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CASCADING LANDSLIDES AT MORINO-RENDINARA, L'AQUILA, CENTRAL ITALY: NUMERICAL MODELLING OF SLOPE-SCALE PROSPECTIVE DEBRIS FLOW PROPAGATION

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EXTENDED ABSTRACT

Le cosiddette *cascading landslides* sono sequenze o serie di frane multiple che possono innescarsi in successione a seguito di un evento di frana iniziale responsabile dell'innesco. Questa tipologia di eventi coinvolge solitamente volumi di materiale significativi e all'evoluzione spaziale (sequenza d'innesco) di solito consegue anche un'evoluzione reologica che si manifesta con un progressivo incremento della mobilità e della velocità fino a valori tipici delle colate di detrito. Per tale ragione, le cascading landslides possono avere gravi conseguenze, causando vittime e significative perdite economiche anche a distanza ragguardevole dall'evento innescante. Data la complessità di questi eventi, la loro mitigazione passa attraverso lo sviluppo di metodologie analitiche utili alla comprensione delle relazioni causa-effetto tra evento iniziale innescante e processi successivi indotti in cascata. In questo quadro, questo lavoro ha l'obiettivo di analizzare le caratteristiche del cascading landslide di Morino-Rendinara, in provincia di L'Aquila, applicando una procedura capace di fornire dati inerenti ai meccanismi e cinematica del sistema, alla anatomia dei corpi di frana, e ai possibili scenari di evoluzione futura.

La *cascading landslide* di Morino-Rendinara (AQ) si trova nella Valle di Roveto, attraversata dal fiume Liri. In tale area i versanti si presentano costituiti da rocce carbonatiche del Mesozoico, talora dislocate da faglie normali, a cui si sovrappongono formazioni arenaceo-pelitiche del Messiniano e depositi del Quaternario. Lungo i versanti, alle quote più elevate, sono presenti sorgenti di notevole portata, alimentate da acquiferi carbonatici altamente fratturati che affiorano tipicamente nei settori immediatamente superiori. La *cascading landslide* di Morino-Rendinara (AQ), oggetto d'interesse, è costituita da una frana profonda da scorrimento, attualmente attiva, caratterizzata da un meccanismo rotazionale prevalente a cui sono associati eventi di colata di detrito a valle, lungo il Rio Sonno (affluente del fiume Liri) e valanghe/crolli in roccia a monte, lungo il settore superiore del versante meridionale dei Monti Ernici. Di particolare significato è l'evento di colata di detrito sviluppatosi nel marzo 2021, responsabile dello sbarramento del fiume Liri con conseguenti alluvionamenti locali e danni al costruito. Da tali elementi è possibile evincere come il sistema di Morino-Rendinara (AQ) non si limiti a comprendere eventi di frana diversificati dal punto di vista dei meccanismi, ma anche processi di transizione verso il dominio alluvionale. Ciò rende tale sistema particolarmente complesso e di grande significato ai fini della comprensione delle caratteristiche dei processi a cascata.

Data la complessità del fenomeno, l'analisi delle sue caratteristiche in termini di anatomia, proprietà dei materiali e cinematica è stata eseguita sulla base dell'integrazione di metodologie multiple quali rilievi di sito supportati dall'acquisizione di immagini da drone, perforazioni geognostiche e prove di laboratorio su campioni prelevati durante l'esecuzione delle stesse, indagini geofisiche e dati di velocità/spostamento derivati dal processamento di immagini Sentinel-1 InSAR e Google Earth. Ciò ha permesso di identificare le geometrie della frana profonda, le proprietà dei materiali coinvolti, la profondità della sua superficie di scorrimento, la velocità di movimento del fenomeno, il volume e le aree coinvolte dalla colata di detrito avvenuta nel marzo 2021, le caratteristiche dei materiali coinvolti, la forma e il volume dei blocchi potenzialmente instabili lungo la porzione superiore del versante dei Monti Ernici e le aree suscettibili al distacco.

Su questa base, specifici approfondimenti modellistici sono stati eseguiti per i fenomeni a cinematica rapida rappresentati dagli eventi di colata detritica per il settore inferiore del versante e dagli eventi di crollo in roccia per quello superiore. Assumendo condizioni sorgenti simili a quelle osservate in sito, il fenomeno di colata detritica del 2021 è stato analizzato attraverso l'applicativo MADflow (Chen, 2020) e, sulla base dei parametri calibrati a tal fine, è stato sviluppato uno scenario di prospettiva per la propagazione di eventuali ulteriori colate di detrito considerando condizioni di innesco simili e volumetrie differenziate. In associazione, è stata condotta un'analisi per la stima delle traiettorie di propagazione di blocchi lungo la porzione superiore dei Monti Ernici attraverso l'applicativo Rockyfor3D (Dorren & Simoni 2014).

I dati derivati dalle analisi condotte, inerenti ai fenomeni di frana identificati, sono poi confluiti in un elaborato di sintesi rappresentante la suscettibilità da frana dell'area.

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ABSTRACT

Cascading landslides are sequences of multiple landslides that commonly involves significant volumes of material and exhibit variable velocity up to several m/s. The impact of these processes is generally significant so that they can claim victims and be responsible of significant losses. Considering the complexity of the process, their mitigation involves the understanding of cause-effect relations between the initial triggering event and subsequent cascading processes as well as the development of methodological framework for their analysis. On this basis, this work aims to analyse the characteristics of the cascading landslide event of Morino-Rendinara, in the L'Aquila province, applying a procedure that, comprising multiple methods, is capable of providing data depicting mechanism and kinematics of the system, anatomy of landslides and prospective susceptibility scenario.

Keywords: *cascading landslide, debris flow, rockfall, back analysis, satellite images.*

INTRODUCTION

Cascading landslides have been described as a sequences or series of multiple landslide events that can be successively triggered by an initial event responsible for the initiation. These series of events commonly involves significant volumes of material and their spatial evolution is consistently associated to a change in material rheology responsible for a progressive increase in mobility and velocity up to values commonly exhibited by debris flows. For this reason, cascading landslides can claim victims and can be responsible of significant economic losses, even at a considerable distance from the initiation zone.

Given the complexity of the process, their mitigation needs to be based on a comprehensive understanding of cause-effect relations between the initial triggering event and subsequent cascading processes, as well as on specifically developed methodological framework for their analysis. Such framework should account for factors controlling the initiation and evolution of the cascading landslide event and might be able to provide data about intensity of processes expected to directly or indirectly impact settlements.

Significant cascading landslides and associated hazard (*i.e.* earthquakes, floods etc…) have been observed in a number of regions of the world but the central sector of Himalayan region and the mountainous areas of China seems to be particularly prone to these processes also as consequence of the ongoing climate change (Sharma *et alii*, 2023; Zhou *et alii*, 2012). Although not so common as in these regions, in Italy such events have been observed both along the Alps and at specific locations of the Apennine Mountains. The Morino-Rendinara cascading landslide event, developed along the southern slope of the Ernici Mountains in the L'Aquila province is among the most significant cascading landslides of the Apennine Mountains because of its differentiation in terms of landslide mechanisms and impact on settlements. More precisely, this is located next to the village of Rendinara (Morino) in the upper Roveto Valley, which marks the boundary between the Abruzzo and Lazio regions.

On this basis, this work aims to analyse the characteristics of the cascading landslide event of Morino-Rendinara (Figure 1) by applying a procedure that, comprising multiple methods, is capable of providing data depicting mechanism and kinematics of the system, anatomy of landslides and prospective susceptibility scenario. A combination of data derived by conventional field surveys aided by Unmanned aerial vehicle (UAV)-based image acquisition, boreholes logging and laboratory testing, geophysical surveys was adopted in order to understand the anatomy of the system. Advanced satellite interferometric analysis of SENTINEL 1 imagery and digital image correlation of Google Earth imagery were used to reconstruct the kinematics of the system and provide data suitable for deciphering the evolution of the mechanism along the involved slope. In addition, numerical modelling of debris flow and rockfall propagation was adopted in order to identify potential propagation areas for these events. Finally, data derived by the combination of these multiple methodologies were used to derive a susceptibility scenario that might guide land planning and mitigation measures design.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE STUDY AREA

The Morino-Rendinara cascading landslide develops along the eastern side of the Liri River valley, mostly comprised of Messinian siliciclastic deposits and secondarily of polygenic breccias and puddingstones (Figures 1a - 1b). The terrigenous deposits appear highly deformed due to both the Apennine tectogenesis and the intense glaciation-driven deformation. The slope affected by the event belongs to the Ernici Mountain range, which in association with the Simbrunini range, forms a continuous ridge featured by the overthrusting of the Jurassic-Miocene carbonate units over the terrigenous formation of Valle Roveto (Parotto *et alii*, 1971).

Being consistent with the regional context, from a geological pint of view, the Morino-Rendinara cascading landslide area is characterized by the presence of Mesozoic formations (heavily jointed carbonate rocks) cropping out in the upper sector of the involved slope and displaced by normal faults, overriding the Messinian arenaceous-pelitic formations (clays and sandstones) widely outcropping at the middle and lower sector of the slope.

The significant rock fracturing associated to the climate regime of the area has led to the accumulation of slope deposits at the middle sector of the slope where the inclination change from higher that 60° to an average of 18°. Moreover, the area is marked by the massive presence of Holocene fluvial deposits and detrital cones associated with debris removal by flowing water and re-deposition next to the Liri river valley.

Fig. 1a - Overview of Morino-Rendinara cascading landslide

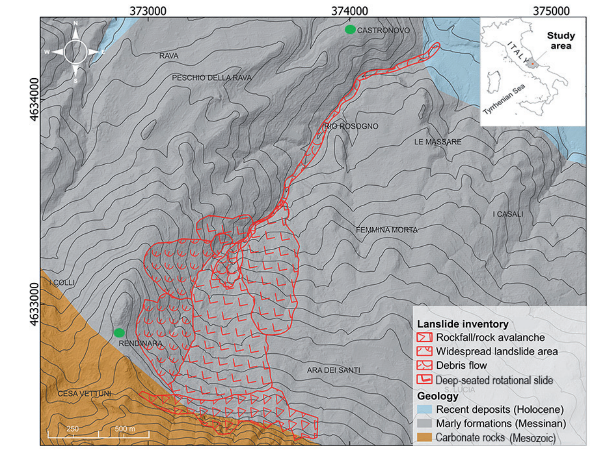

Fig. 1b - Geological sketch of the study area; Legend: green dots indicate city centre of Rendinara (Morino) and Castronovo

From a tectonic perspective, the overriding of the Meosozoic carbonate rocks over the Messinian siliciclastic deposits of the valley floor has been interpreted by previous authors (Devoto, 1967; Parotto, 1971; Cavinato *et alii*, 1993) as the effect of differential north-eastward translation and anticlockwise rotation of the carbonate structure, characterised by greater shortening in the southern sector. The overriding plane is almost always covered by a thick band of detritus recognizable along the whole tectonic front (Devoto, 1967b; Parotto, 1971). The geometry of the tectonic overlap plane, where recognizable, is characterized by the presence of low-angle planes (10°-20°) dipping W and SW.

The area is also characterized by the presence of a regionally important carbonate aquifer consisting of locally extremely fractured limestones and dolomitic limestones. Local flow lines follow the general trend of the slope and the circulation within the aquifer creates conditions for the presence of multiple springs along the slope. Here, the hydrogeological regime is influenced by the ongoing tectonics and numerous groundwater springs are present in the contact zone between the Messinian arenaceous-pelitic formation and the slope deposits locally covering such rocks.

Slope deposits are extremely heterogeneous, thus forming layers with different permeabilities. This type of cover and substrate configuration tends to create areas where the normal underground water circulation is characterized by large volume of water moving from the fractured carbonate aquifer toward the Messinian rocks tending to form suspended aquifers which sometimes emerge as springs along the slope (due to the different grain sizes of the deposits and permeability contrasts).

DATA AND METHODS

The methodological framework adopted for the analysis of the Morino-Rendinara cascading landslide is highlighted in the flow chart of Figure 2. Overall, each landslide mechanism identified on the basis of field observations was individually analysed by multiple methods. The analysis of the upper sector of the slope, in which conditions for rockfall development were pointed out by field surveys, focused on the estimation of rock mass properties, stability analysis, and rockfall propagation simulation.

Eight geomechanical stations (scan-line 5/10 m long) were set up following the procedures proposed by the International Society for Rock Mechanics (ISRM, 1978). Based on the gathered data, it was possible to define the classification indexes Rock Mass Rating (Rmr - Bieniawski, 1989), and Slope Mass Rating (Smr - Romana, 1985). This allowed the identification of significant geomechanical parameters as well as potential slope failure mechanisms.

At each geomechanical station, for the most significant discontinuities, the JCS (compressive strength) of the discontinuity surfaces was measured using uniaxial compressive strength tests with an L-type "rock sclerometer" (Schmidt hammer), which has an impact energy of 0.705 Nm and a measurement range of 10-200 N/mm².

To analyse the rockfall susceptibility of the carbonaceous fractured rock mass, some simulations were carried out through Rockyfor3d. Rockyfor3D (Dorren & Simoni, 2014) allows for the analysis of two-dimensional propagation of rockfalls phenomena using simulation procedures based on raster data. The added value of Rockyfor3D, compared to other software on the market, lies in its ability to consider the geometry of blocks and the damping effect associated with the possible presence of vegetation in the propagation area. The model is based on the combination both stochastic and deterministic algorithms, incorporating physical parameters used to simulate trajectories through sequences of free falls, bounces, and rolling of rocks. The simulations utilize a slope model constructed using parametric raster maps, enabling the association of specific parameters with each cell. These parameters are useful in defining the trajectories of rock blocks, both in the phase of free movement through the air and in the phase of single or repeated impact with the slope surface.

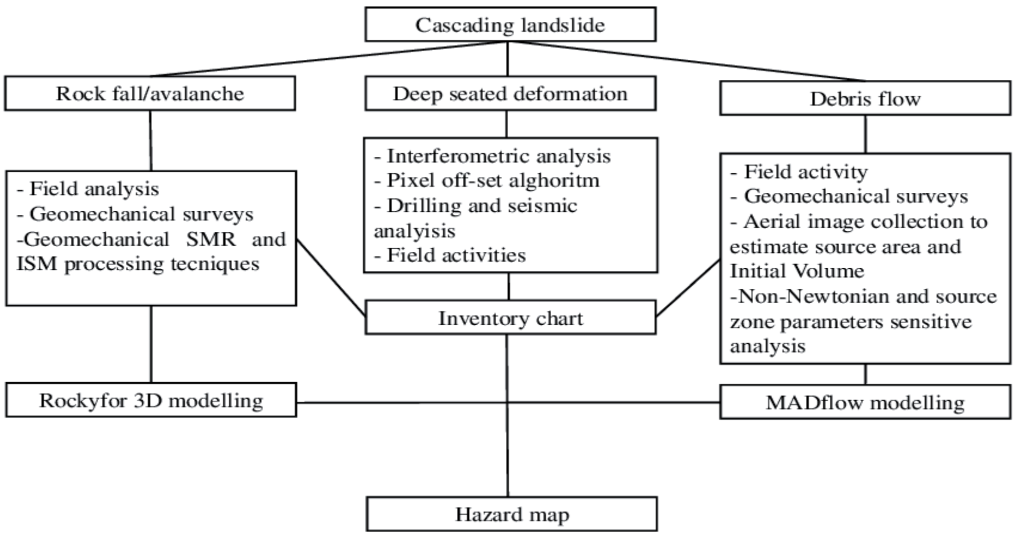

Fig. 2 - Flow chart depicting the methodological procedure of analysis of the cascading landslide of Morino-Rendinara

The size and shape of the blocks have been derived based on geomechanical survey data, simulating block shapes as parallelepipeds. The volume of the blocks varies significantly across different slope areas investigated. In the areas surveyed through geomechanical surveys, the average volume of the blocks has been calculated around 2 m^3. From the analysis of data obtained from photogrammetric surveys using drones, it was possible to identify areas where stratification exhibits larger spacing values (often related to the tectonics of certain areas), leading to the potential generation of blocks with volumes up to 50/60 m^3. Therefore, two different analysis were performed using 2 and 50 m^3, respectively. The density of the rock material has been set to 2400 kg/m^3. The estimation of normal restitution coefficients was performed by employing a specific zoning of the study area based on the characteristics of the soil/slope surface. The analysis of simulations using Rockyfor3D allowed for the identification of preferential trajectories along which any rock blocks could potentially move after detaching from the identified slope areas.

The analysis of the middle sector of the slope, in which the presence of a deep-seated landslide was pointed out by field surveys, focused on the identification of landslide thickness and velocity estimation. The thickness of the landslide was estimated by interpreting stratigraphic logs derived by boreholes and seismic pseudo-section reconstructed on the basis of data acquired at seismic lines. The surface movements of landslide was assessed using the DInSAR (Gabriel *et alii*, 1989). technique. Initially, the interferometric products obtained from the radar image processing, through the state-of-the-art PSP-IFSAR algorithm (Costantini *et alii*, 2008), were interpreted. These were acquired from the Very High-Resolution (VHR) COSMO-SkyMed satellite constellation of the Italian Space Agency (ASI). These data were obtained as part of the Second Extraordinary Environmental Remote Sensing Plan, funded in 2014 by the Ministry of Environment, for the period 2011-2014.

Subsequently, to update the assessment of the landslide's activity, SENTINEL-1 images from the European Space Agency (ESA) were used for the period 2020-2023. This latest dataset was processed using the SUBSIDENCE software, developed at the Universitat Politecnica de Catalunya (Spain), and which relies on the Coherent Pixels Technique (Cpt - Mora *et alii*, 2003) algorithm. In addition, to supplement the analysis of landslide kinematics by estimating the cumulative displacement between 2016 and 2022, a digital image correlation of Google Earth imagery was completed following the procedure developed by Guerriero *et alii* (2020). The use of this algorithm allows for precise and continuous investigation even in areas where interferometric data are subjected to inherent method limitations (such as orientations of the phenomenon relative to the Line of Sight - LoS). Especially, Google Earth colour images saved in .JPG format with dimensions of 4800×2674 pixels were used. The images depicting the area affected by the debris flow were acquired in July 2016 and June 2022. Following the digital image correlation technique, the older frame was used as the master, and the more recent one as the slave.

The analysis of the lower sector of the slope, in which a debris flow was documented in March 2021, focused on the identification of condition for debris flow propagation by numerical modelling. Among the most suitable numerical codes for studying the phenomenon under investigation are those relating to a classical approach (see MADFlow) or the new generation SPH (Smoothed Particle Hydrodynamics) (Pasculli *et alii*, 2104).In this case, the evolution of the debris flow and its potential impact on settlement along the Liri River valley was analysed thought the use of the MADflow code (Chen, 2020) accounting for sediment entrainment and flow dilution due to the presence of the river.

Developed for academic research, MADflow is a numerical simulation code able to examine the mobility of gravitational flows characterized by mixtures of soil, rock, and/or water, such as debris flows, lava flows, mudflows, mudslides, and avalanches. MADflow is based on a robust, compact, volume-conserving, quasi-three-dimensional (using average depth) dynamic model. The code incorporates commonly used rheological models for non-Newtonian flows, including granular flows. The stress in response to deformation during the movement of high-concentration solid flows is governed by the Savage-Hutter equation. This equation accounts for the conservation of momentum along the flow in the presence of gravitational forces and shear resistance, representing a simplification of the complex phenomena influencing granular flows. The flow incorporates stringent material balance error controls and automatic selection of the time interval. The time interval dimensions, and computational grid resolution can be freely adjusted for numerical convergence/sensitivity testing or rapid preliminary studies (subject to internal CFL restrictions for numerical stability).

The mathematical formulation of the code is based on Chen and Lee (Chen *et alii*, 2006; Chen & Lee, 2000, 2003).

To build a correct rheological Bingham (1920) parameters, τ and μ have been estimated by a sensitivities analysis starting from O'Brien and Casson formula (Casson 1959, O'brien 2001).

In MADFlow models, the flow rate was derived from the estimation of the riverbed cross-section at 4 points distributed across the study area, assuming to have a trapezoidal shape. Regarding the flow peak, it was assumed that the Liri River and Fosso delle Massare had a flow rate equal to 20% of the maximum channel height.

RESULTS AND DISCUSSION

Result from field surveys indicate that the Morino-Rendinara cascading landslide is dominated in the upper sector by rockfalls, in the middle sector by the presence of a deep-seated rotational slide and in the lower sector by debris flow involving material disrupted by the upper deep-seated rotational landslide.

From the gomechanical analyses of the upper sector appears that the rocky slope is not uniform, hence the stability and quality of the mass vary significantly in space. The rock mass quality assessed through RMR fall between 31 and 60, indicating a low quality.

In Figures 3a and 3b, Rockyfor3d-based propagation analysis results, for blocks of 2 and 50 m^3, respectively, are exhibited. These results show the probability of propagation, estimated from the number of trajectories in a given position divided by the total number of simulations conducted for each detachment

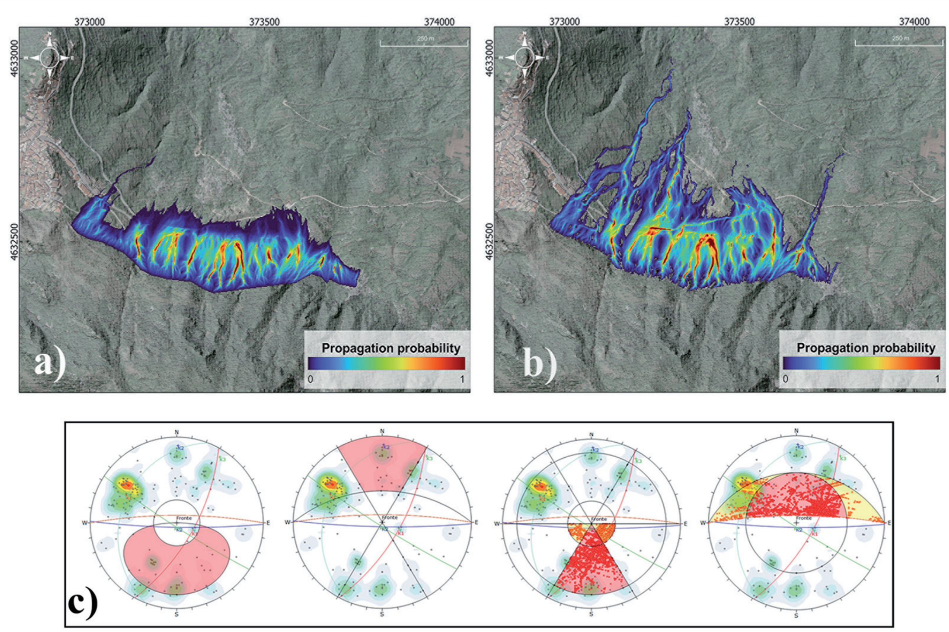

Fig. 3 - Modelling Results: a) Rockyfor3D Simulated scenarios 2 m^3 blocks; b) Rockyfor3D Simulated scenarios 50 m^3 blocks; c) possible kinematics from SMR analysis (from left to right: Planar sliding, flexural toppling, direct toppling, wedge failure)

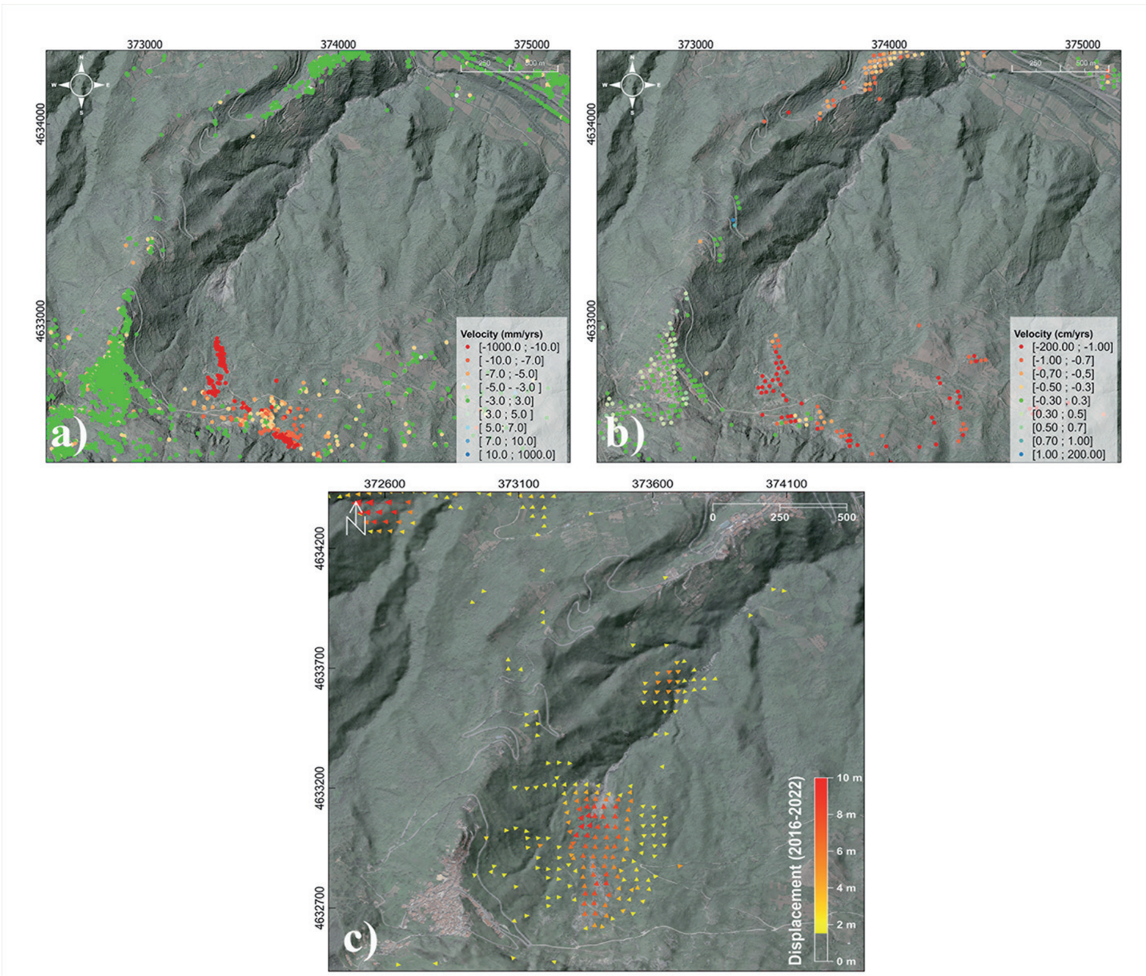

Fig. 4 - Synthesis of field and remote sensing analysis; a) 2014-2016 interferometric analysis b) 2020-2023 interferometric analysis c) 2016-2022 pixel offset analysis

area ((Number of passages * 100) / Total number of simulations). Values close to zero (blue) indicate lower probabilities (Figure 3a and b). It is important to highlight that both simulations show the potential for blocks to affect infrastructure such as roads and houses (especially near the Rendinara hamlet). The simulation also indicate that 50 m^3 blocks (Figure 3b) can impact a significantly wider area due to the increased kinetic energy. The possible kinematics derived through the stability analysis are planar sliding, wedging, and direct or oblique toppling (Figure 3c)

Interferometric analysis (see Figure 4a and b) highlights the active movement of the deep seated rotational landslide and the presence of further instability phenomena in the area, showing significant displacements over the entire temporal span. Moving persistent scatterers can be also identified at the edges of the deep-seated rotational landslide (Figure 4a and b, red dots), suggesting potential regression and involvement of the roadway.

In this area, the results of the analysis for the 2011-2014 period (Figure 4a) show a linear displacement trend, with slight accelerations observed mostly during periods of heavier rainfall. This could confirm hypotheses that the kinematics of the deep seated rotational landslide is associated with variations in subsurface water levels. The results for the 2020-2023 period (Figure 4b) show significant displacement rates, indicating an actively moving deep-seated landslide. The most unstable sector is instead the eastern area, characterized by displacement rates with values exceeding 2 cm/year.

Results from digital image correlation of Google Earth imagery (Figure 4c) highlight that the highest cumulative displacement occurred in the axial sector of the deep-seated landslide upslope from the source area of the debris flow triggered in March 2021. Consistent with the results obtained from interferometric analyses, the area below the SP66 road is also affected by movements probably related to the evolution of the deep-seated landslide phenomenon. The analysis reveals that the averaged highest cumulative displacement rate stands at 10.43 cm/year.

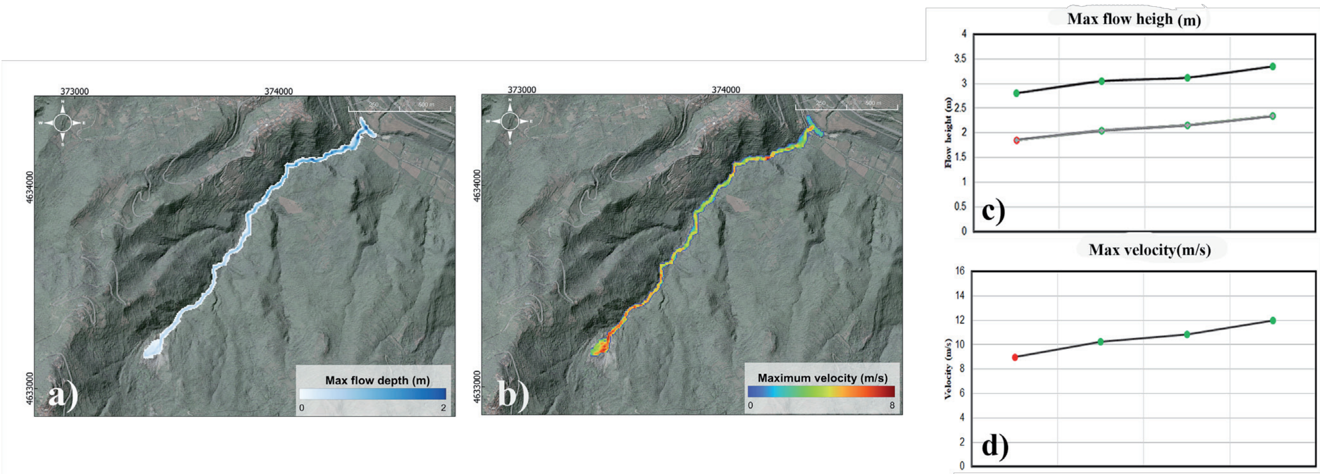

Fig. 5 - MADFlow modelling resultsin terms of a) flow height of the back-simulated march 2011 debris flow, b) maximum velocity of the back-simulated march 2011 debris flow, c) flow height change as a consequence of variation of initial volume (red dot indicates the back-simulated scenario, green dots indicate the estimated volume change in source zone, results with grey line are referred to scenarios without Liri river, black line are simulated results considering the Liri River), d) flow velocity change as a consequence of variation of initial volume (red dots indicate the back-simulated scenario, green dots indicate prospective scenarios)

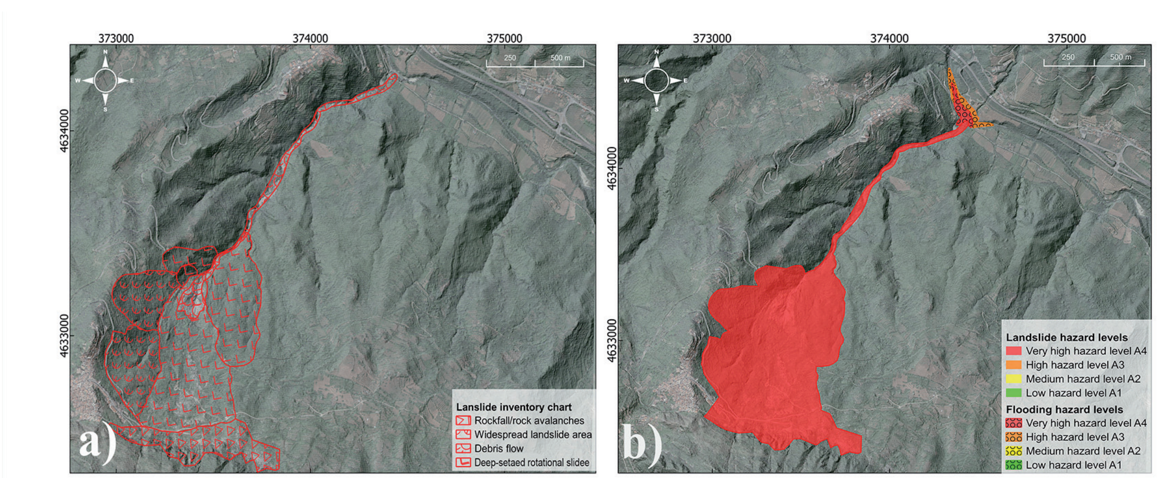

Fig. 6 - Final Results: a) Landslide inventory chart; b) Hazard map

This rate is notably higher compared to the rates detected through interferometric data, where velocities are around 1.25 cm/year for the period 2011-2014 and 2.20 cm/year for the period 2020-2023.

Figures 5a, 5b, 5c and 5d present the results of MADFlow back analyses. The model was evaluated using field data, measuring flow heights downstream from the catchment and along the Liri River, where possible. A simplified form of the super-elevation formula derived from Rieckmann (1999) was used to estimate velocity.

The model results are coherent with field and calculated data. Figure 5 c and d show the maximum flow depth (Figure 5c) and velocity (Figure 5d), compared to the calibration scenario "March 2021 event".

Trends in both cases linearly increase based on the variation of parameters set at the source area (volume and position) (Figure 5c and 5d). The simulated maximum flow depth is approximately 3.30 meters (Figure 5c), while the highest velocities are recorded in the steeper areas and scenarios involving larger volumes, reaching peaks of 12 m/s (Figure 5d) in the analyses conducted considering the Liri River, resulting in the flooding of adjacent flood terraces.

All of the observed and simulated data were summarized in a landslide inventory chart (Figure 6a) underlining the complex interactions between rockfalls (upper sector), deep-seated rotational slide (middle sector) and debris flow (lower sector) involving material disrupted by the upper deep-seated rotational landslide propagation (last recorded in March 2021 event). On this basis a susceptibility map (Figure 6b) was derived showing both the susceptibility derived from active landslides recognized on the basis of data derived by the analyses and the debris flow modelling.

CONCLUSIONS

In conclusion, the study of the Morino-Rendinara cascading landslide in the L'Aquila province of Central Italy unveils the intricate dynamics and multifaceted nature of geological phenomena featured by multiple landslide mechanisms.

The conducted analysis pointed out the complex interactions between rockfalls, deep-seated rotational slide, and potential debris flows propagating toward the Liri river valley with further hydrologic effects related potential formation of a landslide dam and related flooding.

Each debris flow simulated scenario exhibited a differentiated impact on the distribution of velocities, flow depths, volumes, and consequently, the intensity of the debris flows as shown in Figure 4a, b, c and d.

The analysis reveals that the highest cumulative displacement rate stands at 10.43 cm/year in the central sector. This rate is notably higher compared to the rates detected through the upper sector, where velocities are around 2.20 cm/year. These results indicate an active landslide slower in the upper sector and faster in the central one.

By employing a multi-method approach joining conventional field survey methods with cutting-edg technologies such as drone imaging and satellite interferometric analysis, the research endeavours to decode the mechanisms governing this cascading landslide events.

Moreover, the exploration of the event's most recent reactivation in 2021 through numerical simulation played a key

role in reconstructing the evolution of the landslide and, at the same time, in forecasting potential future scenarios.

The multi-scenario analysis conducted on the Morino-Rendinara debris flow provides an in-depth view of potential impacts and variations in associated risks related to the phenomenon. Through the examination of various scenarios and simulated conditions, it became evident that downstream areas along the river course are most susceptible to potential blockages (Figure 6b).

Understanding the interplay of geological context, modelling and remote sensing techniques is fundamental not only for enhancing current mitigation strategies, but also for formulating robust frameworks for a pre-emptively tackle and mitigate the impact of geological hazards in the future.

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