and obtaining a reliable comprehension of the soil-atmosphere interaction mechanisms. This approach can lead to a better identification of shallow landslides triggering conditions, in terms of both the failure mechanism and the occurrence time.

I. INTRODUCTION

In recent years, integrated hydro-meteorological techniques were developed to investigate soil hydro-mechanical behaviour and triggering conditions in slopes prone to shallow landslides [1-4]. Moreover, monitoring data were useful to improve the implementation of physically-based models able to predict shallow landslides triggering times and source areas [5].

A comprehensive monitoring system should take into account different soil hydrological parameters, that can help to understand soil behaviour. All these parameters should require measurements according to appropriate accuracy and range, while different measures have to be coupled to prevent the loss of important information on the soil hydrological dynamics [2].

With the purpose of improving the main methodologies adopted for classical hydrological field monitoring, the aim of this work was the development of an integrated monitoring system. To this aim, a monitoring station was installed on a slope susceptible to shallow landslides in north-eastern Oltrepò Pavese (Northern Italy) (Fig. 1). This allowed for a better identification of soil behaviour

and of soil conditions leading to shallow failures in consequence of rainfalls.

II. MATERIALS AND METHODS

A. The study slope

The monitored slope is located in the hilly sector of north-eastern Oltrepò Pavese (Fig. 1).

The topographic gradient is medium-high (26-35°). The slope is east-facing and its elevation ranges from 170 to 210m a.s.l., with the monitoring station located at 185 m a.s.l. The land use is mainly constituted by grass and shrubs. The climatic regime is temperate/mesothermal with a mean yearly temperature of 12°C and a mean yearly rainfall of 684.4 mm.

The area where the study slope is located is characterized by a high density of past shallow landslides occurred in the period 2009-2015 (Fig. 1). The study slope, in particular, was subjected to shallow failures on 27-28 April 2009, due to an extreme rainfall of 160 mm in 62 h [6], and during the event of 28 February–2 March 2014, due to a rainfall of 689 mm in 42 h [5]. The last shallow landslide occurred 15 m far from the monitoring station (Fig. 1), during the monitoring activity. The source area has the same slope angle of the zone where the monitoring station is located (30°), and the failure surface is at 1 m from the slope surface.

A multidisciplinary study was carried out to characterize the superficial soils and the weathered bedrock of the study slope. According to [7] the soil is classified as Calcic Gleysol (Abruptic, Silty), with five main soil horizons (Tab. 1). The weathered bedrock (R) was identified at 1.3 m from the slope surface.

From a pedological point of view, redoximorphic features were detected at depths between 0.4 and 1.1 m. They resulted from alternating periods of reduction and oxidation of iron and manganese compounds in the soil.

Soil levels are calcareous (13.7-16.1%), with the presence of a calcic horizon at 1.2 m from the slope surface (level G), where the carbonate content is of 35.3%.

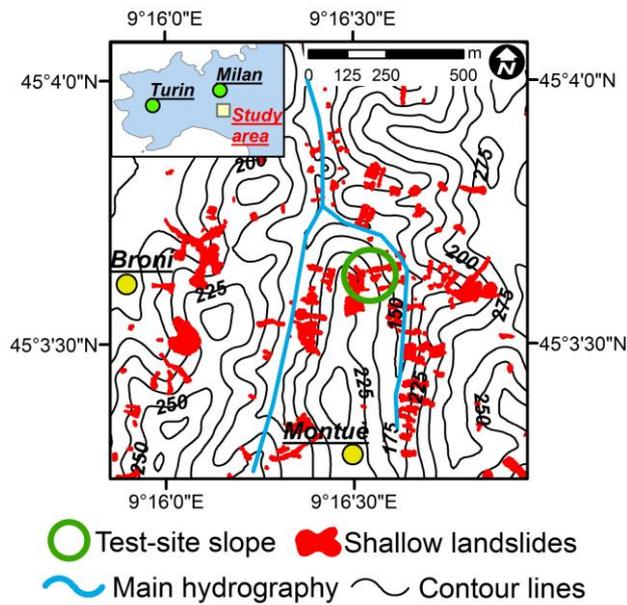


Fig. 1. Monitored test-site slope location

Table 1. Main geotechnical features of study slope soils and weathered bedrock.

	Depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	USCS	γ (kN/m ³)
C	0.2	12.3	12.5	53.9	21.3	CL	17.0
D	0.4	1.5	11.4	59.4	27.7	CL	16.7
E	0.6	8.5	13.2	51.1	27.2	CL	16.7
F	1.0	2.4	12.2	56.4	29.0	CL	18.6
G	1.2	0.5	7.5	65.6	26.4	CL	18.3
R	1.4	0.2	75.0	24.8	0.0	-	18.1

Soil horizons have a high silty content (51.1-65.6%), and clay content higher than 21.3% (Tab. 1). Gravel and sand contents are rather low in the soil layers, till 0.5% and 7.5% in horizon G, respectively. Instead, the weathered bedrock has a loamy-sand textural class, with a sand content of 75% (Tab. 1).

According to the USCS classification, soil horizons are prevalently non-plastic or slightly plastic (CL). The unit weight (γ) has a significant increase in the F horizon from 16.7 to 18.6 kN/m³ and then keeps rather steady with depth (Tab. 2).

B. The monitoring equipment

The test-site for the installation of the monitoring equipment was chosen thanks to its representativeness of the surrounding area. The choice was also due to: a) the presence of past shallow landslides; b) its representativeness of the whole study area in terms of the geomorphological (medium-high topographic gradient)

and hydrogeological features (conglomeratic bedrock levels overlying impermeable marly levels); c) the presence of access roads to easily reach the slope and install instrumentation; d) its east-facing orientation, allowing for a good recharge of the photovoltaic panel of the station that supplied power to the devices.

The station collects data with a time resolution of 10 min. Several meteorological parameters are measured. In particular, the station has: a rain gauge (Model 52203, Young Comp., Traverse City, MI) to measure rainfall amount; a thermo-hygrometer (Model HMP155A, Campbell Sci. Inc., Logan, UT) to measure air temperature and humidity; a barometer (Model CS100, Campbell Sci. Inc., Logan, UT) to measure atmospheric pressure; an anemometer (Model WINDSONIC, Campbell Sci. Inc., Logan, UT) to measure wind speed and direction; a net radiometer (Model NR-LITE 2, Kipp & Zonen, Delft, Netherlands) to measure net radiation.

The meteorological probes are linked to six Time Domain Reflectometer (TDR; Model CS610, Campbell Sci. Inc., Logan, UT), equipped with a multiplexer (SDMX50, Campbell Sci. Inc., Logan, UT), for measuring the soil water content at different depths, both in the soil layers and in the weathered bedrock layer (at depths of 0.2, 0.4, 0.6, 1.0, 1.2 and 1.4 m). The measurement accuracy of soil water content is in the order of 0.01-0.02 m³.m⁻³. TDR probes allow for measuring also the electrical conductivity of the water at each investigated depth.

A combination of three tensiometers (Model Jet-Fill 2725, Soilmoisture Equipment Corp., Santa Barbara, CA) and three Heat Dissipation sensors (HD; Model HD229, Campbell Sci., Logan, UT) measure the pore water pressure in the soil at 0.2, 0.6 and 1.2 m. The HD sensors only allow measurements of pore water pressures lower than -10¹ kPa (Bittelli et al. 2012); thus, tensiometers have been installed to measure pore water pressures above -10¹ kPa. The accuracy of both tensiometers and HD sensors is 1.5-2 kPa. To obtain appropriate measurements of high levels of suction, HD sensors were calibrated in the laboratory before field installation, according to a procedure previously described in [8, 2], by using soil samples taken in the test slope where the monitoring system was installed.

Field data are collected by a datalogger (CR1000X, Campbell Scientific, Inc.) powered by a photovoltaic panel. In this work, field data acquired between 27 March 2012 and 13 December 2015 are considered. The devices apt to measure hydrological parameters were positioned in the undisturbed soil next to a trench pit, purposely dug for the installation of the datalogging system and then they were connected to the same system. Meteorological sensors were installed on the slope surface, in correspondence of the datalogging system.

The main maintenances of the instrumentation concerned the distilled water refilling of tubes and caps of the tensiometers, in particular during summer and autumn

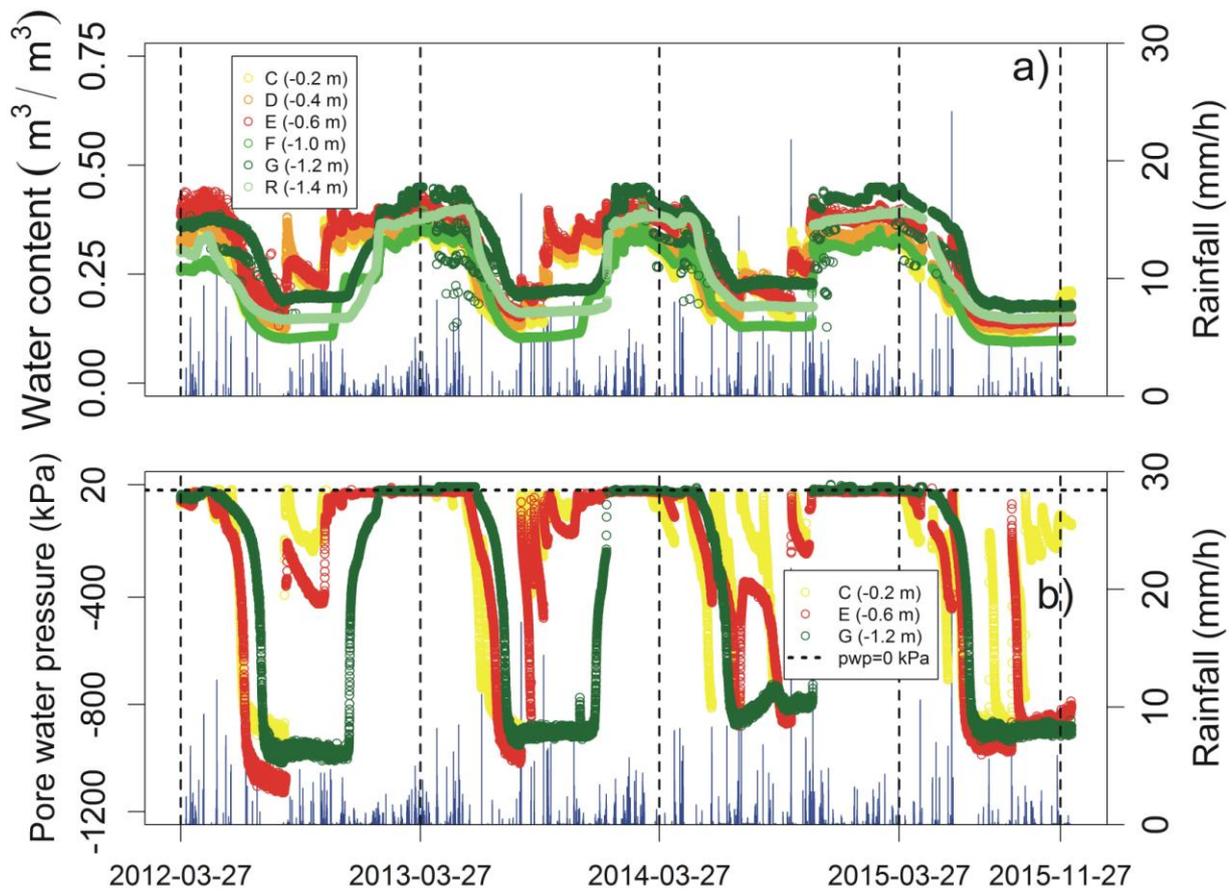


Fig. 2. Soil water content (a) and soil pore water pressure (b) trends during the monitored time span at different depths in test-site slope.

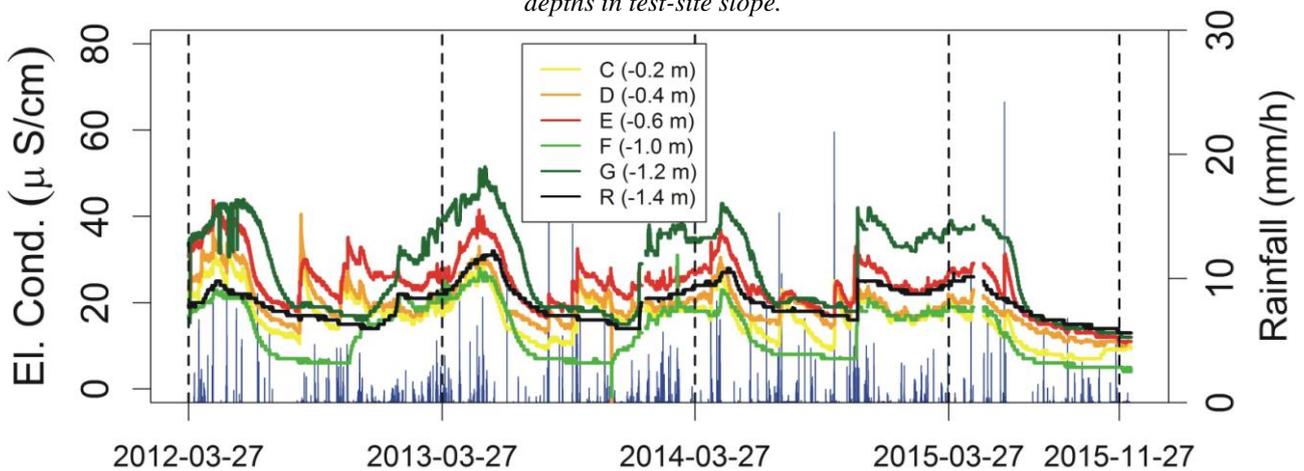


Fig. 3. Water electrical conductivity (El. Cond.) trends during the monitored time span at different depths in test-site slope.

months, as usually required for Jet-Fill tensiometers. After the refilling, air bubbles, which could be entrapped in the tube during this phase, were expelled by pushing a button on the cap. Recovery of the device was in the order of 1-2 hours. Furthermore, the tensiometers were covered with plastic panels to avoid the freezing of the water in the caps, especially during winter months.

III. RESULTS AND DISCUSSIONS

A. Observed hydrological behaviour of the monitored soils and of the weathered bedrock

Long-term continuous monitoring allowed for identifying the main hydrological behaviour of different

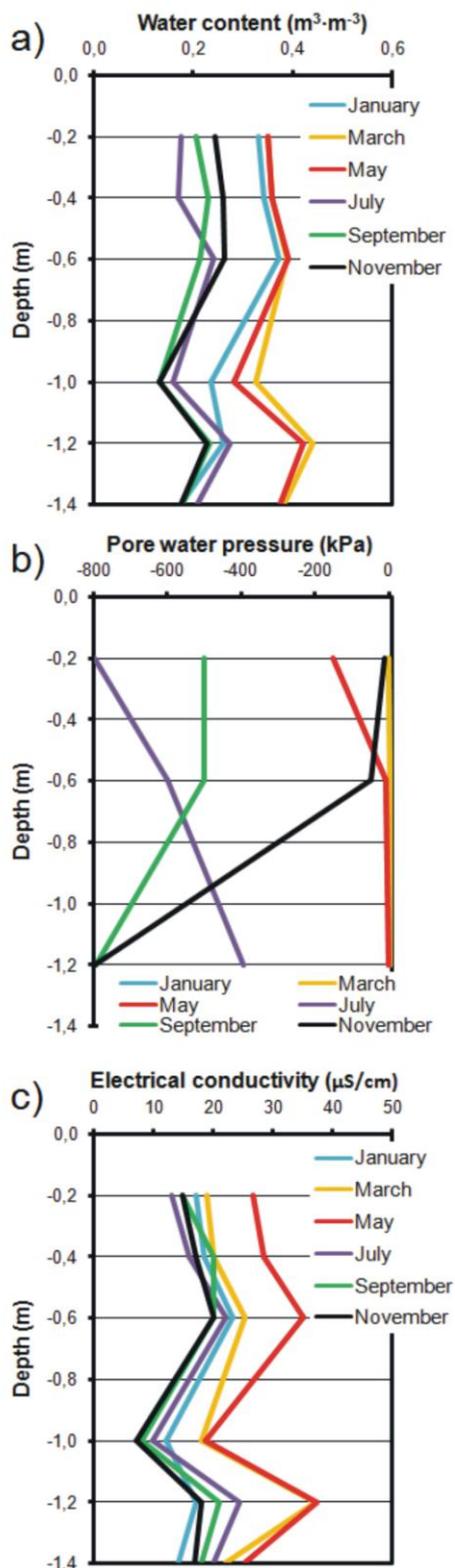


Fig. 4. Typical seasonal trends of the monitored hydrological parameters at the test-site slope: a) water content; b) pore water pressure; c) water electrical conductivity.

soils layers and of the weathered bedrock. In particular, the behaviour was related to the time trends of soil water content, pore water pressure and water electrical conductivity associated with rainfall trends (Figs. 2, 3). For the analyses, average hourly values were considered. Due to the breakage of the tensiometer installed at 0.2m from the slope surface, at this depth pore water pressure in the range between 0 and -10^1 kPa was not measured since November 2012 till the end of the analysed period. No data were acquired only in the periods when an incorrect functioning of the station alimentation system occurred. This was linked to periods of prolonged absence of solar light able to recharge the alimentation system through the solar panel. In particular, due to this inconveniences, the station did not acquire in the following periods: 9-15 January 2014, 28-29 November 2014, 25-26 June 2015. No data were acquire between 1 and 15 May 2015 for an accidental disconnection of the alimentation system. Only 26 days of data were then lost during the 45 months.

TDR measurements of water content were checked in the first stages of the monitoring period and, in order to reject uncorrected values, such as those around $1.0 \text{ m}^3 \cdot \text{m}^{-3}$, an appropriate algorithm has been developed and applied. Moreover, this expedient reduced the degree of scattering (Fig. 2a), thus favouring the interpretation of the data. Instead, for the first three months after the installation of the monitoring station, the interpretation of water content and pore water pressure trends resulted rather difficult, due to the persistency of a high degree of scattering even after the algorithm application (Fig. 2). This was more pronounced for TDR probes at depths of 0.6 and 1.2 m (Fig. 2a). It can be observed that this behaviour was due to a required initial period in which sensors (in particular, the ceramic stone of the tensiometers, the HD sensors and the sticks of the TDR probes) had to progressively adhere to the surrounding soil after installation, in order to reach the required balance and thus allowing data acquisition.

Moreover, the installed tensiometers required a correction of the measured values due to the height of the water column present in the device, thus causing an increase of 1 kPa of the initial values for each 0.1 m of depth in the soil. For the same reason, it was possible to measure also positive values of the pore water pressure [9].

Pore water pressure measurements had a good level of confidence. In different seasons, some laboratory tests were carried out with the filter paper and field tests were performed through a portable tensiometer (Model Quick Draw, Soilmoisture Equipment Corp.). They gave pore water pressure values very similar to those measured by the field monitoring system. The differences were in the order of 1–2 kPa, very close to saturation, till 10-20 kPa far from the saturated conditions. Thanks to these indications, field acquired data allowed for identifying the main hydrological features of the test-site slope.

In the analysed period, the water content ranged between

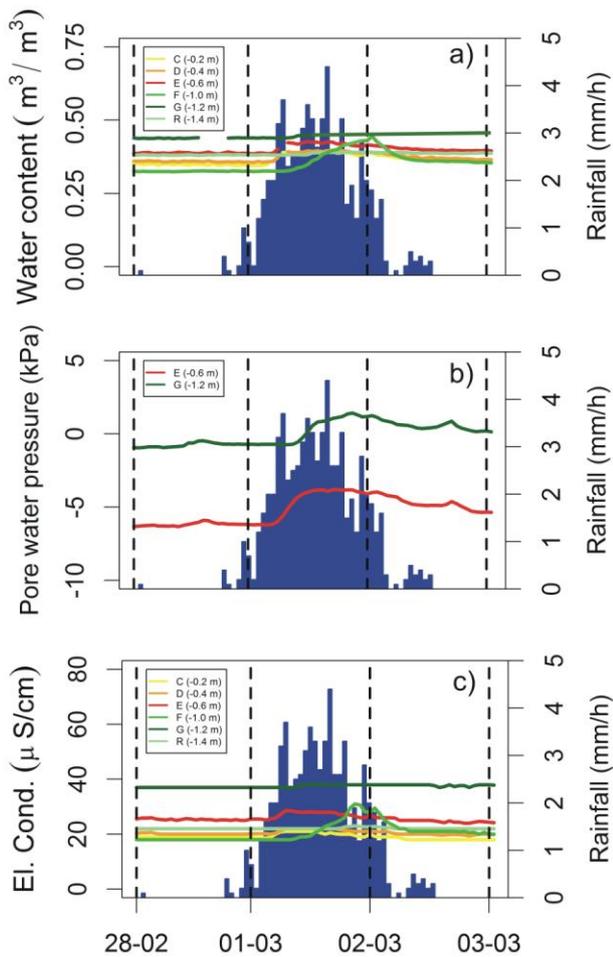


Fig. 5. Monitored hydrological parameters trends during the triggering event of 28 February-2 March 2014: a) water content; b) pore water pressure; c) water electrical conductivity.

0.10 and $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ in the soil, and between 0.15 and $0.38 \text{ m}^3 \cdot \text{m}^{-3}$ in the weathered bedrock (Fig. 2a). Instead, pore water pressure ranged from positive values, till 12.7 kPa in the G horizon, to values in the order of -10^3 kPa (Fig. 2b). Water electrical conductivity ranged between 10 and $55 \mu\text{S}/\text{cm}$ (Fig. 3).

Tensiometers correctly measured pore water pressure only when the horizons were close to saturation, in a range of pore water pressure higher than -50 kPa. This happened usually in the period November-May at 0.6 m from the slope surface, and in the period January-May at the depth of 1.2 m.

Typical hydrological behaviour of shallow soil layers, till 0.6 m from slope surface, was very different with respect to the deeper layers (Figs. 2, 4). The response of soil horizons till 0.6–0.7 m from the slope surface was quicker than the deepest ones during long dry (summer months) or long wet (winter-spring months) periods (Fig. 2). Only prolonged rainy periods, especially during winter months, could cause an increase in soil saturation, testified by an increase of pore water pressure and of soil

water content at depths higher than 0.7m.

The typical conditions of the most wet months, between December and May, showed that frequent precipitations provoke an increase of the soil wetness until it approaches or reaches saturated conditions (Fig. 4). Completely saturated conditions were reached in the G horizon only in winter and spring, as testified by values of pore water pressure slightly lower or higher than 0 kPa (Figs. 2b, 4b). In wet periods, shallow soils till 0.6 m approached saturated conditions, with an increase of pore water pressure till values of -3 kPa and with values of measured soil water content around $0.40 \text{ m}^3 \cdot \text{m}^{-3}$. During wetting periods, water content in the weathered bedrock was lower than in the overlying G horizon (Fig. 2a). According to the monitored data, it could be supposed that during wet periods (winter and spring) a perched water table forms in the G horizon, and this condition keeps for the most wet period of the year (Figs. 2, 4).

The thin perched water table formed at the interface between the shallow soil and the weathered bedrock, and then it up-raised till the G horizon, for a thickness of about 0.1-0.2 m. The trends of water electrical conductivity measured through the TDR probes confirmed that this water table was not linked to an up-rise of a deep groundwater level of bedrock materials. The electrical conductivity at a depth of 1.2 m, in the G horizon, reached the highest monitored values of $50 \mu\text{S}/\text{cm}$ in the periods when the water table developed (Figs. 3, 4c). The soil horizons above the G level and the weathered bedrock were characterized by values lower than $40 \mu\text{S}/\text{cm}$ (Figs. 3, 4c). It seemed clear that there was no uprising of a deep water table from the bedrock to the superficial soil, as demonstrated by water electrical conductivity values in the range of rainfall water.

During the most dry periods and for the re-wetting events in early-autumn, the re-wetting of the soil horizons till 0.6–0.7 m was very rapid (Figs. 2, 4). In correspondence of concentrated summer rainstorms, generally more than 10 mm in 2 h, pore water pressure increased but it was not coupled with a correspondent increase in water content (Figs. 2, 4). This could be linked to non-equilibrium processes due to fast infiltration [10] in which pore water pressure or water content trend lags behind each other by the water retention equilibrium. The evidences of these processes were collected thanks to the measurements of the HD sensors, which allowed for measuring pore water pressure dynamics also in soil conditions starting from values of pore water pressure around -10^2 and -10^3 kPa.

B. Identification of shallow landslides triggering mechanism

Thanks to the shallow landslide occurred near the field station during the monitoring activity, the triggering mechanism could be detected and identified. In correspondence of the triggering rainfall event of 28

February-2 March 2014 (68.9 mm in 42 h), the shallow soil till 0.6–0.7 m, the G horizon and the weathered bedrock at 1.4 m behaved as in the other rainfall events in winter–spring months, with a slight increase of soil water content (less than $0.05 \text{ m}^3 \cdot \text{m}^{-3}$) and of pore water pressure (less than 3–4 kPa) (Fig. 5). On the contrary, the F horizon at a depth of 1 m was affected by a significant increase of water content, passing from $0.32 \text{ m}^3 \cdot \text{m}^{-3}$ to values similar of those measured in the G horizon (higher than $0.40 \text{ m}^3 \cdot \text{m}^{-3}$; Fig. 5a). This increase testified an uprising of the perched water table, which was usually present in the G horizon in wet months, till 1.0 m, leading to the complete saturation of the F horizon, which was enough for the triggering of the shallow landslide at that depth. During this event, water electrical conductivity kept steady in all the investigated levels except for the F horizon at 1.0 m of depth, which was affected by an increase till around $30 \mu\text{S}/\text{cm}$ (Fig. 5c), thus confirming the up-rising of the perched water table. The temporary uprising of the water table above the G horizon during intense rainfalls could be also confirmed by the redoximorphic features at the same depth. This behaviour can be considered the triggering mechanism of rainfall-induced shallow landslides in the test-site slope.

IV. CONCLUSIONS

Hydrological monitoring of slopes prone to shallow landslides can be a fundamental tool for the identification of the soil condition, which lead to failures triggering. In this research, a traditional scheme of field monitoring was enhanced with some expedients, in order to improve the comprehension of soil-atmosphere interaction. In particular, the main innovations made by this working scheme regarded the following aspects:

- the implementation of an algorithm for TDR values of water content in the first stages of the monitoring activity allowed for checking measurements, in order to reject uncorrected values and decrease their degree of scattering;
- coupling HD sensors and tensiometers allowed for covering the entire range of variation of pore water pressure, identifying complete soil hydrological behaviour related to different rainfall trends;
- the correction of the measurements of the installed tensiometers, due to the height of the water column present in the instrument, allowed for measuring also positive values of the pore water pressure, detecting the formation of a perched water table in the soil;
- simultaneous measurements of water content and pore water pressure dynamics highlighted the main soil hydrological behaviours, and also particular phenomena as non-equilibrium processes in the most superficial horizons during summer storms;
- monitoring of water electrical conductivity improved the comprehension of soil behaviour, in particular to

detect the dynamics of the water table in the soil.

This setting of a monitoring system improved the comprehension of the phenomena and the triggering mechanism of shallow landslides. This system could represent an effective tool also in other geological and environmental contexts affected by shallow landslides. In fact, future developments will be the analyses of a similar monitoring system in a slope with clayey soils.

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