The PROMISE Project: An integrated approach for mitigation of flowslide risk – Preliminary results from the Salerno Test Site

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Abstract. Flow-like landslides are a significant global hazard, threatening human life and causing extensive damage to structures and infrastructure. These events often occur on slopes composed of partially saturated soils and are typically triggered by intense rainfall, which reduces matric suction and, consequently, soil shear strength. Despite advancements in identifying key predisposing factors and preparatory factors, interpreting the mechanisms that trigger flow-like landslides remains challenging. The PROMISE project, 'Integrated appPROach for MItigation of flowSlidE risk: full-scale test and advanced numerical modelling' aims to address this gap. Its objective is to design and implement a full-scale test involving the application of an artificially induced critical rainfall event on an instrumented soil slope, with the aim of analyzing the hydro-mechanical response under failure conditions and validate a numerical predictive model. The study focuses on an area within the Lattari Mountains (Campania Region, Italy), historically affected by high-risk flow-like landslides. Specifically, the investigation area is located in a limestone quarry owned by ITALSUD Srl, situated in the municipality of Salerno, to the east of the Lattari Mountains. This paper presents preliminary results from the geological and geotechnical investigation of the area, along with the initial field monitoring data collected under natural weather conditions.

1 Introduction

Flow-like landslides are a significant global hazard, threatening human life and causing extensive damage to structures and infrastructure. These events often occur on slopes composed of partially saturated soils and are typically triggered by intense rainfall, which reduces matric suction and, consequently, soil shear strength [1,2]. Despite advancements in identifying key predisposing factors (e.g., stratigraphy, topography, and buried morphology) and preparatory factors (e.g., hydraulic conditions within the slope and antecedent rainfall patterns), interpreting the mechanisms that trigger flow-like landslides remains challenging. This difficulty stems largely from the scarcity of full-scale datasets capturing slope behaviour up to failure, with only a few documented cases available in the literature [3,4].

The PROMISE project, 'Integrated appPROach for MItigation of flowSlidE risk: full-scale test and advanced numerical modelling' seeks to bridge this gap. Its objective is to design and implement a full-scale test involving the application of an artificially induced critical rainfall event on an instrumented soil slope. The goal is to observe the hydro-mechanical slope response up to failure and to validate a coupled hydro-mechanical numerical model capable of predicting such events. The study is applied on an area within the Lattari Mountains (Campania Region, Italy), historically prone to flow-like landslides. The experimental site is situated on a natural slope within a limestone quarry owned by ITALSUD Srl, located in the municipality of Salerno, on the eastern flank of the Lattari range.

This paper presents preliminary results from the geological and geotechnical investigation of the area, along with the initial field monitoring data collected under natural weather conditions. The rationale behind selecting a small, safely isolated test zone for the artificial critical rainfall experiment is also discussed.

2 Test site

A pyroclastic slope in the Lattari Mountains, located in the Campania Region of Southern Italy, was selected as a suitable test site due to its known susceptibility to flow-like landslides [1, 2]. The site lies close to a limestone quarry owned by ITALSUD Srl, in the municipality of Salerno, on the eastern flank of the Lattari range (coordinates: 40°41′51″N, 14°45′16″E) (Fig. 1). This area has a history of flow-like landslide events, including the significant Molina landslide of 1954. The slope exhibits a patchy vegetation cover: some zones are bare, while others are populated by holm oaks and Mediterranean shrubland. Root systems in vegetated areas generally extend to a depth of approximately 1 meter [5, 6].

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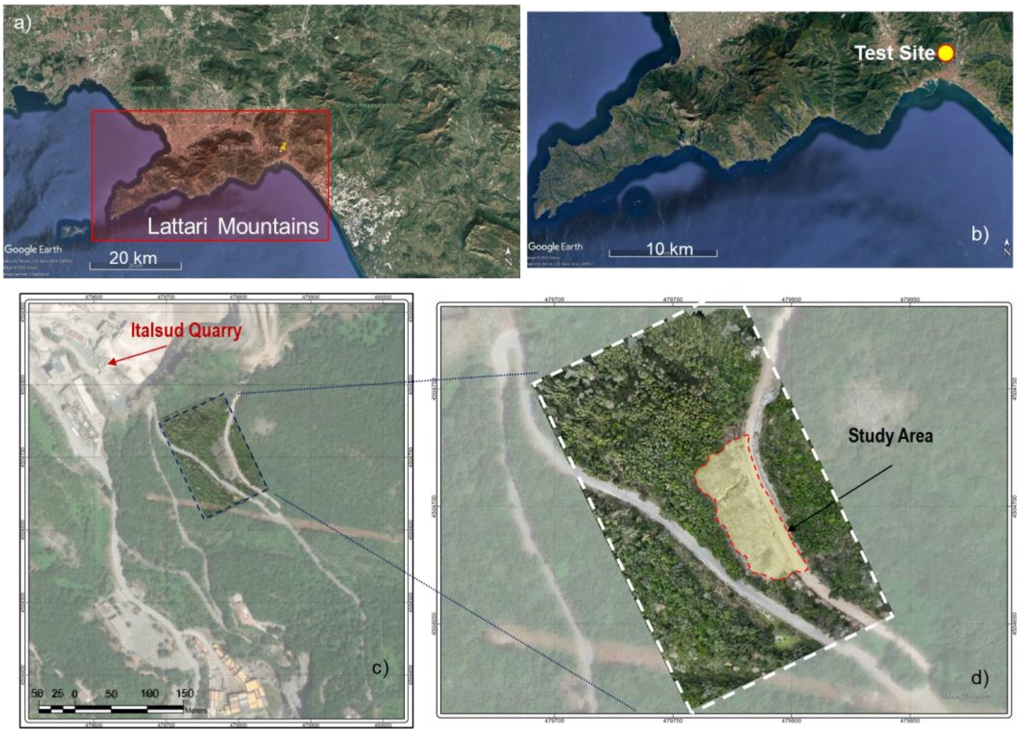


Fig. 1. a) Map of the Lattari Mountains in the Campania region, Southern Italy; b) zoomed-in view of the Salerno Test Site location; c) the study area near the quarry; d) zoomed-in view of the study area. The images in a) and b) were taken from Google Earth Pro 2025; the photos in c) and d) were acquired through drone surveys.

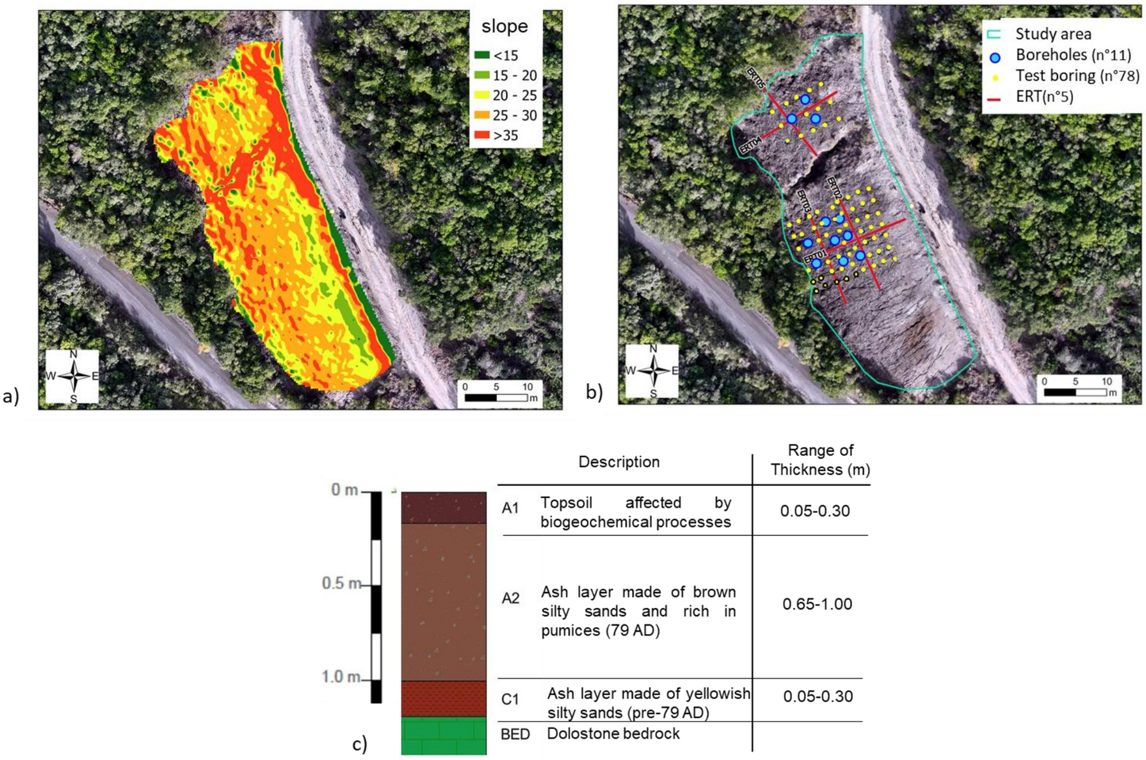
The quarry was specifically selected to conduct the artificial rainfall simulation test under fully controlled and safe conditions. In the event of slope failure, the induced landslide is expected to be naturally channelled into a pre-identified watershed and will terminate within the quarry yard. Access to this area will be restricted to the public for several days following the test, as a precautionary measure to mitigate any potential risk. Nonetheless, no amplification phenomena are anticipated, given that the downslope boundary is defined by a stable limestone cliff, which prevents further propagation of the landslide.

An area of approximately 700 m² was selected for the development of the geological model (Fig. 1c, d). The site includes a deep gully and exhibits clear evidence of past shallow landslides, such as detachment niches observed further downslope. To ensure that vegetation would not inhibit the triggering mechanisms of flow-like landslides, the area was previously cleared from vegetation. A high-resolution Digital Elevation Model (DEM) was created using drone photogrammetry, achieving a spatial resolution of 3 m². The slope inclination map (Fig. 2a), generated by uploading the DEM into ArcGIS Pro, shows values mainly ranging from 25° to 30°, with localized inclinations exceeding 35° near the gully and the road cut. All geological and geophysical investigations are indicated on the site map (Fig. 2b). A total of 78 test borings were excavated to investigate the bedrock depth. These were complemented by five Electrical Resistivity Tomographies (ERTs), which revealed a pyroclastic cover approximately 1.6 m thick, overlying dolomite bedrock. The dolomite was found to be highly fractured, with a friable matrix and closely spaced joints. The stratigraphy of the pyroclastic cover was reconstructed through 11 boreholes and corresponding stratigraphic logs. The sequence closely resembles that of another instrumented pyroclastic slope in the Lattari Mountains [3,4]. From top to bottom, the following layers were identified (Fig. 2c):

- A1: A biogeochemically active topsoil layer influenced by vegetation and microbial processes, 15 cm thick on average;
- A2: A brown silty sand ash layer, rich in pumices from the 79 AD eruption, with a thickness ranging from 0.65 to 1.3 m;
- C1: A yellowish silty sand ash layer, predating the 79 AD eruption, 15 cm thick on average.
- BED: dolostone bedrock.

3 Soil profile and properties

A representative soil stratigraphic profile is illustrated in Fig. 2c. It is important to note that the presence of layer C1 is discontinuous across the test site, as confirmed by stratigraphic and geophysical investigations. A comprehensive geotechnical characterization of all layers within the pyroclastic cover was conducted, and full details can be found in [7]. Here a brief summary is reported. All the layers are composed of volcanic silty sand and exhibit geotechnical properties typical of pyroclastic soils found in the Campania Region. Their physical, mechanical, and hydraulic characteristics are summarized in Table 1.



	Description	Range of Thickness (m)
A1	Topsoil affected by biogeochemical processes	0.05-0.30
A2	Ash layer made of brown silty sands and rich in pumices (79 AD)	0.65-1.00
C1	Ash layer made of yellowish silty sands (pre-79 AD)	0.05-0.30
BED	Dolostone bedrock	

Fig. 2 a) Map of slope inclination; b) Map showing the location of test borings, boreholes, and ERT survey lines; c) Mean stratigraphic profile showing soil layers and their thickness ranges.

Table 1. Mean soil physical, hydraulic and mechanical parameters with the indication of the number of the soil specimens used to determine the mean value.

Soil	Gs	n	γ_d (kN/m^3)	Ksat (m/s)	φ_{cv}' (°)
A1	2.67	0.646 (n°1)	9.30 (n°1)	1.03 E-06 (n°1)	37.0°
A2	2.69	0.592 (n°6)	10.78 (n°6)	8.03 E-06 (n°5)	37.0°
C1	2.74	0.64 (n°6)	9.05 (n°6)	4.14 E-06 (n°1)	36.7°

All layers exhibit high porosity, *n*, (0.55–0.65), and low soil dry unit weight, γ_d, (9.05-10.78 kN/m^3), consistent with typical values for pyroclastic soils [3,4]. Since the slip surface is expected to develop within the A2 layer, a greater number of soil specimens were collected from this layer for hydraulic and mechanical characterization [7].

Saturated hydraulic conductivity was determined through constant-head permeameter tests, yielding values between 1.03 × 10^{-6} and 8.03 × 10^{-6} m/s, comparable to those obtained from pyroclastic layers at another test site within the Lattari Mountains [5,6, 8, 9-11]. Layer A2 exhibits higher saturated hydraulic conductivity, likely due to the significant presence of pumice within the soil matrix.

The effective friction angle at critical state was determined through direct soil shear test on undisturbed specimens, submerged during consolidation, collected from all the layers A1, A2 and C1 [7]. The pyroclastic cover appears relatively homogeneous in terms of shear strength, as all layers exhibit the same critical-state effective friction angle of 37°, which falls within the typical range for pyroclastic soils (35°–39°).

4 Field monitoring

Within the 700 m² area, two zones were selected for instrumentation to investigate the slope's response to both natural (designated ‘Test Site_A’) and artificial rainfall (designated ‘Test Site_B’) events. Both zones are marked in Fig. 3a. The first zone serves as the 'reference' site, providing data on slope behavior under natural weather conditions. The second zone, where high-intensity artificial rainfalls will be applied to trigger slope failure, was selected based on a combination of the slope’s inclination map (Fig. 2a), pyroclastic cover thickness map, and Class-A predictive numerical analyses simulating the artificial rainfall. This zone was positioned downslope within the study area, where the slope inclination exceeds 35° and some detachments have already been observed. Test Site_A has already been instrumented, and preliminary results are presented below. Test Site_B is scheduled to be instrumented by the end of 2025.

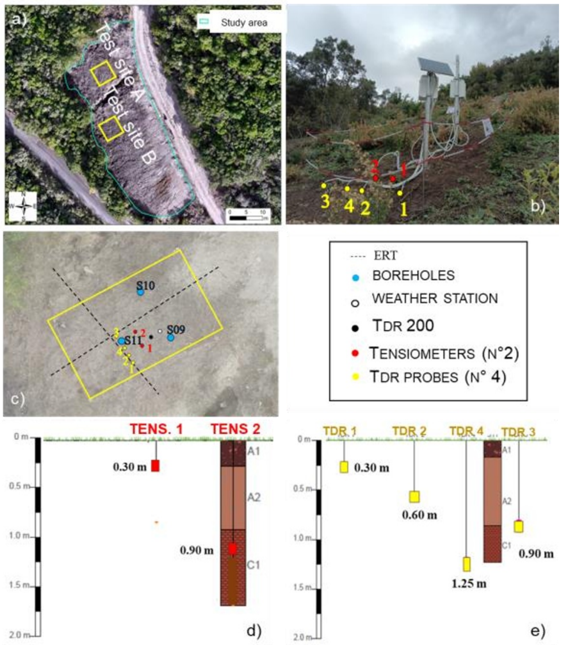


Fig. 3. a) Location of Test Site A and Test Site B; b) Photo of the installed instrumentation, with indications of the locations of the instrumented vertical profiles; c) Map showing the instrument locations with a chart key; d) Layout of the installed tensiometers; e) Layout of the installed TDRs.

3.1 Test site A: preliminary results

The location of Test Site A and the layout of the installed instrumentation are shown in Fig. 3. Specifically, starting from 28 November 2024, a meteorological station was installed at a height of 2 m above ground level to record rainfall, wind velocity and direction, net radiation, air temperature, and relative humidity on an hourly timescale. Additionally, four TDR probes were installed on 28 November 2024, and two Tensiometers were installed on 19 December 2024 within the pyroclastic cover to measure hourly values of volumetric water content and matric suction. The length of the TDR probes' rods is 15 cm, and the calibration curve obtained by [12] for similar pyroclastic soils from the same eruption was adopted.

Regarding the tensiometers, Full-Range sensors were used, capable of measuring pore pressures from 100 kPa to matric suctions up to 500 kPa. This was made possible by using a biopolymer inside the porous stone instead of water. The calibration curve provided by the manufacturer was used, after being verified in the laboratory by comparing the measures from Full-Range sensors with those obtained through traditional tensiometers in a trial soil sample.

Two pairs of TDR probes and tensiometers were installed at similar depths to track the hydraulic path followed by the soil on the retention water plane.

All data were acquired by a battery-powered datalogger, equipped with a solar panel, and transmitted remotely. The type of instrument, acquisition frequency, time span, and installation depth are summarized in Table 2.

Table 2. Description of the measurements and instruments installed at the test site.

Measure-ment	**Instrument**	**Monitored period**	**Frequency**
Matric suction	Tensiometer Full-Range (UGT) n°=2 depth (m): 0.30, 0.90	Ongoing from 19-12-2024	1 hour
Volumetric water content	TDR probes (Campbell Scientific) n°=4 depth (m): 0.30, 0.60, 0.90, 1.25	Ongoing from 28-11-2024	1 hour
Weather variables	Raingauge, Anemometer, Radiometer, Thermoigrometer (Campbell Scientific) Elevation: 2 m a.g.l	Ongoing from 28-11-2024	1 hour

In Figure 4, daily rainfall and air temperature recorded by the weather station at the Test Site, located at 110 m a.s.l., are compared with those measured by the weather station at the municipality of Salerno, 2 km away and situated at 13 m a.s.l. The discrepancies between the two-measurement series are primarily due to the difference in elevation. For instance, the air temperature at the Test Site is often lower than that recorded at the Salerno station, with minimum values occurring during rainfall events. Regarding rainfall, it is notable that, aside from discrepancies in intensity, there are instances when the timing of the rainfall events does not align between the two stations. These observations emphasize the importance of installing a weather station directly at the Test Site.

In Fig. 5, field measurements of matric suction and volumetric water content (VWC), collected at hourly intervals over two wet months, are plotted. Hourly rainfall data are also superimposed.

Suction measurements at the surface layer oscillate between a few kPa and 20 kPa (Fig. 5), consistent with other pyroclastic slopes monitored in the same geological context.

Both variables reflect the rainfall pattern; however, measurements at 30 cm depth respond quite quickly to hydraulic loads, showing an increase in VWC and a sudden decrease in matric suction in correspondence with rainfall. As expected, the response at a depth of 90 cm is less intense and delayed by a few hours.

The difference in hydraulic response observed between the two depths, primarily related to their distance from the soil surface, is amplified by two factors:

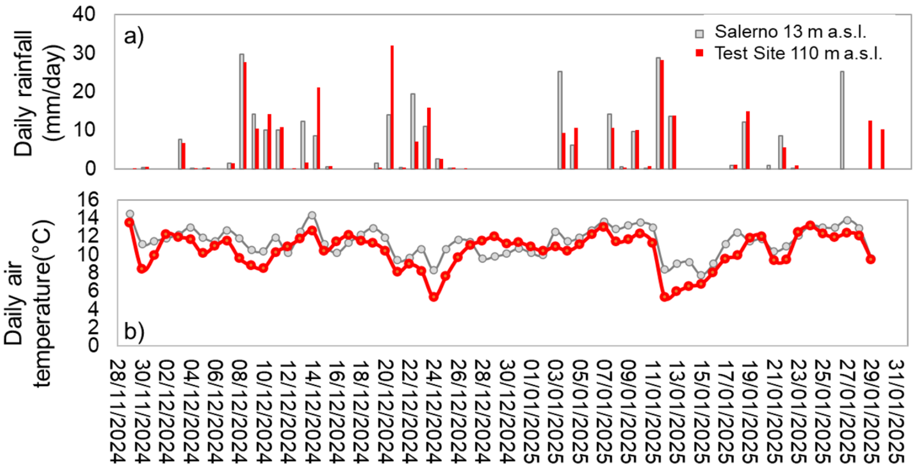


Fig. 4. a) Daily Rainfall and b) air daily temperature registered at site compared to that registered from the weather station at the municipality of Salerno over two months.

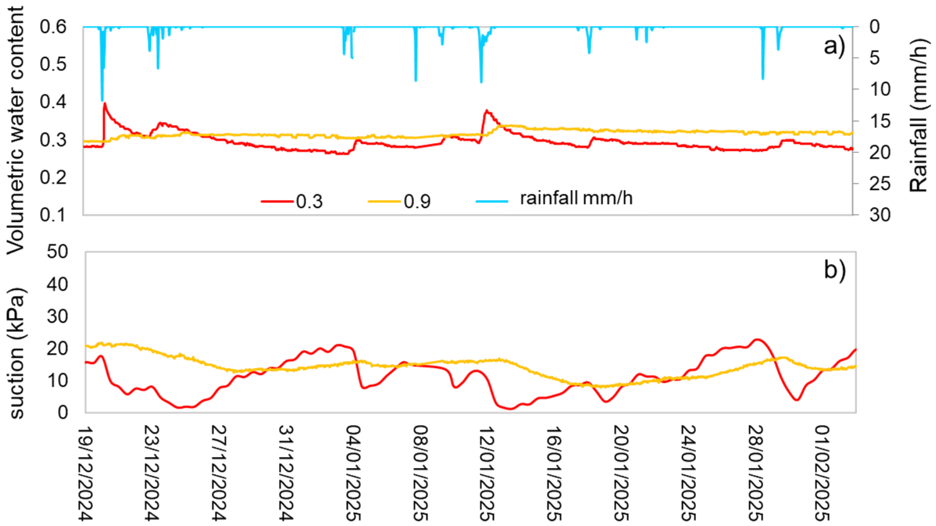


Fig. 5. Field measurements of rainfall, volumetric water content a) and matric suction b) from 19 December 2024 to 2 February 2025.

- The instruments at 30 cm depth are located in layer A2, while those at 90 cm are installed in layer C1, which is slightly less permeable than the layer above (Table 1).
- The total rainfall preceding the monitoring period (from September to November 2024) did not allow the entire pyroclastic cover to reach near-saturation conditions (matric suction less than 10 kPa). Therefore, the bottom half of the profile exhibited higher matric suction, indicating lower hydraulic conductivity. This condition was also evident from the observation of the upper scarp of the test field in December 2024 (Fig. 6). Even though the area in Figure 6 is covered by vegetation, the infiltration front appeared to be established between layers A2 and C1, and the top layer appeared wetter compared to the layer below (Fig. 6).

The consistency of field measurements is further supported by plotting the pair of suction and VWC data collected at similar depth (30 cm) on the retention plane, along with the main drying curve determined in the laboratory by [7] (Fig. 7). Field data points lie below the main drying curve, forming scanning paths due to hydraulic hysteresis, a common field condition, as demonstrated by [3,4].

5 Conclusions

Preliminary results from the PROMISE project, aimed at studying the triggering of flow-like landslides in pyroclastic unsaturated slopes, are presented. Geological modelling and geotechnical soil characterization have been discussed.

Fig. 6. Picture of the scarp upslope of Test Site A, taken on 19 December 2024.

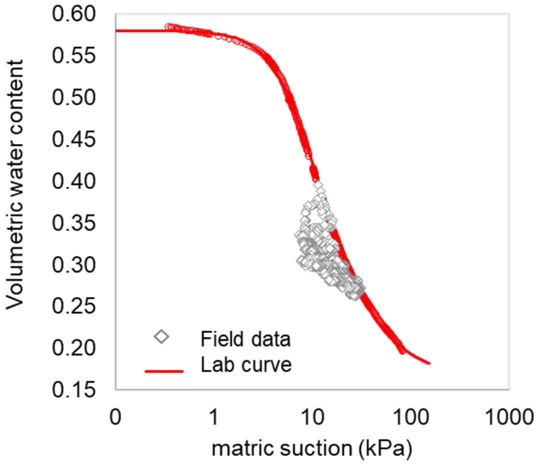


Fig. 7. Field measurements of volumetric water content and suction collected at 0.30 m depth, superimposed on the main drying curve determined in the laboratory [7].

The pyroclastic cover, with an average thickness of 1.6 m, rests on dolomite, with slope inclinations mainly ranging between 25° and 35°, and locally exceeding 35°. The geotechnical properties of the cover are consistent with those found in other pyroclastic soils sampled in the Lattari Mountains [3,4,11]. However, the bedrock in this case is dolomite, whereas other sites in the same geological context feature calcarenite. Therefore, further investigations are necessary to fully characterize the bottom of the cover and its interaction with the bedrock. A first test site has already been instrumented, and a preliminary interpretation of the field data collected between the end of 2024 and the beginning of 2025 shows that they are likely to be reliable and consistent with each other.

Future work will focus on setting up the second test site, where artificial rainfall experiments will be conducted. A zone with inclinations greater than 35° has been chosen for instrumentation, but further investigations are needed to identify local factors (e.g., buried morphology, irregularities in stratigraphy) that typically favour triggering in this type of geological context.

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