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Observations on hydrological state of volcanic soil covers: the Celario slope case

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Abstract. On November 26, 2022, a persistent rainfall triggered several landslides in volcanic soil covers and tuff rock slopes in the northern part of Ischia Island (Italy). The most destructive event was triggered by the impact of a weathered rock mass falling from an above-standing vertical front, then a mudflow was channelized along an open slope with convex morphology, known as "cava Celario". The main preparatory factor for this landslide was the rainfall-induced drop in suction throughout the pyroclastic cover. Further insights into the amount of suction evolution at the landslide trigger time were thought to be helpful to define proper mitigation strategies. An on-site monitoring activity was undertaken, aiming at characterizing the evolution of the hydrological state of the deposits, through the monitoring of suction within the still-intact deposit located laterally to the landslide initiation zone of Celario, approximately 50 m below the uppermost triggering zone. The suction measurements were correlated with meteorological variables, hence recognizing that the accuracy of the forecast could be improved by increasing the density of available measurement points and locating additional monitoring instruments at higher elevations.

1 Introduction

The rapid formation of volcanic areas can give rise to environmental conditions highly susceptible to different types of instabilities. During episodes of intense rainfall, these settings are particularly vulnerable to sudden and rapid mass movements, such as debris flows, that could potentially put at risk human lives and infrastructures [1, 2]

Among the volcanic areas, the island of Ischia has been repeatedly affected by such events. It is a complex volcanic field located in the northwestern sector of the Gulf of Naples, and regarded as one of the highest-risk areas in Italy for landslides and flooding [3, 4, 5].

The literature addresses several aspects of landslide hazard in Ischia, including general assessments [6], modelling approaches [7, 8] and technical reports [5]. However, scientific literature has so far rarely reported examples of hydrological monitoring conducted in the Ischia context, referred to instability mechanisms triggered by meteorological events.

Within this framework, the present study focuses on the hydro-geological disaster occurred on November 26, 2022, when an unusually intense rainfall triggered widespread landslides in the island's northern sector. The most severe of these was a debris flow, known as the 'Celario landslide', that originated uphill the municipality of Casamicciola Terme [9, 10].

Specifically, this paper first characterises the triggering rainfall event, analysing the cumulated rainfall both since the beginning of the hydrological year and for the day of landslide occurrence. Thereafter, it describes the monitoring activities carried out during one year and still ongoing to investigate the hydrological state of the pyroclastic deposits located along the unstable area.

2 The Celario landslide

At the end of November 2022, several landslides occurred on the weathered volcanic soil covers of the northern slope of Mount Epomeo, on Ischia Island. These phenomena were triggered by heavy rainfall, which, according to the closest rain gauge (located in the Forio municipality), accumulated 131 mm over 6 hours (Figure 1a), with about 40 mm in the last hour. The total precipitation since the beginning of the hydrological year amounted to around 400 mm (Figure 1b).

Among the many phenomena that occurred on the above mentioned slope, primarily triangular or ribbon-shaped, the one tragically known as the Celario landslide (Figure 2a) originated from the topmost pyroclastic deposits, about 50 cm thick. Video footage taken with a drone showed that the landslide crown area has a triangular geometry, with an apex located at the foot of the ridge of a higher sub-vertical slope (Figure 2b). This triangular shape results from progressive phenomena, which, due to the unstable stress-strain response of the material involved, expand in the direction of propagation, starting from a triggering point at the apex.

The drone footage confirmed that the trigger occurred at the apex, which was impacted by several cubic meters of pyroclastic debris and rock blocks that failed from about 50 m above. After displaying a

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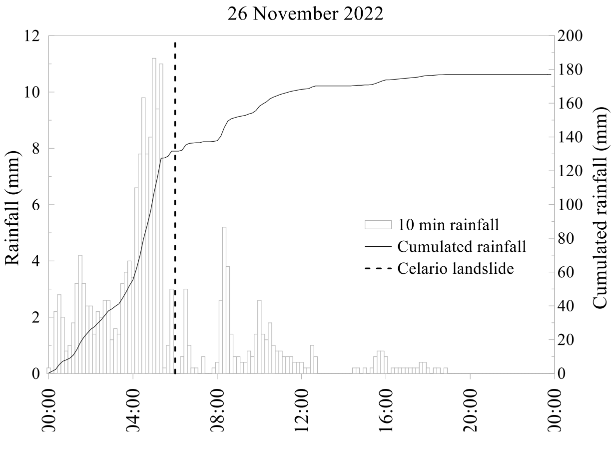
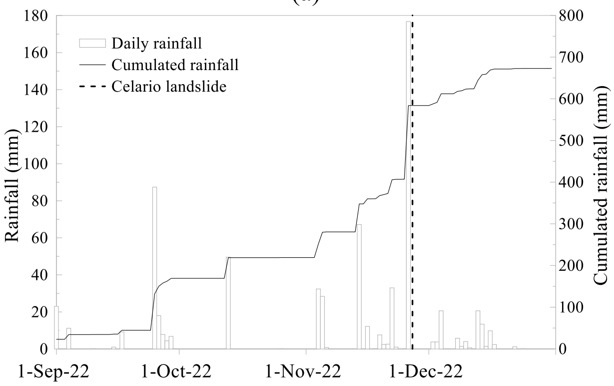
triangular shape, the landslide channelled downstream into a groove in the tuff slope containing pyroclastic residuals of different sizes, from silty sand to blocks of several cubic meters, generated by past erosion or landslide phenomena (Figure 3). Inside the channel, the debris increased in volume and speed, uncovering the green tuff formation and turning into a flowslide of considerable magnitude. The landslide determined the loss of twelve lives, including a newborn and two children.



(a)



(b)

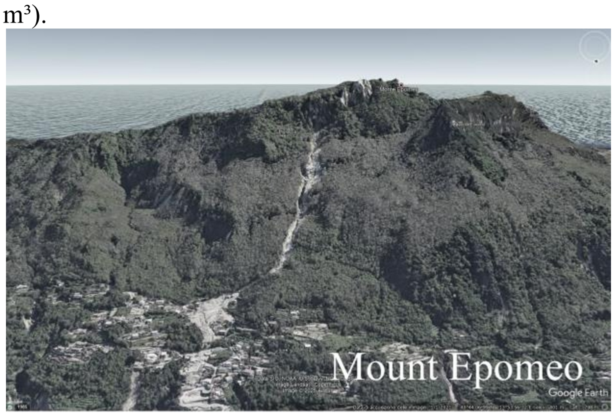
Fig. 1. Forio raingauge measurements: a) for November 26, 2022; b) since the beginning of the hydrological year (September 2022)

The initial debris-flow stage matches recurrent phenomena that have occurred in similar formations in the Campania region over the last three decades, causing fatalities: Pozzano/S. Pantaleone in 1997 [11], Sarno in 1998 [12], Cervinara in 1999 [13] and Nocera Inferiore in 2005 [14].

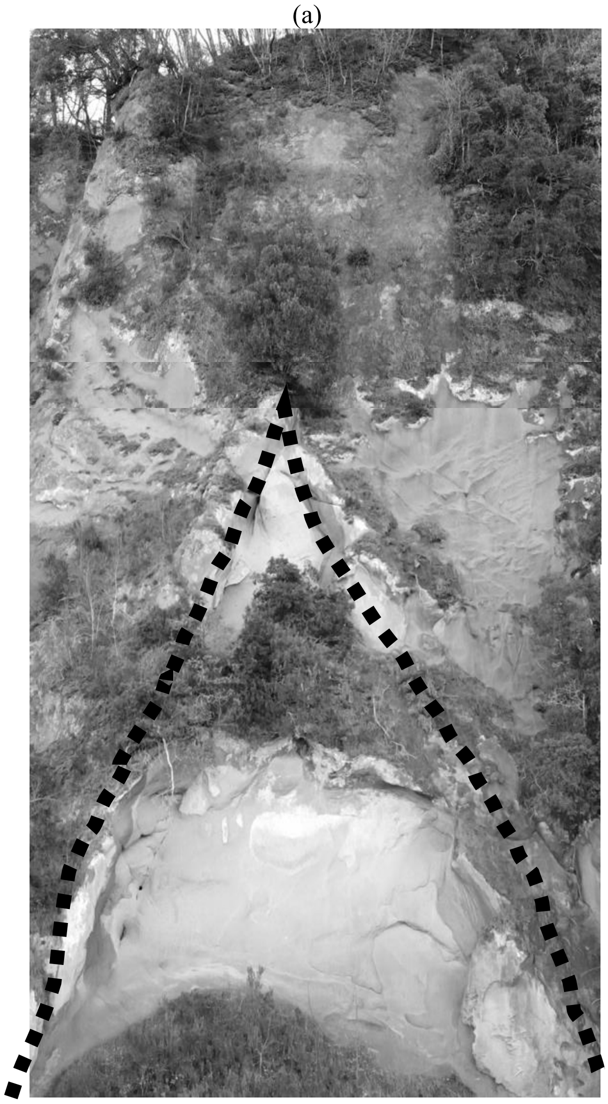
Compared to the events above, the differences can be attributed to the following two aspects:

1. The preceding rainfall for the Celario phenomenon was lower (about 400 mm) compared to over 700 mm for the previous events.
2. The precipitation during the triggering event was similar in volume to that of the previous phenomena, but concentrated over a shorter period (6 hours, compared to 14 hours or more for the previous events), with a particular intensity (50 mm) in the last hour; in this regard, the Celario landslide is similar to the flash flood that affected the same area in 2009 [5].

The channelized propagation stage resembles several phenomena occurred at Sarno (1998), with the singularity that this flowslide involved not only medium-fine grained pyroclastic soils (about 40,000 m³) but also significant volumes of rock blocks from the previous disintegration of the green tuff formation (about 1,000 m³).



(a)



(b)

Fig. 2. a) View of northern slope of Mount Epomeo from Google Earth (year 2024); b) picture of video footage taken with a drone of the landslide area

Fig. 3. Picture of blocks of tuff rock involved in the runout of the landslide.

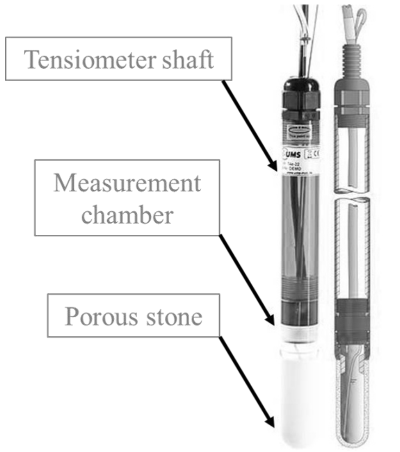
3 The field monitoring activity

The research activity was aimed at characterising the infiltration and evaporation fluxes that occur in the pyroclastic deposits near the initiation area of the Celario landslide, and how these fluxes modify the hydrological state of the deposits themselves.

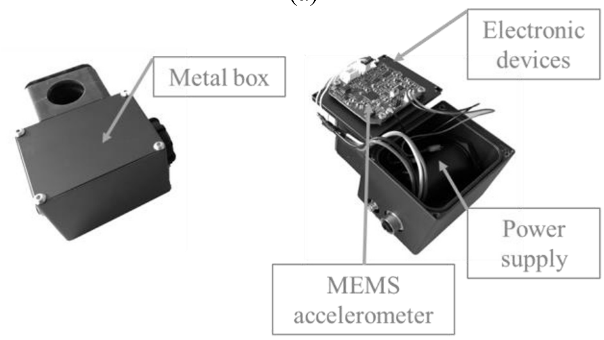
Rainfall data were collected at Forio raingauge. Other meteorological variables have not been monitored so far. The installation of a weather station and additional sensors is planned as part of the future developments of the research activity. They will allow for a direct measurement of infiltration and evaporation fluxes; insofar, they have been supposed as proportional to the reduction and the increase of the measured suction, respectively.

The activity began by monitoring soil suction levels and relating them to the evolution of meteorological variables. The monitoring device installed consists of a commercial tensiometer (Figure 4a), featuring a variable-length shaft that houses a small measurement chamber at the lower end, placed behind a porous stone. The instrument measures negative pore water pressure (i.e. suction) values up to -80 kPa and positive pore water pressure values up to +100 kPa. The tensiometer, originally designed and developed to be acquired and powered by a traditional datalogger, was converted into a "stand-alone" device, autonomous in terms of power supply, data acquisition, storage, and wireless transmission [15]. The instrumentation required for the inclination measurement and the relevant electronic modifications were mounted in a metal box attached to the upper end of the tensiometer shaft (Figure 4b). The instrument is particularly suitable for on-site monitoring due to the ability to create a fully wireless monitoring system. The presence of wiring connecting multiple instruments to a control unit would introduce significant logistical issues (e.g., cable damage, malfunctioning of the power supply system for the control unit, etc.). This update was fundamental in allowing all monitoring activities for the case in hand, due to the rough and steep slope morphology of the installation site.

By equipping the shaft with a triaxial MEMS accelerometer, the measurement of pore water pressure (both in the positive and negative ranges) was integrated with the measurement of the tensiometer shaft inclination, to form a 'tensio-inclinometer' prototype providing a kinematic quantity, the inclination, combined with the hydrological factor (suction) that could affect it.



(a)



(b)

Fig. 4. a) Scheme of the commercial tensiometer; b) metal box containing the electronics required for the inclination measurement

4 Results

The monitoring activity, still in progress, began in June 2023, when two tensio-inclinometers were installed by pressure insertion from the ground level in the area next to the landslide site (Figure 5), approximately 50 m downstream of the apical zone. One measurement device was installed superficially, at a depth of 10 cm. The other was pushed deeper, 50 cm below the ground level. The devices are inserted in a layer of gravelly sand constituting the weathered cover of an ancient green tuff formation (Santo et al., 2009).

The two tensio-inclinometers were configured to acquire data at a frequency of 15 minutes. Figure 6

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shows the first suction measurements plotted together with the precipitations recorded downslope at the meteorological station placed in the Forio town. The shaft inclinations were measured as invariably constant over the monitoring period presented.

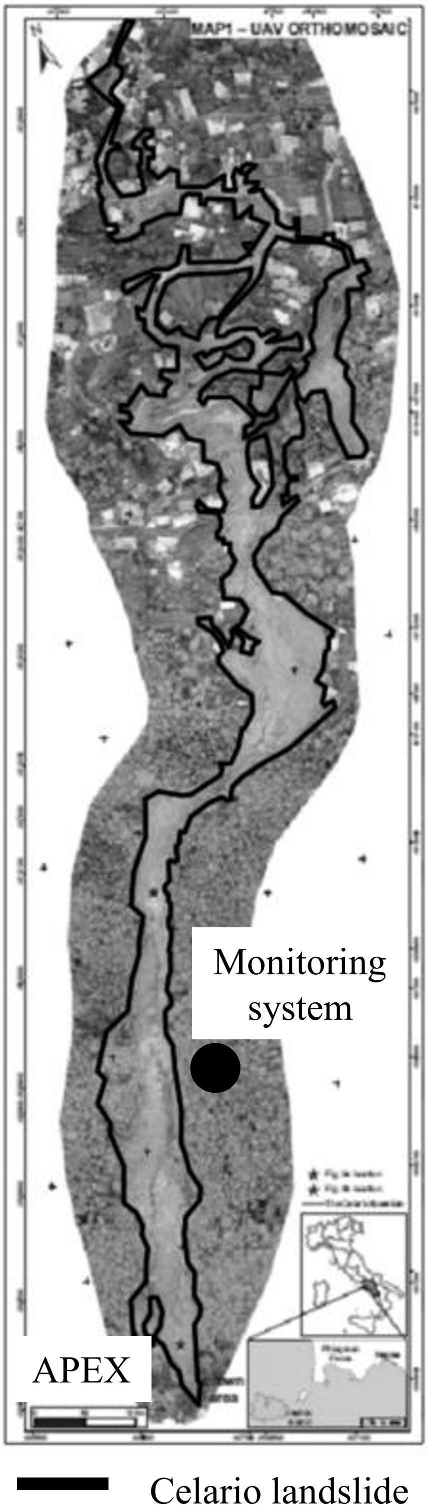


Fig. 5. Representation of the development of the Celario landslide [9] and location of the monitoring system (after De Falco et al., 2023).

The first results presented refer to the installation phase and two following dry and wet periods (Figure 6a). Upon installation, both devices recorded suction levels around 15 kPa.

Figure 6b shows how rainfalls that followed the installation stage induced significant suction drops, almost immediately vanishing at a depth of 10 cm, and decreasing with some time lag to 8 kPa at 50 cm.

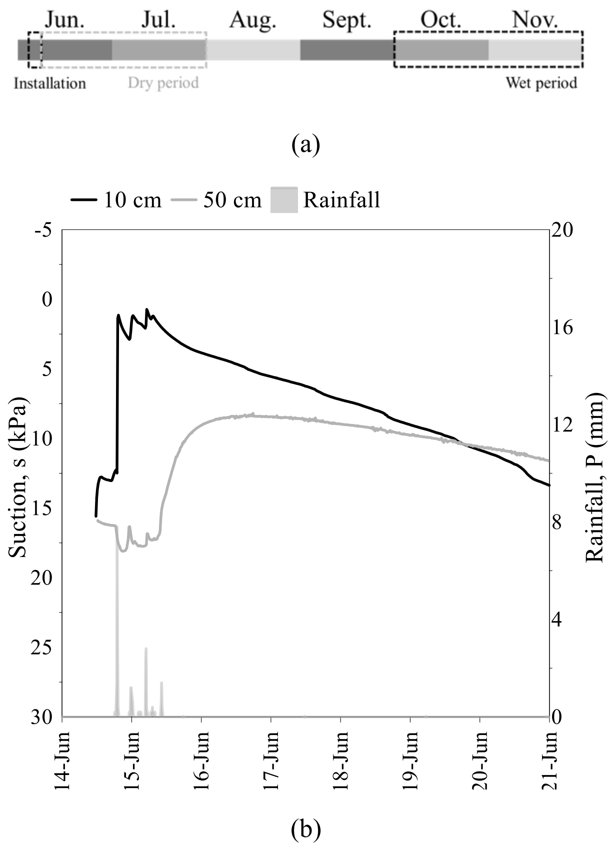
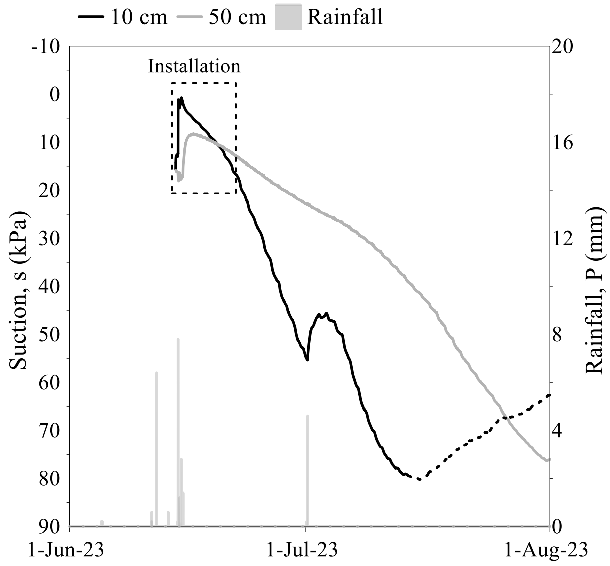


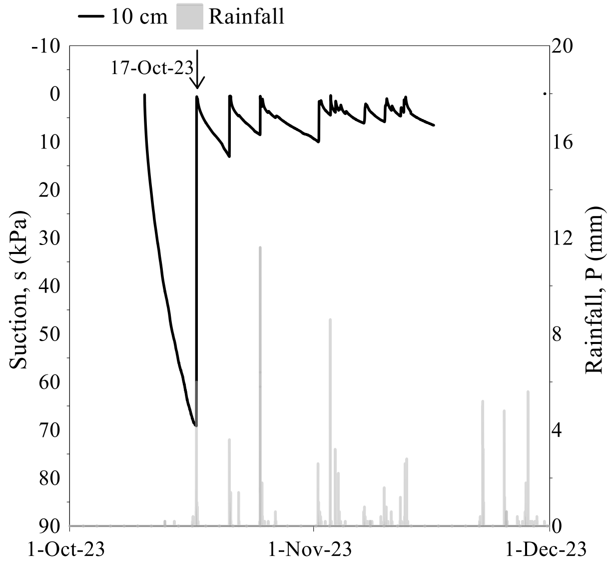
Fig. 6. a) Time schedule of the monitoring activity. Suction trends combined with rainfall values measured by Forio rain gauge for the: b) installation phase.

Figure 6c indicates that the rainfall that occurred at the beginning of July was only slightly significant in affecting the surficial trend of progressive increase in suction level, induced by the very intense evaporative processes active during that dry period. The outgoing flows that occurred in the exceptionally hot month of July determined a significant increase in suction up to the cavitation threshold of the instruments (80 kPa). As expected, the more superficial instrument measured a faster increasing suction trend, resulting in earlier cavitation attainment. The tensiometers were saturated again and reinstalled at the beginning of October in the layer that was still in a dry state, a week before the first rainfall event.

Unfortunately, the tensiometer installed at 50 cm failed in recording data. Figure 6d shows the evolution of suction recorded by the superficial measurement point over the period 10 October- 16 November. The dry state initially increased suction at 70 kPa. The first significant rainfall (October 17) subsequently reduced suction to nearly null values. Alternated dry and wet periods then drove suction swinging between 10 and 0 kPa.



(c)



(d)

Fig. 7. a) Time schedule of the monitoring activity. Suction trends combined with rainfall values measured by Forio rain gauge for the: c) dry period; d) wet period (see frames in the above time schedule).

5 Conclusions

The rainfall event that hit Ischia Island during the night of November 26, 2022, triggered multiple landslides. The municipality of Casamicciola was the most severely affected, particularly by the "Celario landslide". The monitoring activity is still in progress, highlighting that the suction levels typically drop to a few kPa during the autumn season, while they tend to increase to several tens of kPa during spring and summer. This suggests that a measurement trend leading to suction vanishing (i.e. pointing towards positive pore water pressure) may indicate the key for calibrating non-structural risk mitigation countermeasures. These might consist of early warning systems referring to alarm thresholds based on the combination of values or gradients of suction, as measured at different depths and different locations around the triggering area. For such a reason, an effort is currently in progress to spatially extend the monitoring network and to integrate the tensio-inclinometer prototype devices with further instruments, including sensors for recording soil water content and meteorological variables at the same site.

This study was carried out within the framework of the agreement between the « Commissario straordinario per gli interventi di riparazione, di ricostruzione, di assistenza alla popolazione e di ripresa economica nei territori dell'isola di ischia » and the Department of Civil, Architectural and Environmental Engineering of the university of Naples, Federico II.

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