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Urban-Scale Risk Assessment of Rainfall-Induced Rock-Slope Instabilities: The Case Study of Popoli Terme (Abruzzo, Italy)

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Abstract: Rainfall-induced rock-slope instabilities threaten urban areas and infrastructure set at the foot of steep slopes. Urban-scale hazard appraisal is essential for risk estimation, prevention and emergency planning. Within this framework, the Italian SLIDE project, together with the MULTI-TWIN project, provides an integrated hydrogeological and seismic hazard assessment by combining literature and newly acquired data. We present the urban-scale hazard and risk assessment of rainfall-induced rock-slope instabilities in the municipality of Popoli Terme (Abruzzo, Italy). The methodology fuses datasets and performs quality control; statistically models boulder-detachment areas; performs 3D simulations of trajectories, kinetic energy, and runout; and derives building-level vulnerability and risk. Hazard, vulnerability, and risk maps are available within the MULTI-TWIN platform to support urban planning. The maps highlight the buildings most exposed to rainfall-triggered rock-slope instabilities. The same platform provides final multi-risk maps by combining independent natural hazards (seismic, hydraulic, and hydrogeological) at both the building and urban scales. The risk is expressed as expected economic loss per square meter to guide local mitigation and prevention policies.

Keywords: ***Data-driven analysis, Rainfall-induced rock-slope instabilities, Structural vulnerability, Risk assessment.***

Introduction

Rainfall-induced rock-slope failures can cause significant economic losses to the urban structures and infrastructure lying at the foot of rocky slopes. In such settings, rigorous hazard and risk quantification is essential to underpin prevention and emergency management. First, the SLIDE project defined a methodology to calculate the hazard related to rock-slope instabilities in the Province of Pescara (Abruzzo). The results achieved were then integrated into the MULTI-TWIN project, which aims to build a digital platform for the integrated evaluation of hydrogeological and seismic risks within a multi-hazard framework. While the project addresses multiple hazards - spanning seismic, hydraulic, and hydrogeological ones - this contribution focuses on rainfall-induced rock-slope instabilities. We implemented a data-driven workflow combining physically informed indicators, statistical modelling of boulder sources, 3D simulations (trajectories, kinetic energy, runout), and building vulnerability functions to derive the hydrogeological risk. This last was then mapped in terms of economic losses at the building scale.

Study area

Popoli Terme (Abruzzo Region, Central Italy) is a historic town situated in the central sector of the Apennines, along the Aterno-Pescara Valley, north-west of the Maiella Massif. It is set in a hazardous area, where endogenous and exogenous phenomena shape the physical environment. The city center lies within a tectonic valley, filled with hundreds of meters of soft sediments and crossed by the Sagittario and the Pescara rivers. On the eastern side, the town of Popoli is bordered by the slopes of Mount Morrone, with cliffs and scarps highly susceptible to rock instabilities. The historic center's building stock is dominated by masonry constructions, with a limited presence of reinforced-concrete structures; typical heights are 3-4 storeys with heterogeneous maintenance conditions.

Climatically, the area exhibits a Mediterranean climate with hot summers, modulated by the Apennine Mountains, with pronounced precipitation seasonality and sharp valley-mountain contrasts (Curci et al., 2021). The geomorphological and climatic setting fosters the activation of rainfall-induced slope instabilities, as documented through national rainfall-landslide event catalogues and related studies in Italy.

Methodology

To evaluate the hazard, we collected several datasets including rainfall-induced instabilities from the ITALICA catalogue (Brunetti et al., 2023), rockfalls from the IFFI (Inventario dei Fenomeni Franosi in Italia) inventory, and local pluviometric time series for Popoli Terme. We rely on the assumption that the activation of rainfall-induced rock-slope instabilities depends on the slope (morphometric parameter) and rainfall (meteorological parameters: duration, D, and cumulative, C) features. To account for rainfall conditions, based on (D,C) pairs associated with rainfall-induced rock-slope instabilities within the ITALICA dataset, we binned rainfall durations [h] on a logarithmic scale, computed the 15th percentile of cumulative rainfall [mm] within each bin, using the bin median of D as centroid, and fitted the corresponding log–log threshold lnCT(D):

$$\ln C_T(D) = \alpha + \beta \ln D \quad (1)$$

where α and β are regression coefficients equal to 1.89 and 0.49, respectively. We then defined a logistic transition function to obtain the soft exceedance probability of C conditioned on D:

$$P(C|D) = \frac{1}{1+e^{\{-k[\ln C - \ln C_T(D)]\}}} \quad (2)$$

We set k = 1 to enforce a moderately gradual, non-abrupt transition. Concerning the morphometric parametrization, using IFFI data, we defined the frequency of rock-slope instabilities per slope class to evaluate their susceptibility (Rs). Finally, the rainfall-triggered rock-slope instability hazard was conceived as the product of P(C|D) and Rs. To characterize rock-slope instability dynamics, we delineated scenario-specific source areas based on the hazard analysis. We then performed 3D simulations with Rockyfor3D v6.0 (Dorren, 2024) for hazard scenarios with return periods of 50, 100, 200, and 500 years. The transit and accumulation zones and the associated impact kinetic energies, as identified by the simulations, were used to estimate building vulnerability. The latter was derived from the expected kinetic energy and the structural characteristics of the buildings. The risk was then assessed as the expected economic loss per square meter at the building level (Al-Shaar et al., 2024).

Results and discussion

The results are rockfall hazard maps highlighting strong morphological and litho-structural control (Figure 1). Highest hazard and risk occur along slope-foot transitions on the north-western flanks of Mount Morrone, where fractured carbonate bedrock forms multi-meter blocks prone to collapse. Falling trajectories follow preferential corridors, yielding higher impact energy and creating extensive transit and accumulation zones. Hydrogeological risk decreases with distance from slope toes and where smaller blocks originate from continental Quaternary units. Higher rainfall severity increases susceptibility, expanding the hazard footprint and the number of exposed buildings. At the building scale, expected losses depend on impact energy and structural resistance as recorded in Italian national survey forms.

Conclusions

This study provides scenario-based hazard layers and building-level risk estimates. Integration into the MULTI-TWIN platform enables multi-risk aggregation and dynamic updates as new observations become available, strengthening decision support. The proposed workflow is readily transferable to other urban contexts and directly supports risk mitigation, emergency management, and resilience planning.

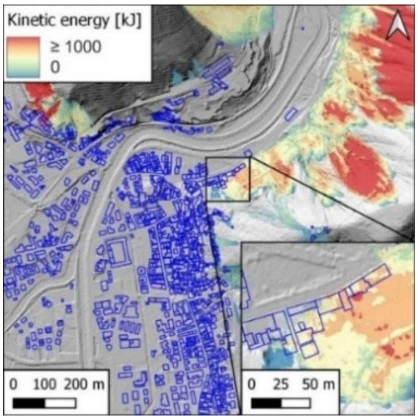

Figure 1, Rainfall-induced rock-slope instability hazard expressed in terms of kinetic energy [kJ].

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