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SLOPE RESPONSE TO EFFECTIVE RAINFALL OF A LARGE, COMPLEX ROCK-SLIDE IN FLYSCH MATERIAL

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EXTENDED ABSTRACT

La frana di Camugnano, Provincia di Bologna, interessa un'area di 9.1×105 m^2. È classificabile come un fenomeno complesso, che unisce scorrimenti roto-traslativi all'interno del flysch arenaceo della Formazione di Camugnano (con superficie di scorrimento profonda profonda fino a oltre 60 m) e scorrimenti-colate di terra che interessano i prodotti della degradazione del flysch e di altre formazioni argillitiche che affiornano nella parte inferiore del pendio.

La frana è caratterizzata da spostamenti molto lenti (~4 cm/anno) e ha subito in passato eventi di accelerazione, l'ultimo importante dei quali nel 2014. A seguito di quest'ultimo evento, il pendio è stato oggetto di indagini e monitoraggio, tra cui sondaggi, indagini geofisiche e monitoraggio degli spostamenti e delle acque sotterranee, con inclinometri, capisaldi Global Navigation Satellite System (GNSS) e Stazione Totale Robotizzata (RTS).

In questa nota, si vogliono sintetizzare i risultati ottenuti dal monitoraggio, confrontandoli con l'andamento delle precipitazioni efficaci, al fine di evidenziare la risposta del pendio alle forzanti meteo-climatiche su un periodo pluriennale. In particolare, la precipitazione efficace è stata calcolata mediante la formulazione di Thornthwaite avvalendosi dei dataset di temperatura media giornaliera e di precipitazioni cumulate giornaliere acquisiti dalla stazione Diga del Brasimone, posta a circa 5 km di distanza dalla frana.

Il dataset di monitoraggio inclinometrico, ha permesso l'individuazione delle superfici di scivolamento, e di estrarre serie temporali integrando gli spostamenti sulle superfici di scivolamento. Le campagne GNSS periodiche hanno rivelato tassi di spostamento variabili da 30 a 70 mm/anno, in generale progressiva diminuzione dal 2014 al 2022. Il monitoraggio RTS ha indicato movimenti lenti ma visibili all'interno della frana. Il confronto tra spostamenti GNSS e precipitazioni mostra tassi di spostamento relativamente costanti indipendentemente dalle variazioni delle precipitazioni efficaci. Ciò si osserva anche in riferimento ai dati inclinometrici. Il monitoraggio delle piezometrie ha rivelato fluttuazioni stagionali con picco durante il periodo invernale nella maggior parte dei piezometri. Tuttavia, non è stata osservata alcuna tendenza della falda a lungo termine.

I risultati del monitoraggio mostrano una diversa risposta del versante instabile all'andamento delle precipitazioni efficaci che appare dipendente dal tempo intercorso rispetto l'ultima maggiore riattivazione: si evidenziano, a seguito della riattivazione del 2014, temporanee e localizzate accelerazioni gradualmente meno rilevanti negli anni successivi. Ciò evidenzia come la relazione tra piogge e variazioni di velocità di queste grandi frane sia in realtà una questione piuttosto complessa, e che non possano farsi semplificate assunzioni circa il fatto che periodi maggiormente piovosi o siccitosi possano necessariamente corrispondere ad accelerazioni o rallentamenti del tasso di movimento di queste frane, e che le strategie di mitigazione possano di conseguenza essere adattate in accordo a questo complesso stile di attività che è stato possibile definire solo grazie a tecniche di monitoraggio di lungo termine e di analisi dei dati, che risultano essere valide metodologie per ottenere una comprensione più precisa della dinamica dei pendii in fenomeni franosi complessi.

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ABSTRACT

The Camugnano landslide, located in the Province of Bologna, affects an area of 9.1×105 m^2. It is considered a complex phenomenon involving both roto-translational kinematics within the Camugnano Formation's arenaceous flysch and translational slides that affect the degraded products of the flysch and other clay materials in the lower sector of the unstable slope. The activity of the landslide is characterized by very slow displacement rates (4 cm/year), with occasional acceleration events in the past. The most recent significant event occurred in 2014. In response, various surveys and monitoring activities were conducted, including the use of boreholes, geophysical surveys, displacement measurements through inclinometers, Ground Navigation Satellite System (GNSS), and Robotic Total Station (RTS), and groundwater monitoring through pressure transducers installed in piezometers. The aim of this note is to summarize the monitoring results and compare them with the trend of effective rainfall over multiple years. To determine effective precipitation, the Thornthwaite formulation was used, based on mean daily temperature and daily cumulative rainfall data from the Diga del Brasimone gauge station, located approximately 5 km from the landslide site.

The inclinometer monitoring helped identify the sliding surfaces and obtain time series data by integrating displacements on these surfaces. GNSS campaigns conducted periodically revealed displacement rates ranging from 30 to 70 mm/year, generally decreasing progressively from 2014 to 2022. RTS monitoring indicated slow but detectable movements within the landslide. Then comparing GNSS displacements with precipitation data, it was found that displacement rates remained relatively constant regardless of variations in effective precipitation. This trend was also observed when analysing inclinometer data. The groundwater monitoring showed seasonal fluctuations, with peak levels occurring during the winter period in most piezometers. However, no long-term groundwater trend was observed.

The displacement record highlights a variable sensitivity of the slope to effective rainfall with respect to the last major reactivation event. Temporary, localized accelerations are in fact recorded after 2014, gradually decreasing in magnitude in the next years.

These findings suggest that mitigation strategies could by modified according to this style of activity and indicate that assumptions linking rainy or dry periods to variations in movement acceleration or deceleration may be overly simplistic.

Keywords: *deep-seated landslides, northern Apennines Flysch, displacement monitoring, effective rainfall.*

INTRODUCTION

Rainfall is generally acknowledged as a crucial factor in controlling landslides triggering and movement rates, primarily due to the process of water infiltrating the soil, which leads to an increase in pore water pressure and, consequently, a decrease in shear strength (Iverson, 2000; Wieczorek, 1996). However, the specific relationship between rainfall rates and the variation of velocity of large, deep-seated landslides remains in most cases unclear (Preisig, 2020; Preisig *et alii*, 2016; Vallet *et alii*, 2016). This is due to the fact that large deep-seated landslides are complex due to their size, volume and heterogeneity (Tacher *et alii*, 2005), as well as because they involve different kinematics (Eberhardt *et alii*, 2007; Zangerl *et alii*, 2010) and geo-mechanical behaviours (Petley & Allison, 1997). Deep-seated landslides often exhibit very slow (< 1.6 m/year) or extremely slow (< 16 mm/year) displacement rates, as a consequence, their characterization is attainable only by multi-method, long-term, high resolution monitoring instruments (Simeoni *et alii*, 2020), while other remote sensing techniques are generally less effective in this context (Tondo *et alii*, 2023).

These landslides may also alternate periods of dormancy or slow movements and periods of reactivation during which velocity increases significantly (Bertolini *et alii*, 2017). In some geologic settings, they can also lead to catastrophic paroxysms (Azzoni *et alii*, 1992; Brideau *et alii*, 2005; Chigira & Kiho, 1994). This highlights the need of monitoring large landslides response to effective rainfall, so to support, also, scenarios of their possible evolution in the frame of climate changes.

This research focuses on the long-term monitoring of a large deep-seated landslide in the Northern Apennines and on the identification of its limited response to effective rainfall over several years.

THE CAMUGNANO LANDSLIDE

The Camugnano landslide extends over an area of 9.1 × 105 m^2 in Northern Apennines (Figure 1). In the upslope sector, deep-seated roto-translational rock-slides (units A and B), affect the late-Cretaceous arenaceous flysch rock masses of the Camugnano Formation (CAU, Bettelli *et alii*, 2002). In the lowermost portion of the slope, earth slides (unit C) affect fine-grained deposits resulting from the disaggregation and weathering of the Camugnano Formation as well as of the clayshales of the Grizzana Morandi Formation (AVT). It can thus be considered a complex phenomenon according to the classification of Cruden & Varnes, (1996). A reference cross section that shows the units arranged in a nested configuration is presented in Figure 1b.

The landslide is active continuous at very slow displacement rates, in the order of few cm/year (Bayer *et alii*, 2018) and it has undergone at least six main acceleration events in historic times, the first one dating back to spring 1934 and the last one to spring 2014 (Piacentini *et alii*, 2018). After the 2014 acceleration event, which caused significant damages to some buildings of Camugnano village and the main road serving the area, the

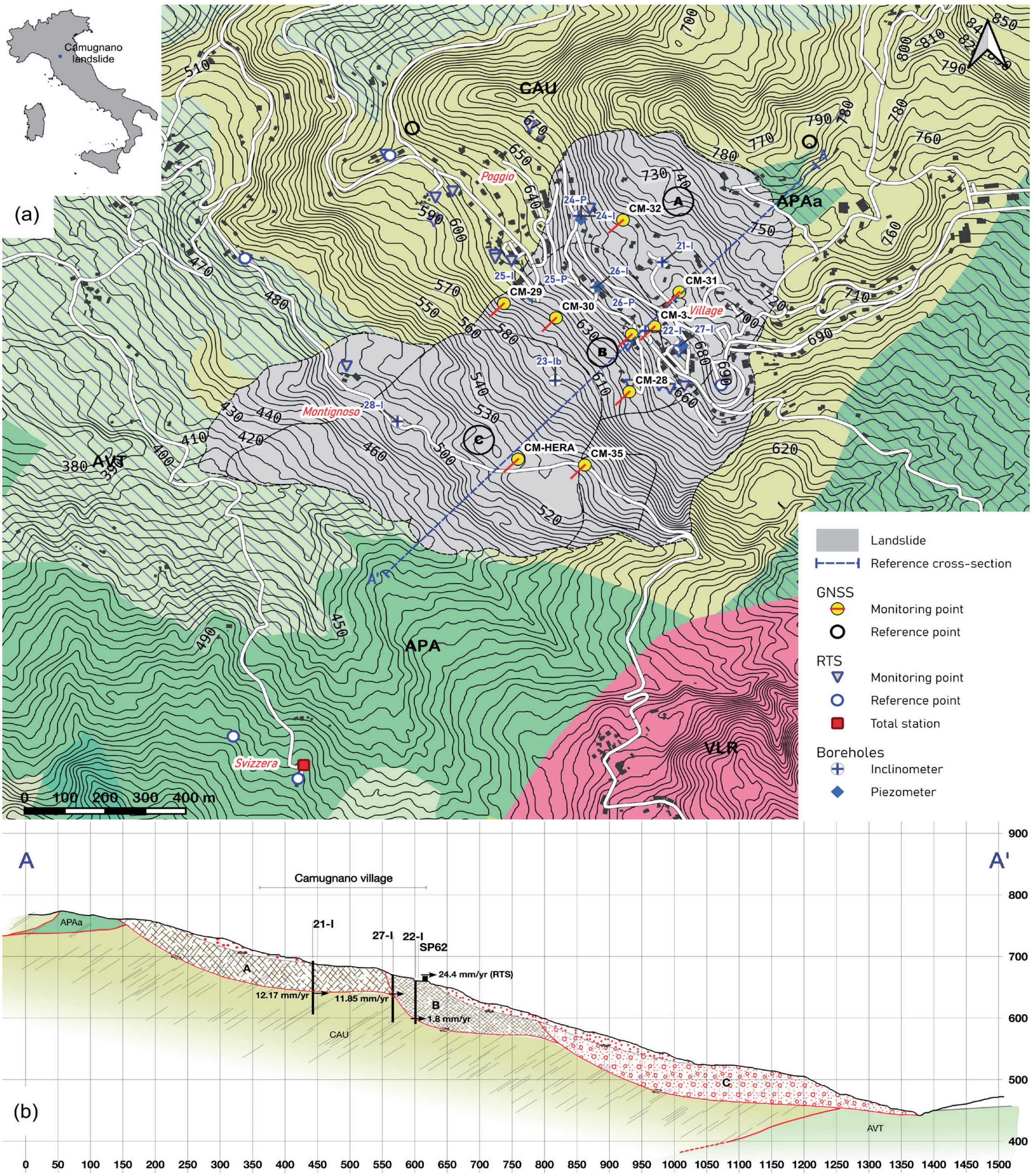

Fig. 1 - - Camugnano landslide. (a) reference map; (b) cross section. Letters A, B and C refer to landslide units mentioned in the text. Bedrock geology: Camugnano Formation (CAU), Argille variegate di Grizzana Morandi (AVT), Argille a Palombini (APA), Argille a Palombini (shale lithozone, APAa), Arenarie di Vallorsara (VLR)

Emilia-Romagna Region has undertaken an in-depth study of the phenomenon, based on field surveys, underground exploration as well as slope movements and groundwater levels monitoring.

MATERIALS AND METHODS

Available data

The research is based on data obtained by: (*i*) 12 boreholes (for a total of 695 m of continuous coring); (*ii*) geophysical surveys, including 6 electrical resistivity tomography profiles (ERT, 1512 m in total), 2 seismic refraction profiles (RFR, 1045 m in total), 2 seismic reflection profiles (RFL, 495 m in total) and 129 passive seismic noise surveys (HVSR); (*iii*) 8 inclinometer casings with periodic surveys (3 campaigns per year since 2017); (*iv*) 4 open-pipe piezometers equipped with pressure transducers (since 2018); (*v*) periodic GNSS surveys (from 3 to 4 campaigns per year since 2014); (*vi*) continuous Robotic Total Station monitoring (since fall 2020) (Figure 2). To assess the relationships between variations in the velocity of the landslide and effective rainfall, slope movements monitoring data and rainfall and temperature data have been used.

Inclinometer monitoring

Sub-surface deformations were monitored through the installation of 8 inclinometers casings (see Figure 1a for location). Monitoring was carried out since 2017, on a three times per year schedule on two grooves with 1 m step. The data were made available from local Authorities. The recorded dataset appears to be affected by limited bias shift error, which do not limit the possibility to detect quite clearly the main sliding surfaces. To compute cumulated displacement over sliding surfaces, measurements were integrated over the depth intervals corresponding to the sliding surfaces (Simeoni & Ferro, 2015).

Periodic GNSS monitoring

The differential GNSS technique (Leick *et alii*, 2015) has been extensively applied in the natural hazard field (Corsini, 2015b; Malet *et alii*, 2002; Mantovani *et alii*, 2022; Mulas *et alii*, 2016, 2020). In this case study, 21 differential GNSS surveys are performed in 9 different benchmarks (Figure 1a) covering the period in between March 2013 and March 2022. Raw coordinates are recorded from both GLONASS and GPS satellites and processed according to the double difference methodology with respect to a local reference whose stability along time is verified by using data from the INGV-RING GNSS network (Avallone *et alii*, 2010).

Continuous RTS monitoring

Robotic Total Stations have been widely adopted by the for landslides monitoring (Corsini, et al., 2015a; Corsini & Mulas, 2017; Dematteis *et alii*, 2022; Manconi *et alii*, 2018; Mulas *et alii*, 2016, 2018). The RTS in Camugnano is installed on the southwest side, opposite to the landslide (see Figure 1a), at approximately 1500 m distance. The topographic monitoring system is made up of 5 reference prisms and 16 monitoring prisms. The dataset presented in this contribution covers the period in between November 2020 and December 2022. In this specific case, it is important to note that the RTS is operational only from 8 am to 5 pm to reduce energy consumption with a cycle duty of 9 hours. Currently, the RTS is powered by a battery and solar panel. Based on the data collected so far, the measurements are estimated to have a real accuracy of 1-2 cm.

Groundwater monitoring

The local authorities also commissioned the installation of four piezometers located near an inclinometer (Figure 1a). The 24P, 25P, and 26P piezometers were installed between July and October 2014, while the 27P was installed in October 2019. The piezometric pipes are fenestrated in the vertical section characterized by the rock mass belonging to the CAU formation and are all equipped with "HERON dipperLog32" pressure transducers. These transducers have a sampling frequency set to 3 hours, provided by the same regional agency. Additionally, a HERON barLog barometer with a sampling rate of 1 hour is installed near inclinometer 22-I, which is used for barometric compensation of the other transducers.

Effective rainfall computation

Effective rainfall computation was addressed by estimating the potential evapotranspiration according to Thornthwaite formula (Thornthwaite, 1948; Thornthwaite & Mather, 1955). In this case calculation is based upon mean daily temperature and daily cumulative rainfall datasets from 2006 to 2022 acquired in Diga del Brasimone weather station, located 5 km on the south-east direction. Since the potential evapotranspiration is a theoretical physical quantity which does not take account of actual water availability, a further processing is required. Effective rainfall is than computed on a monthly basis by running a simple mass balance model (T-Model, Alley, 1984) where the soil is conceptualized as a reservoir parameterized by a soil moisture storage (STC) value that represents the amount of water, expressed in terms of precipitation height, that the soil is able to retain and makes available for evapotranspiration. The STC parameter can be estimated as a function of the type of surface soil and the depth of the root system (Allen *et alii*, 1998); some authors suggest that a value of 150 mm can be considered representative in most cases (McCabe & Markstrom, 2007). A quantity of water can be added or subtracted from the reservoir, respectively in cases where the rainfall of the given month (P) is greater or less than the potential evapotranspiration (PE) of the same month. In any case, if the water content is greater than the value of STC, the excess is considered effective rainfall. In this research, the T-Model was parameterized by a STC value equal to 150 mm.

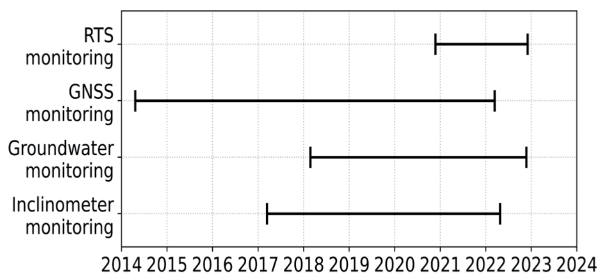

Fig. 2 - Time span of the monitoring data on the Camugnano landslide

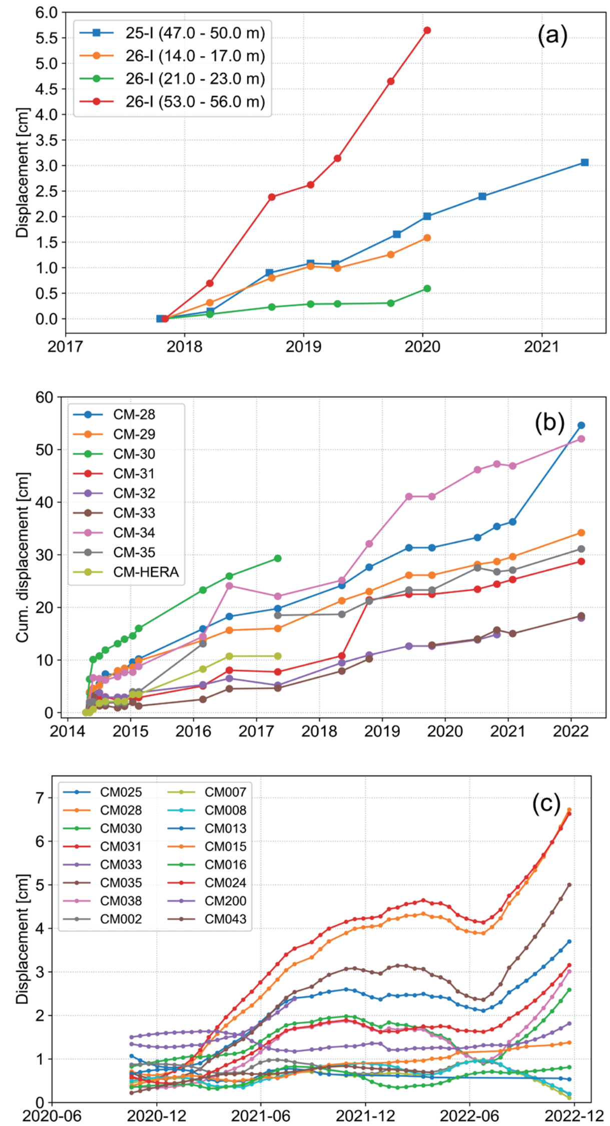

Fig. 3 - Cumulated displacement results. (a) inclinometer displacement on sliding surfaces; (b) GNSS displacements; (c) RTS displacements

RESULTS

Inclinometer monitoring

The inclinometer readings span from February 2017 to April 2022 (inclinometers 21-I, 22-I, 24-I, 27-I, and 28-I). Inclinometers 21-I and 28-I both indicate a single sliding surface located at 54 m and 20 m, respectively. Inclinometer 26-I shows movement along two sliding surfaces at 16 m and 55 m. Inclinometer 23-Ib shows clear movement at 45 m and apparently two closely spaced surfaces at depths of 13 m and 15 m. Finally, inclinometer 25-I, in addition to a surface depth of 48 m, indicates a deformation band between 10 m and 15 m and another between 24 m and 31 m.

Periodic GNSS monitoring

All GNSS benchmarks clearly exhibit signs of movement, with displacements ranging from an average of 20 cm to 50 cm over 7 years, corresponding to movement rates of approximately 30-70 mm/year (Figure 3b). A closer examination to displacement rates reveals a progressive decrease from 2014 to 2022, except for two episodes of increased activity that affected a large portion of the GNSS benchmarks. For instance, benchmark CM-30 reached displacement rates exceeding 0.3 cm/day back in 2014, whereas currently it shows displacement rates lower than 0.05 cm/day. Displacement rates were relatively high until 2015-2016 and then stabilized at very low values, with the exception of two minor and localized accelerations occurred during 2016 and 2018. The azimuth of movements is in all cases along the slope dip.

Continuous RTS monitoring

According to the RTS monitoring displacements are slow and of limited magnitude but remain clearly visible (Figure 3c). In the Camugnano village, widespread movements persist in what appears to be a constant manner, with average rates ranging from 0.003 cm/day to 0.007 cm/day (1-2 cm/year). These movements can be categorized as “extremely slow” (velocity <16 mm/year) or “very slow” (velocity between 16 mm/year and 1.6 m/year). In the Poggio area, only one prism shows significant displacements, characterized by an average displacement rate of 0.003 cm/day (1 cm/year).

Effective rainfall computation

Total rainfall and computed effective rainfall for Diga del Brasimone from 2006 to 2022 are presented in Figure 4a. It is worth to be noted that last large reactivation occurred during 2014, a year characterized by the largest cumulative effective rainfall values. In particular, the water balance model provides a value of 490.7 mm on January 2014. A similar value occurred on November 2019 (434.8 mm) which in turn did not cause major reactivations.

Groundwater monitoring vs Effective rainfall

Time-series of groundwater depth, together with the

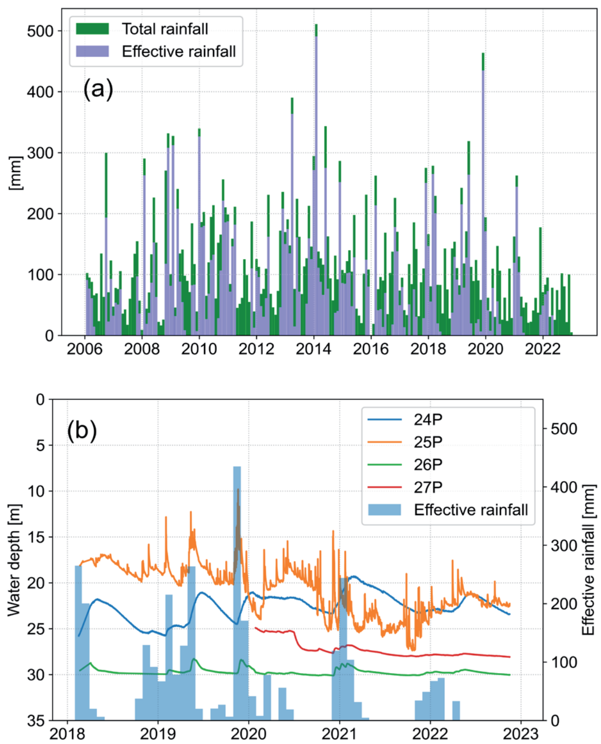

Fig. 4 - (a) Rainfall dataset and effective rainfall from Diga del Brasimone weather station (top); (b) piezometer monitoring data

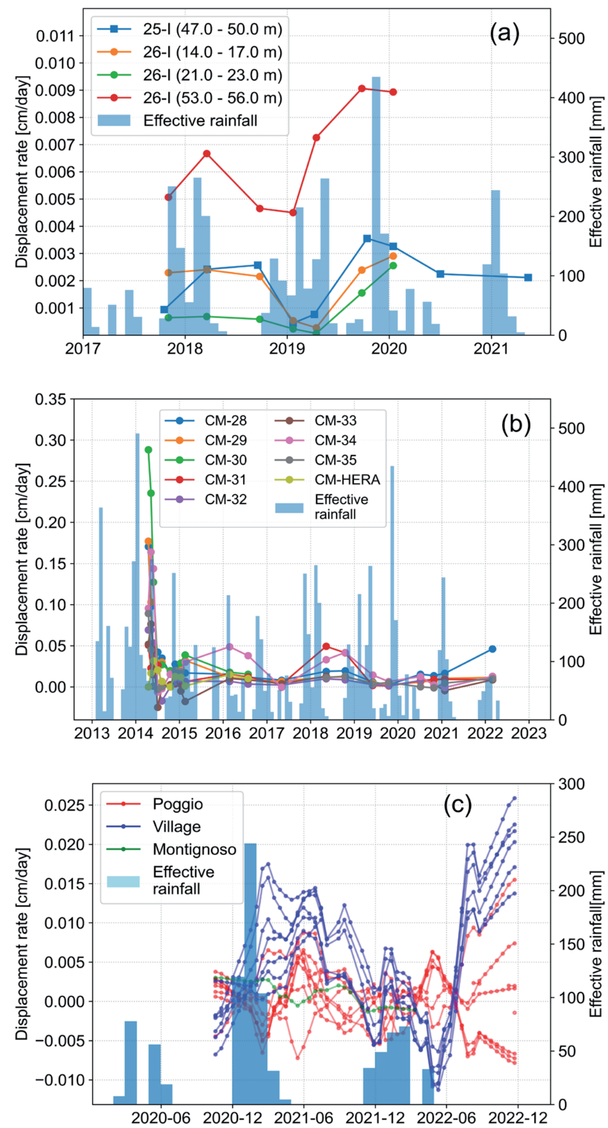

Fig. 5 - Comparison between effective rainfall time series and slope displacements provided by GNSS monitoring (a), inclinometer monitoring (b) and RTS monitoring (c).

previously discussed series of effective rainfall are presented in Figure 4b. The water table is consistently found at significant depths in all piezometers, with average values ranging between 17 and 30 meters from the ground level. Piezometers 24P, 26P, and 27P exhibit similar behaviour, characterized by seasonal fluctuations with an annual peak during the winter period. These piezometers show no immediate response to individual precipitation events. In contrast, piezometer 25P stands out from the others due to its rapid and sudden rises linked to single precipitation events. It is noted that the similarities between piezometer 25P and its nearest neighbour (26P at a distance of approximately 170 meters) indicate that the piezometer may be affected by construction defects allowing direct infiltration along the piezometer-soil interface. However, it is important to highlight that there is no consistent overall trend of raising or lowering the water table in the long term.

Slope movement rates vs. effective rainfall

A similar comparison is made between displacement time series obtained from inclinometer surveys by integrating the incremental displacements over the depth intervals corresponding to sliding surfaces. A reduction in displacement rate is observed after the summer period of 2018 (Figure 5a), after which the previous displacement rate is restored for every sliding surface. However, a clear relationship between displacements and effective rainfall cannot be conclusively determined due to the limited acquisition frequency, which might have led to an aliasing effect and obscured a step-wise pattern in recorded displacements.

By comparing the displacement rates recorded by the GNSS surveys with the effective rainfall time series, it is evident that lower effective rainfall values generally correspond to lower displacement rates (Figure 5b), at least until 2019. After 2019, displacement rates become almost constant and less than 0.01 cm/day. The acceleration observed in 2018 is likely linked to high effective rainfall values estimated for the winter of 2017-2018, whereas a clear relationship cannot be discerned during the 2016 acceleration.

The relatively short time frame covered by the RTS monitoring does not allow for a comprehensive understanding of slope dynamics. However, the high sampling frequency enables the detection of a reduction in displacement rates following the dry season of 2021, consistent with the pattern of effective rainfall (Figure 5c).

CONCLUSIONS

These monitoring techniques provided valuable insights into the relatively slow but clearly visible movements within the landslide.

The analysis revealed a complex relationship between effective rainfall and landslide activity, with lower effective rainfall values generally corresponding to lower displacement rates until 2019. However, in the Camugnano landslide after 2019, displacement rates remained relatively constant, regardless of variations in effective rainfall. This suggests a variable behaviour of the slide over time in response to effective rainfall after the last major reactivation: a more sensitive response is in fact exhibited after 2014, which is progressively lost in the next years, defining a style of activity which could cause modifications to mitigation strategies to be applied on the site. These results emphasize the need for long-term monitoring techniques and thorough data analysis to gain a more comprehensive understanding of the dynamics of complex landslides.

Author contributions

Manuscript preparation: V. Critelli., A. Corsini., M. Mulas, F. Ronchetti; Data processing and integration: V. Critelli; GNSS monitoring: M. Mulas, G. Ciccarese, V. Critelli; Inclinometer monitoring: M. Bernardi, G. Caputo, A. Bernardi; RTS monitoring: M. Berti. Research ideation and supervision: A. Bernardi, M. Berti, A. Corsini.

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