Hydrological field monitoring and geotechnical characterisation of terraced slope prone-to-landslide: the case study of Cinque Terre (Italy)

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SUMMARY: Shallow landslides triggered by strong rainfall represent a widespread geological hazard impacting natural and anthropic environments. The study of geological and hydrological features of soil represents an essential task in understanding the slope behaviour when struck by heavy rainfall, significantly when the presence of man-made terraces modifies the regularity of the relief. To address this purpose, a multi-sensor monitoring system has been operating in the Monterosso al Mare catchment (Liguria region, Italy) since 2018, acquiring both hydrological parameters and weather conditions. The data acquired in this way were interpreted based on the engineering geological model obtained starting from the field investigations to point out the hydro-mechanical characterisation of terraced soils and to evaluate their hydrological behaviour. The first results suggest how the coarse-grained grain size distribution favours the infiltration of meteoric water, inducing sharp changes in soil moisture and pore water pressure and highlighting seasonal trends. The preliminary outcomes provide valuable insights into the evolution of hydrological factors in the slope, laying the groundwork for a better understanding of the time-dependent processes that guide water circulation in terraced systems and the triggering conditions to landsliding.

Keywords: terraced slope, multi-parametric soil monitoring, soil hydrological behaviour, rainfall-induced landslides, Cinque Terre National Park

Introduction

Shallow landslides due to heavy rainfall, like slides and flows, represent a common geological hazard that frequently interferes with the anthropic component of the environment (Marc et al., 2018). In recent years, the frequency of strong rainfall events has increased due to global climate changes amplifying their impact on the environment (Kirschbaum et al., 2012; Gariano et al., 2020). Failure initiation can be correlated to a wide range of destabilising factors, among which the most notable are soil saturation due to the perched water table, slope-parallel or upward groundwater seepage, matrix suction dissipation during rainwater infiltration and groundwater seepage mechanisms from fissures of the underlying bedrock (Crosta, 1998; Guadagno et al., 2005; Bordoni et al., 2015; Bogaard et al., 2016).
Terraced slopes are one of the most widespread man-made landscapes, especially in regions where rural activities have played an important economic role (Tarolli et al., 2014). Today,

these landscapes represent cultural heritage because of their historical and environmental value, increasing tourism and social and economic development (Brandolini, 2017; Varotto et al., 2019). Terraces enable agriculture in steep terrains, and slope gradient reduction is obtained by cutting naturally steep slopes to produce a step-like profile. The slope topography adjustment leads to a mitigation of both runoff and soil erosion processes, which is accompanied by increased infiltration. This increases soil moisture content (Stanchi et al., 2012). However, in the case of intense rainfall, the progressive saturation of soils and the development of critical regimes of pore-water pressures can negatively affect slope stability (Camera et al., 2012, 2014; Preti et al., 2018). The occurrence of mass movements along agricultural terraced slopes can have serious consequences in terms of economic loss also in terms of risk scenarios for infrastructures, settlements, and people (Agnoletti et al., 2019; Giordan et al., 2020). To effectively address the complex hydrological dynamics occurring in terraced slopes, it is essential to investigate the soil's hydromechanical and geotechnical features and acquire the longest possible monitoring data series. The following presents the outcomes of more than two years of continuous monitoring of the soil hydrological parameters in a terraced slope, susceptible to shallow landsliding, in the Cinque Terre National Park (northwestern Italy).

Materials and Methods

A multi-sensors monitoring system devoted to recording both meteorological forcings and hydraulic parameters of the soil has been operating since 2018 on a portion of a terraced slope located within the Pastanelli-Morione stream catchment in Monterosso al Mare (Cinque Terre, Liguria region, Italy). The Cinque Terre are well-known worldwide and represents a well-known example of a man-made area of century-old agricultural terraces retained by dry stone walls. This field study site was chosen because, in the past, it experienced several landslide events like the 25th of October 2011 flash flood when 260 shallow landslides, approximately, were triggered by extreme rainfall as debris slides, many of which evolved into debris flow and debris avalanches. The installed multi-sensors monitoring system consists of i) a fully equipped weather station, ii) soil temperature sensors, iii) soil moisture sensors, and iv) soil water potential sensors. The sensors were installed at different depths to reconstruct a vertical profile of soil hydrological conditions. Before the installation of the monitoring system, a combination of in-situ and laboratory geotechnical and geophysical investigations were carried out to define an engineering geological model across the monitoring site and to characterise the main textural, physical, and mechanical soil features. Three dynamic probing tests (DP) were performed to detect the bedrock's depth. The DP tests were performed along an alignment oriented toward the slope dip. A seismic refraction survey, consisting of one tomographic profile, was also carried out through 12 geophones and developed along the same route as the DP test. Five *in-situ* soil density determinations were also carried out using the sand cone method, sampling the soil for laboratory geotechnical determinations.

Results and main observations

The engineering geological model of the slope is based on the results of both *in-situ* surveys and laboratory determinations. The results of the DP tests highlighted that the soil cover has reduced thicknesses along the monitored section of the slope. The bedrock was detected approximately between 1.0 and 1.7 m depth. From the outcomes of the in-situ soil density measurements, the investigated soils show a natural unit weight of 14.6 ± 1.05 kN/m^3. The grain size distribution, conducted on three different samples, highlighted a sand fraction ranging from 24,7% to 28,5%, whereas gravel content ranged from 50% to 60.2%. Laboratory determination of plasticity characteristics of soil samples showed a range of 27–30% and 35–41% for plastic limit (w_P) and liquid limit (w_L), respectively, while the Plasticity Index (PI) varies between 8% and 13%. Based on the unified soil classification system (USCS), the fine-grained soil fraction is classified as inorganic silts with low to medium plasticity (ML) and organic silts and clays of low plasticity (OL).

The availability of more than two years of monitoring data allowed to analyse the variation of the soil hydraulic parameters during the different seasonal cycles. The most intense rainfall event recorded 225 mm of rain in three days, with a peak of 159 mm in a single day. Regarding hydraulic monitoring, data recorded by tensiometers showed very high matric suction values (i.e., negative soil water pressure) under hot and dry summer conditions (drought periods). These values, reaching up to −900 hPa at the deepest sensor (T1, see Figure 1), became approximately equal to zero immediately after the first autumn rains and remained primarily unchanged until the following summer (wetting periods). Furthermore, soil moisture showed a clear relationship with rainfall peaks. However, the deepest sensor (i.e., W1, see Figure 1) recorded lower values (0.05 to 0.15) than the others (0.10 to 0.3). Regarding the spatial distribution of the sensors (Fig. 3), it is observed that those positioned downstream in the terrace (e.g., W5 and W3, see Figure 1) generally recorded higher soil moisture than the sensor positioned upstream in the terrace at the same depth (e.g., W2–W4 and W1, see Figure 1).

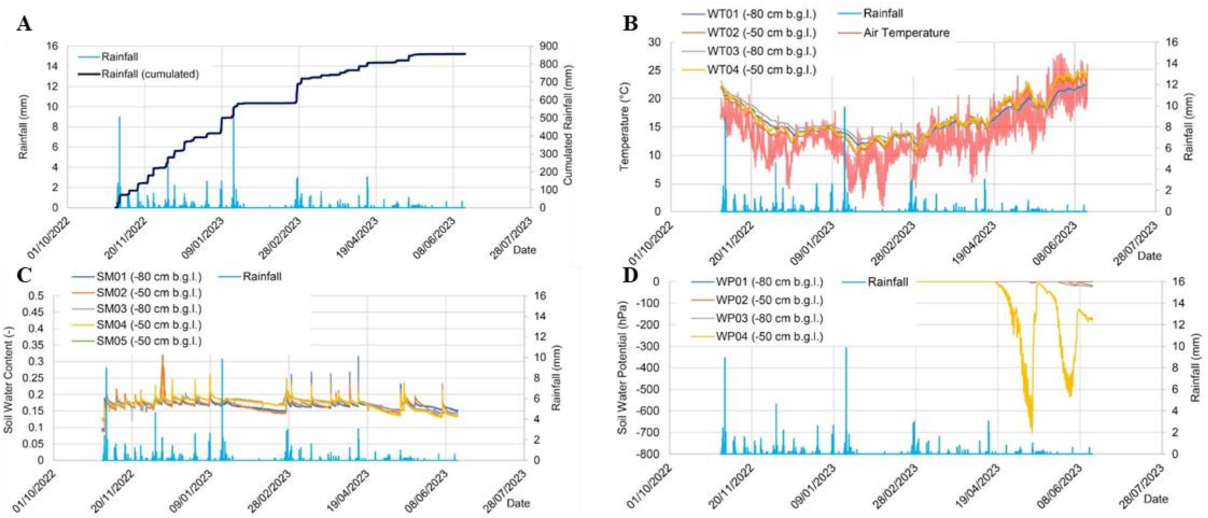

Figure 1: Multi-parametric data acquired from 2018 to 2020: (A) rainfall air and soil temperature, (B) air and soil temperature, (C) soil moisture (W) and (D) pore water pressure data (T).

Thanks to the availability of monitored data, it was possible to investigate the soil hydraulic behaviour through the reconstruction of the Soil Water Retention Curves (SWRCs), obtained by crossing point-by-point the matric suction values and soil moisture conditions. The curve's trend offers an overview of the hydrological properties of the soil and proceeding to their fitting, according to the van Genuchten equation (1980), it is possible to obtain the volumetric water content parameters in saturation and residual conditions (θ_s e θ_r), and the empirical parameters dependent on the pore-air pressure (α) and on the pore size distribution (n). The parameters thus obtained allow us to proceed with stability analysis of the surface beds, which is also possible continuously thanks to site monitoring data, which returns values of the safety factor according to the approach of Lu and Godt (2008).

The developed geotechnical framework undoubtedly affects the soil's hydrogeological behaviour, suggesting that saturation may be rapid in case of rainfall. Hydrological monitoring data from continuous time series confirmed this in the field, showing fast changes in pore water pressure and a peculiar behaviour resulting from terraces and coarse grain size distribution. At this aim, the study of SRWCs from field data suggested that soil saturation is almost contextual to rainfall episodes, both on the small (seasonal) and on the large (daily) time window. As regards the hydraulic conditions of the soil along the investigated section (i.e., considering both the geometry of the slope and of the terrace bench itself with an average inclination of 27°), it is possible to notice that, in the downslope portion of the terrace, higher soil moisture values are recorded than those acquired in the upslope portion (i.e., at the same depth b.g.l.). At the investigated terraced site, the hydrological evidence coming from field monitoring may be explained through a wetting front infiltration scheme, already proposed by Schilirò et al. (2019), according to which the infiltrating water tends to accumulate on the lower edge of the terrace. Following this scheme, a reduction of the matric suction values occurs in the shallower soil layer during rainfall, and, if rain continues, positive pore water pressure can also develop.

References

Agnoletti M, Errico A, Santoro A, Dani A & Preti, F (2019) Terraced Landscapes and Hydrogeological Risk. Effects of Land Abandonment in Cinque Terre (Italy) during Severe Rainfall Events. *Sustainability* 11, 235.

Bogaard TA & Greco R (2016) Landslide hydrology: from hydrology to pore pressure. *Wires Water* 3, 439–459.

Bordoni M, Meisina C, Valentino R, Lu N, Bittelli M & Chersich S (2015) Hydrological factors affecting rainfall-induced shallow landslides: from the field monitoring to a simplified slope stability analysis. *Eng. Geol*. 193, 19-37.

Brandolini P (2017) The outstanding terraced landscape of the Cinque Terre coastal slopes (eastern Liguria). *Landforms and landscapes of Italy*. M. Soldati and M. Marchetti (eds,), (Cham, Switzerland, Springer International), pp. 235–244.

Camera C, Apuani T & Masetti M (2014) Mechanisms of failure on terraced slopes: the Valtellina case (northern Italy). *Landslides* 11, 43–54.

Camera C, Masetti M & Apuani T (2012) Rainfall, infiltration, and groundwater flow in a terraced slope of Valtellina (Northern Italy): field data and modelling. *Environ. Earth Sci*. 65(4), 1191-1202.

Crosta G (1998) Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. *Env. Geol*. 35(2-3), 131-145.

Gariano SL, Melillo M, Peruccacci S & Brunetti MT (2020) How much does the rainfall temporal resolution affect rainfall thresholds for landslide triggering? *Nat Hazards* 100, 655–670.

Giordan D, Cignetti M, Godone D, Peruccacci S, Raso E, Pepe G, Calcaterra D, Cevasco A, Firpo M, Scarpellini P & Gnone MA (2020) New Procedure for an Effective Management of Geo-Hydrological Risks across the "Sentiero Verde-Azzurro" Trail, Cinque Terre National Park, Liguria (North-Western Italy). *Sustainability* 12(2), 561-578.

Guadagno FM, Forte R, Revellino P, Fiorillo F & Focareta M (2005) Some aspects of the initiation of debris avalanches in the Campania Region: the role of morphological slope discontinuities and the development of failure. *Geomorphology* 66, 237–254.

Kirschbaum D, Adler R, Adler D, Peters-Lidard C & Huffman G (2012) Global distribution of extreme precipitation and high impact landslides in 2010 relative to previous years. *J Hydrometeorol* 13, 1536–1551.

Lu N & Godt J (2008) Infinite slope stability under steady unsaturated seepage conditions. *Water Resour. Res.* 44, W11404. DOI: 10.1029/2008W R006976

Marc O, Stumpf A, Malet JP, Gosset M, Uchida T & Hao CS (2018) Initial insights from a global database of rainfall-induced landslide inventories: the weak influence of slope and strong influence of total storm rainfall. *Earth Surf Dyn* 6, 903–922.

Preti F, Guastini E, Penna D, Dani A, Cassiani G, Boaga J, Deiana R, Romano N, Nasta P, Palladino M, Errico A, Giambastiani Y, Trucchi P & Tarolli P (2018) Conceptualization of water flow pathways in agricultural terraced landscapes. *Land Degr. Dev*. 29(3), 651-662.

Schilirò L, Poueme Djueyep G, Esposito C & Scarascia Mugnozza, G (2019) The role of initial soil conditions in shallow landslide triggering: insights from physically based approaches. *Geofluids* 2019, 2453786.

Stanchi S, Freppaz M, Agnelli A, Reinsch T & Zanini E (2012) Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): A review. *Quat. Int*. 265, 90–100.

Tarolli P, Preti F & Romano N (2014) Terraced landscapes: from an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* 6, 10–25.

van Genuchten M, Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898. DOI: 10.2136/sssaj1980.03615995004400050002x

Varotto M. Bonardi L and Tarolli P (2019) World terraced landscapes: History, environment, quality of life, environmental history. Cham, Switzerland: Springer Nature Switzerland AG DOI: 10.1007/978-3-319-96815-5.