Microwave-Assisted Synthesis of Ir-Ni Electrocatalysts for the Oxygen Evolution Reaction in Acidic Electrolyte

International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Hydrogeological analyses of the Champlas du Col deep-seated landslide (NW Piemonte, Italy)

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Abstract

Mountainous regions, due to their geomorphological features, are particularly prone to ground instabilities. In recent decades, there has been growing recognition of the role of climatic factors, such as heavy rainfall, in the occurrence and movement patterns of landslides in these areas, which are also vulnerable due to the presence of population centers and infrastructure.

Slow-moving landslides, such as complex-type landslides or Deep Seated Gravitational Slope Deformation (DSGSD), which involve large slope volumes, are highly dependent on seasonal rainfall patterns and snowmelt. The Susa Valley (in the NW of the Piedmont Region, Italy) is a clear example in this context. The displacement rates are influenced by changes in groundwater pressure, which are closely associated with net rainfall and snowmelt process. Therefore, the reconstruction of ground instability scenarios includes the development of a hydrogeological analysis aimed at improving the comprehension of climate impacts on water resources and, consequently, slope movements.

As a first step, the collection of piezometers or monitoring mountain springs data, along with the implementation of suitable statistical analyses, enables the detection of groundwater fluctuations. The influence of these parameters on the increase in displacement trends, recorded by in-situ instruments (e.g., inclinometers), is further investigated by correlating the landslide body displacements with seasonal variations in spring water levels and precipitation inputs. Within this framework, it is useful to define the main infiltration pathways and to identify the conditions responsible for soil saturation that affect slope stability by performing a numerical analysis. In conclusion, the current research makes a significant contribution to the interpretation of ground instability in mountainous regions, emphasizing the role of predisposing factors.

Keywords

Slow-moving landslides, groundwater level, seasonal displacements, numerical modelling, Alps

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1 Introduction

Slope stability analysis is a crucial and challenging geological and geotechnical topic (Chatra et al. 2017) due to the complex geological and hydrogeological processes that drive soil deformation, posing a significant threat to nearby buildings and infrastructure. Particularly in the mountainous context, the role of rainfall and snowmelt contributes significantly to instability mechanisms. Therefore, understanding the relationship between groundwater regimes and landslide displacement in these areas is essential to improve risk assessment and mitigation.

In the case of slow-moving landslides (Cruden and Varnes 1996), phases of rapid acceleration or catastrophic failure may occur due to the specific contribution of several predisposing factors. Generally, positive pore pressure resulting from rising groundwater levels, which are closely linked to net precipitation and snowmelt, is the main mechanism leading to failure in hydrologically induced DSGSD, implying that water content controls the behaviour of slow-moving landslides (Prokešová et al. 2013; Vallet et al. 2016 and Van Asch et al. 2007).

This work aims to analyse the hydromechanical dynamics of the Champlas du Col deep-seated landslide located in the Susa Valley in the Western Alps of Piemonte region (Italy). This landslide is an interesting example of gravitational phenomenon influenced by groundwater variations. The presence of a monitored water spring on the landslide body allows for the detection of changes in the groundwater recharge system through the acquisition of hydrometric data, providing useful insights into the aquifer's behaviour in response to rainfall inputs and the annual snowmelt process.

Given these assumptions, the following analytical steps were carried out: (i) spectral analysis to clarify the effects of groundwater fluctuations on landslide acceleration and (ii) numerical modelling to simulate deformations under specific soil saturation conditions, mainly due to rainfall and snowmelt contributions.

2 Study area

The investigated landslide site is located in the municipality of Sestriere, in the Champlas du Col locality (1768 m a.s.l.), along the SP23R road connecting the Susa and Chisone valleys. The landslide has been classified as complex phenomenon in the Regional Landslide Inventory (Sistema Informativo Frane in Piemonte-SiFraP) and covers an area of 2 km^2, extending from 2080 m a.s.l. down to the Ripa Valley floor at about 1500 m a.s.l (Fig. 1a). The phenomenon is the superficial expression of a larger DSGSD that extends from the top to the bottom of the relief (Narcisi et al. 2024). Surface movements, such as flows and rotational slides, are very active and periodically cause damage the SP23R road.

A complex system with multiple sliding surfaces has been identified due to the presence of highly fractured calcschists with serpentinites (belonging to Cretaceous period), a factor that contributes to the infiltration of meteoric water inputs. The collapse at the scale of the entire slope is dominated by a viscous-plastic deformation component with the development of creep movements distributed over a large part of the rock mass, as a result of which the phenomenon consists of a dominant sliding component along different planes on structural discontinuities (Fioraso et al. 2014).

Upstream of SP23R, movement occurs along horizons of different permeability due to the presence of gravel alternating with silt and sand. These incoherent soils with local glacial deposits, developed during the Last Glacial Maximum, cover the fractured substrate with a thickness of about 100 m. On the other hand, in the lower part of the landslide on the valley floor, the presence of fluvial deposits is more consistent.

Most of the monitoring points are concentrated near the Champlas du Col buildings and along the SP23R, due to the recurrent damages observed. Given the heterogeneity of surface deformations, landslide displacements of different magnitude are detected. In particular, on the western sector of the landslide body the movement rates ranging between 2 and 4 cm/year, while on the eastern sector the displacements are more pronounced (around 6-7 cm/year) (Arpa Piemonte 2024a).

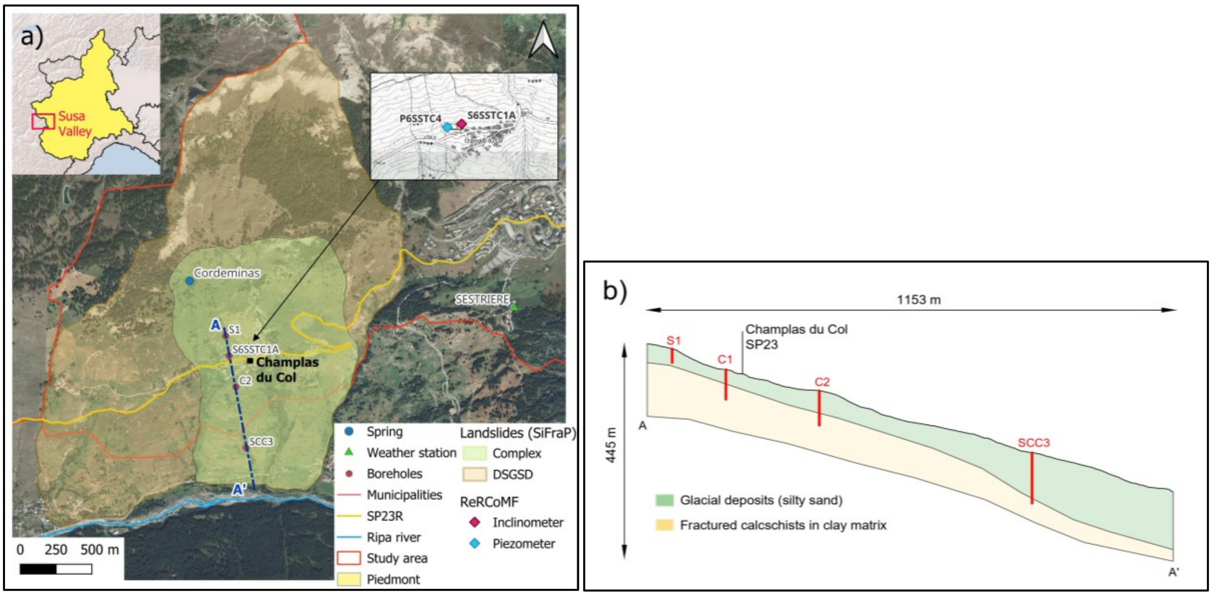

Fig. 1 (a) Location of the Champlas du Col landslide and detail of ReRCoMF monitoring points (b) Cross-section A-A'.

3 Data collection and methodology

The Cordeminas water spring is monitored by the Regional Agency for the Protection of Environment (ARPA Piemonte) in collaboration with the Department of the Environment, Territory and Infrastructures Engineering (DIATI) of the Politecnico di Torino. A multiparameter probe was installed (since 17/10/2020) to measure water level, temperature and electrical conductivity with an hourly time step (Bonomo 2023). The analysed dataset is updated to the last measurement campaign conducted in June 2024.

Spring water levels and precipitation data were considered in order to analyse possible effects on acceleration phases in the landslide deformation trends. Precipitation data were obtained by selecting available weather station from the official ARPA Piemonte regional network. The Sestriere station was chosen because it is close to the investigated site in terms of distance and elevation and it provides daily time series of rainfall, snow depth and temperature (Table 1). To ensure consistency between spring and weather datasets, the hourly water level data were transformed into average daily values.

Table 1 Characteristics of Cordeminas spring and Sestriere weather station

<table>
<tr><th></th><th>Parameter</th><th>Dataset</th><th>Elevation (m a.s.l.)</th><th>Distance (km)</th></tr>
<tr><td>Cordeminas spring</td><td>Water level (m)</td><td>17/10/2020-10/06/2024</td><td>1960</td><td rowspan="2">2.2</td></tr>
<tr><td>Sestriere weather station</td><td>Rainfall (mm)
Snow depth (cm)
Temperature (°C)</td><td>Since 1996</td><td>2020</td></tr>
</table>

The site has been equipped with landslide monitoring instruments by the ARPA Piemonte through the Regional Landslide Control Network (Rete Regionale Controllo Movimenti Franosi–ReRCoMF). Analogous to the choice of the weather station, only suitable instrument with large and continuous datasets, without any gaps within the previously defined monitoring domain were selected (see Table 2). Therefore, inclinometers without automatic acquisition were excluded, and only fixed probe inclinometers, which provide daily cumulative displacement values from the installation date, were considered. On the other hand, the piezometers measure daily groundwater levels and will be exploited in numerical modelling to analyse water level fluctuations over time and hence their effects on the rate of movement.

Table 2 Landslides monitoring instruments (ReRCoMF)

ID code	Instrument	Date of installation	Daily values	Time window in Fig. 6
S6SSTC1A	Inclinometer	2013/09	Displacement (mm)	1 March – 31 May 2018
P6SSTC4	Piezometer	2004/09	Groundwater level (m)	

For the purposes of the analysis, the scenario of the spring season 2018 was identified as the most representative one to simulate the transient evolution of measured groundwater levels and landslide displacements. This is the most typical situation that occurs during spring time, when the progressive saturation of the soil is caused by the snowmelt process, which begins with the first rising temperatures, combined with the rainfall effects. Indeed, according to the data available from the Sestriere weather station, 240.2 mm were recorded in the period from March to May 2018, with 43 days of rain. Moreover, the winter season of that year was characterised by heavy snowfall (636 cm in November-April), which was responsible for a significant supply of the groundwater body following the temperature rise from -2.8 °C (12/04) to 10.1 °C (22/04). This resulted in a reduction of the snow depth of 5 cm/day in the range 17/04-24/04.

3.1 Analysis of spring water levels and inclinometer displacements in the frequency domain

The spectral analysis was carried out to investigate the influence of snowmelt and the consequent rising groundwater level on the increase in the landslide displacement pattern.
By analysing the Cordeminas water levels, the presence of seasonal components in the groundwater fluctuations was detected in order to understand the possible effects on the variations in the movement trend. For this purpose, a periodogram was evaluated for the groundwater level signal and the displacement variable. The periodogram P_k is an estimate of the power spectral density of a signal and it is mathematically related to the autocorrelation sequence r_{xx} by the discrete-time Fourier transform (Oppenheim and Schafer 1989). The P_k function allows to obtain the frequency domain signal from the time domain signal $r_{xx}(m)$ of both parameters (Fiorillo and Doglioni 2010):

$$\mathrm{Pk}(\omega) = \frac{1}{2\pi} \sum_{m=-\infty}^{+\infty} r_{xx}(m)\, e^{-j\omega m} \tag{1}$$

Where m Time
f Physical frequency
f_s Sampling frequency
ω $2\pi f/f_s$
j Imaginary unit equal to $\sqrt{-1}$

3.2 Numerical modelling

The geological section A-A′ (Fig. 1b) of the landslide was defined using borehole data (Table 3) and geological documents of the area provided by Arpa Piemonte Banca Dati Geotecnica to analyse the stratigraphy and define the soil mechanical properties.

Table 3 Boreholes along the cross-section A-A’

ID code	**Elevation (m a.s.l)**	**Depth (m)**	**Groundwater level (m a.s.l.)**
S1	1860	33	1840.2
C1	1760	65	1748
C2	1720	75	1710
SCC3	1590	110	1550

The stratigraphy was then estimated and the slope layers consist of two main materials: (1) overlying formation (glacial and alluvial deposits) characterised by silty sand with gravel and (2) fractured calcschists in a clay matrix. The resulting slope model was generated with a finite element mesh (Fig. 2).

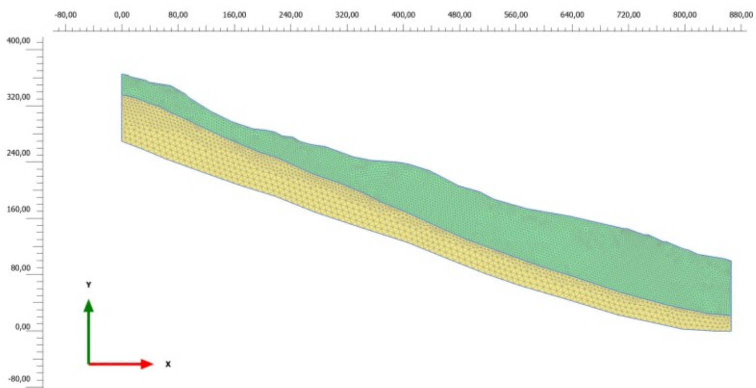

Fig. 2 Geometric configuration of the model

Due to the lack of information from boreholes on the geomechanical properties of the soil, supplementary material was retrieved from the literature (Barla et al.; Comune di Sestriere – Relazione geologica and Monte et al. 2024) to select reasonable values of mechanical and hydraulic parameters. These were then iteratively adjusted through a series of simulations. The following parameters (Table 4) are therefore purely indicative and approximate.

Table 4 Geotechnical and hydromechanical parameters adopted in the modelling: unsaturated (γ_{unsat}) and saturated (γ_{sat}) unit weight, porosity (n), Elastic Modulus (E), Poisson's ratio (υ), cohesion (c), friction angle (φ), permeability (k)

Layer	General			Mechanical				Groundwater	
	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	n	E (10^6 kN/m^2)	υ	c (kN/m^2)	φ (°)	Soil class (USDA)	k (m/day)
Upper	21	23	0.2	5	0.25	40	30	Sandy loam	1
Lower	24	26	0.4	30	0.2	500	34	Clay loam	0.6

A numerical analysis with Plaxis® 2D software (Version 2024.2.0.1144) was performed to model slope stability, identify slope portions along cross section A-A' affected by high strains, and simulate the landslide movement rate under different conditions. The Hardening Soil (HS) model (Schanz et al. 1999), an elastoplastic soil constitutive model, was used to describe the behaviour of subsoil layers.

Slope safety was assessed using the ϕ-c reduction technique. In particular, the mechanical information derived from drilling samples was supplemented with literature data and several iterations of modelling to obtain a framework as close to the real case as possible. Vegetation, soil heterogeneity and anisotropy were not considered. A coupled hydromechanical finite element analysis was adopted to simultaneously assess changes in pore water pressure and slope displacements caused by transient infiltration due to rainfall and snowmelt, controlled by the permeability of the two soil layers.

As it will be explained in detail in the Chapter 4.2, the numerical simulation on the spring 2018 was carried out in two main stages: (1) pre-event conditions in which the groundwater level derived from borehole measurements was assumed to be constant and (2) the hydromechanical response of the landslide body under the rainfall and snowmelt action, generally observed during spring season. In this stage, the data provided by the piezometer P6SSTC4 are exploited to simulate groundwater level changes over time.

4 Main results and discussions

4.1 Cause-effect relationship between groundwater fluctuations and landslide displacement trends

Daily time series of snow depth and incremental displacement recorded by the S6SSTC1A inclinometer are shown in Fig. 3. It is clear that the acceleration phases of the landslide are closely linked to the snowmelt; in particular, winters with heavy snowfall are followed by high displacement rates. Noteworthy are the highest peaks occurred during spring 2018 (as mentioned in the Chapter 3) and 2024, due to the abundant snowfall combined with prolonged rainfall of the previous months (Arpa Piemonte 2024b and 2024c). It is also recognised the role of the temperature in influencing the snowmelt process: the winter 2024 had the warmest temperatures in the last 67 years (Arpa Piemonte 2024d) and this had a greater impact on the variation of peak displacements than, for example, the scenario between 2021 and 2023.

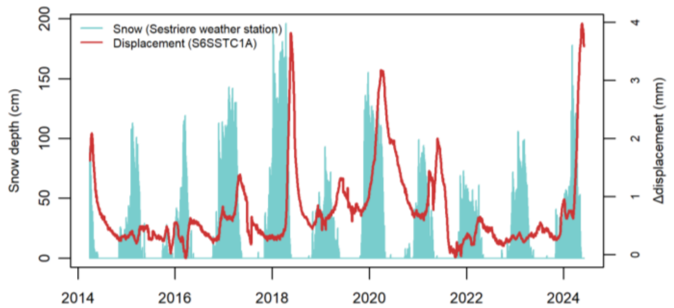

Fig. 3 Daily snow depth and landslide displacement shifts.

The periodogram (Eq. 1) of the spring water levels and the inclinometer displacements in the time interval 17/10/2020 – 10/06/2024 further supports the comprehension of the snowmelt role in increasing landslide movement rate Fig. 4.

A peak at approximately 365 days was detected, indicating the presence of an annual component in the water level signal. This finding suggests a relatively consistent pattern typical of a mountain spring discharge across hydrological years, as the snowmelt process occurs once a year. However, additional significant peaks appear in the water level response, recurring at frequency ranging between 0.005 and 0.015. These peaks are attributed to the spring's greater sensitivity to surface runoff and rainfall events. The hydrometric level pattern depends on the position of the spring monitoring. Indeed, Cordeminas spring is embedded in a shallow system, which makes it strongly influenced by rapid flow contributions, characterised by water level peaks following intense rainfall events (period Apr-Nov 2021 taken as an example in Fig. 5), which overlap with the base flow component driven by snow accumulation.
At the same time, the displacements spectrum evaluated within the same time window of the Cordeminas spring, also shows a peak at 382 days, suggesting a close dependence of displacement variations on the groundwater recharge system and consequently on the annual snowmelt cycles.

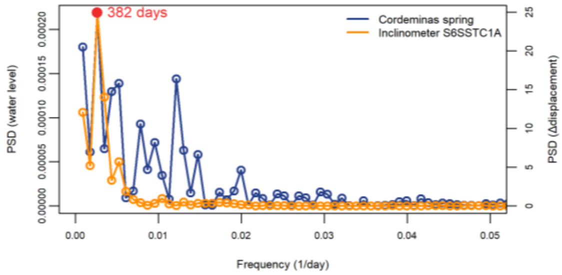

Fig. 4 Power spectral density (PSD) of the water levels and displacement shifts evaluated on the entire spring dataset (17/10/2020-10/06/2024).

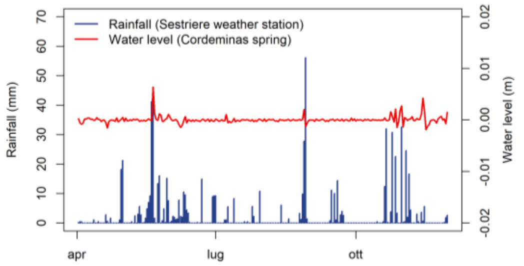

Fig. 5 Daily rainfall and spring water level fluctuations

4.2 Hydromechanical response of the landslide to rising groundwater levels

The scenario occurred in the spring 2018 was taken as an example, in which the piezometer P6SSTC4 recorded an increase in the groundwater level of approximately 5 m (from -13.07 m on 04/03/2018 to -8.71 m on 10/05/2018).
In particular, the numerical analysis was focused on a shorter time window (Fig. 6) to reduce the modelling computation time, but still meaningful for the interpretation of the phenomenon.

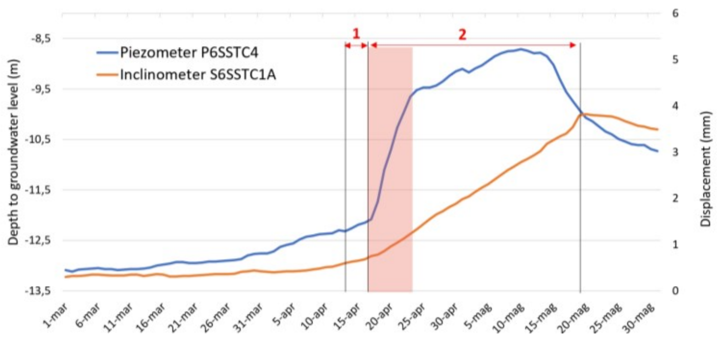

Fig. 6 Scenario of the spring 2018: acceleration of the landslide following the rising groundwater level occurred on 17/04/2018-24/04/2018 (red time window).

Therefore, since a significant groundwater level rise of about 3 m occurred in 7 days (17/04/2018 to 24/04/2018), the changes in the displacement pattern in the following 30 days were investigated. The Table 5 is consistent with the model setup described in the Chapter 3.2.

Table 5 Numerical analysis steps and hydraulic boundary conditions

Stage	**Hydraulic boundary conditions**
(1) Pre-event (3 days)	No infiltration rate Constant hydraulic head
(2) Scenario (37 days)	Infiltration rate along the slope surface (snowmelt: 0.05 m/day on 17/04 – 24/04 and rainfall: 0.01 m/day on 01/05-10/05) Time-dependent head at left and right sides

The time interval of 30 days following 24/04/2018 was chosen because, as shown in the Fig. 6 (the displacement values are monthly, so for example on 24/04 the cumulative displacements from 25/03 are observed), at the end of phase 2 the displacement rate returns to the pre-high ground level measurement level.
As it can be seen in Fig. 7, the main distribution of the obtained displacements along the landslide section is close to the slope surface, where the main sliding planes are assumed to be located. In particular, the resulting increase in displacement evaluated at the mesh node where the inclinometer fixed probe is located coincides with the 3 mm shift recorded by the instrument. The safety factor values at the end of the phases (1) and (2) were compared: the graph in Fig. 8 clearly shows how the rise in groundwater level causes a reduction in slope stability, correlated with total landslide displacements (*u[m]*) for both phases.

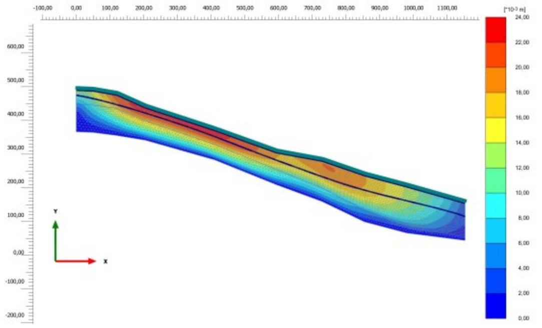

Fig. 7 Distribution of total displacements in Plaxis® at the end of the 2° stage (30 days following 24/04/2018). It is also represented the water load on the upper surface due to the infiltration boundary condition and the groundwater level (blue line).

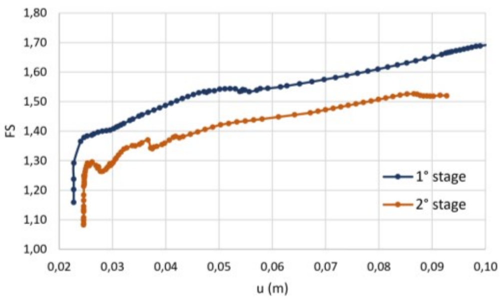

Fig. 8 Evaluation of safety factor at 1° stage (initial condition) and 2° stage (after the increase of groundwater level).

5 Conclusion

In this work, the hydromechanical behaviour of the Champlas du Col deep-seated landslide (Susa Valley, NW Italy) was evaluated. Spectral analysis and numerical modelling approaches clarified the cause-effect relationship between precipitation, rising groundwater levels and the acceleration of landslide movements. A preliminary comparison of the displacement time series with cumulative snow height over the years has shown that landslides accelerate mainly in the spring and summer period due to the annual snowmelt action. This suggests that it is not the single intense rainfall event that triggers the landslide, but rather the complete saturation of the landslide body due to continuous infiltration. In addition, the contribution of heavy rainfall to the rise in groundwater levels was also recognised (Amarasinghe et al. 2024; Cappa et al. 2014; Conte and Troncone 2011). In the second part of the analysis, dedicated to numerical modelling, the case of the spring 2018 was used to demonstrate that the main acceleration phases occur after a period of intense precipitation. The analysis could be extended to simulate other possible scenarios, such as the spring of 2024, or to derive landslide movement thresholds for a possible early warning system.

Acknowledgement

This study was carried out within the "Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate" (RETURN) Extended Partnership - Spoke VS2 (Ground Instabilities) funded by the PNRR - CUP E13C22001860001

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