Revisiting Hazard Assessment for the Deep-Seated Gravitational Slope of Paterno (Central Italy).

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Summary

The study presented here proposes an approach, based on the combination of InSAR techniques and geological field observations, to assess and quantify the hazard of the Deep-Seated Gravitational Slope of Paterno (Rieti, Central Italy). The deformation process that affected the Paterno slope has already been identified and featured by high landslide hazard rank in the PAI catalogue, which designs territorial planning documents. Until nowadays, the Paterno slope movement has never been investigated in depth. The new data collected contribute to revisiting of landslide hazard level in the study area, where old settlements and other infrastructures are located. The lack of evidence of activity of this deformation process suggests a lower hazard rank concerning that assigned in the PAI and, therefore, needs reviewing.

Keywords: Deep-seated gravitational slope deformation, Central Apennines, Structural Control, Hazard, Satellite Interferometry

Introduction

Deep-seated gravitational slope deformations (DSGSDs) are geological time-dependent processes driven by gravity, affecting entire hillsides and involving volumes larger than several tens of millions of cubic meters (Zischinsky, 1969; Crosta, 1996). While the displacement rates may be relatively slow, returned as millimetres or centimetres per year, they may damage local infrastructure and trigger smaller-scale failures (Chigira, 1992; Panek & Klimes, 2016). In this work, we focused on the Paterno DSGSD, located in the central-eastern sector of the Apennine chain. The slope of interest is under the competence of the Basin Authority of the District of Central Apennines, connected with the Italian Government, which has started, in collaboration with the Structure of the Commissioner for the Reconstruction of the municipalities affected by the 2016-2017 Central Italy seismic sequence, an activity carried out to update the landslide hazard plan of the area (labelled PAI). These actions aimed to indicate a high hazard, namely P3, and very high hazard, namely P4, areas interacting with the post-earthquake reconstruction plan.

Paterno DSGSD

The Paterno rock-slope is located close to the San Vittorino Plain, in the province of Rieti (Lazio Region, Italy), NE-SW oriented and with a highest elevation of approximately 1010 m a.s.l (Fig 1a). The structural general framework, with regional faults and folds, imposed a complex jointing system on the carbonate rocks, facilitating karst processes. This latter, which is a dissolution process, led to the emergence of various peculiar landforms such as sinkholes and dolines. These effects are prominently observed in the San Vittorino Plain by decametric-sized collapse dolines and diffused sinkholes, such as the Paterno Lake (Salvati & Sasowsky, 2002; Petitta, 2009), situated at the footslope within alluvial deposits. The Paterno DSGSD is characterised by two flat/low-angle surfaces which define the upper and lower parts of the slope. The morphological features associated with the upper part of the Paterno slope are double ridges, trenches, scarps, and counter-slope portion while bulging, scree slopes and buckling foldes characterize the slope toe (Radbruch-Hall et al., 1977; Varnes et al., 1989; Agliardi et al., 2001). The survey of these morphologies is crucial for their inventorying and accurately quantifying landslide hazard conditions, potentially posed by their tertiary paroxysmal evolution (Chang et al., 2015; Vick et al., 2020).

Materials and methods

A 1: 5.000 map was used as cartographic base during the field survey. A project on the Geographic Information System (GIS) was developed to store geological and geomorphological data derived from the surveys, data from geomechanical stations, and elaborating analyses. Photointerpretation and the geomorphological analysis were combined with satellite images (by Google Earth®) and a 5x5 m Digital Elevational Model (DEM). Morphometric dataset and satellite images allowed the preliminary identification and interpretation of geomorphological features (i.e., main scarps, secondary scarps, landslide, dolines), verified during the geological field survey. In addition, 20 geomechanical stations have been conducted to assess the degree of fracturing and evaluate the extent of the slope involved in the deformation process. Field survey was combined with two sets of Satellite Synthetic Aperture Radar (SAR) stacks of images for conducting an interferometric analysis. These analyses aim to derive displacement results by utilising Persistent Scatterers (PS). This technique allows the analyses of the spatial and temporal evolution of slope instabilities, in particular of DSGSD phenomena, characterised by low velocities (Cignetti et al., 2023; Antonielli et al., 2019). The SAR techniques detect the ground deformation velocity along the satellite's line of sight (LOS). A stable region where the velocities are included between -1.5 mm/yr and 1.5 mm/yr is recognised (Figure 1b). Otherwise, velocities greater than 1.5 mm/yr or less than -1.5 mm/yr represented displacements relative to the LOS. The application of the satellite interferometry technique in the case study of Paterno aims to assess the DSGSD activity and its associated hazard level.

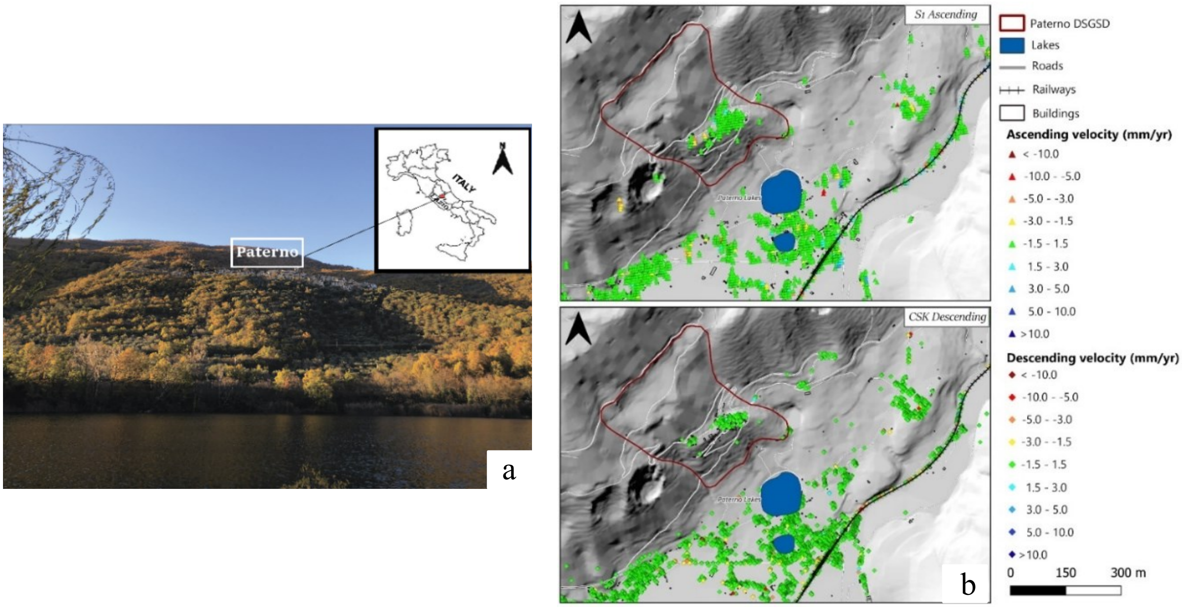

Figure 1: a) Geographic location of the study area; b) Mean displacement rate maps for Sentinel-1 (5-02-2017/21-06-2022) and Cosmo-SkyMed (7-02-2017/29-06-2022) datasets. The Paterno DSGSD is bordered by the red line.

Evidence of Paterno slope instability

The complex network of joints can be attributed to the interplay between tectonic and slope deformation processes, such as faults and shear zones. These features have driven the formation of weakness zones, facilitating the development of the Paterno DSGSD. The counterslope topographic surface, also affected by a regional fault, represents the most highly fractured area of the slope. This is highlighted by the validation of data collected from the geomechanical stations, which identified zones with heightened fracturing that define the deformation process. As a result, the main scarp has been indicated in that area. Geological surveys and morphometric analysis illustrate that the bedrock displacements derived from the combined influences of fault slip and gravitational process. Although the presence of gravitational processes and geomorphic features associated with the Paterno DSGSD are notable, there is no evidence of its current activity. Geological surveys do not show cracks on buildings or other signs of active deformation, which was confirmed also by the InSAR monitoring of ground movements. The analysed dataset, composed of Sentinel-1 and COSMO-SkyMed Persistent Scatterers (PS), reveals the absence of active displacements in the Paterno DSGSD. Otherwise, deformations in the San Vittorino Plain near sinkholes were detected during the observation period.

Assessing Hazard of Paterno DSGSD

Our results emphasise the dominant role of tectonic influence in driving the overall slope deformation. Several field surveys have been conducted, and no evidence has been found to attribute an active state to the DSGSD. Therefore, based on the field surveys, it can be affirmed that the landslide is currently in a quiescent or inactive state. Alluvial deposits cover the Paterno footslope, which does not appear deformed on field, and shows no signs of recent activity. The alluvial deposition occurred under non-deforming conditions, representing a minimum temporal limit of inactivity or quiescence state for the DSGSD. Differently, karst processes persisted and matured even after Paterno DSGSD activity. These landforms constitute, at present, the main geological hazard in the study area that can endanger buildings, infrastructure, and human lives, causing structural damage or even leading to accidents and fatalities. The geomechanical stations provided valuable insights into the spatial extent of the deformed area, with direct observations and measurements on the ground, while the InSAR data measurements have contributed to defining the state of activity. The analyses performed in this study have enabled us to delineate the boundaries of the Paterno DSGSD, assess its evolutionary model, and evaluate its associated hazard. The confirmed perimeter of the DSGSD does not directly correspond to the hazard rank assigned to the process by PAI. The associated state of inactivity, resulting from our analysis on the slope, allows us to attribute a low degree of hazard to the Paterno DSGSD. However, we cannot exclude the possibility of reactivation due to potential near-field earthquakes.

Conclusion

This work contributes to assessing the hazard associated with a DSGSD process through a combination of field surveys and interferometric analysis. This multi-technique approach highlights no signs of recent deformation activity, indicating a state of inactivity or, at least, quiescence. Therefore, revisiting the high landslide risk of the Paterno DSGSD allows us to attribute a lower risk to this process. The results of this study can contribute to updating the landslide risk areas in the PAI catalogue.

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