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# ASSESSMENT OF ROCKFALL-INFRASTRUCTURE INTERACTION: A CASE STUDY OF A VIADUCT IN NORTHEASTERN ITALY

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Determining the interaction between landslides and infrastructure is a complex task, given the wide variability in landslide types and infrastructure designs. Accurate risk assessment must consider landslide characteristics, structural vulnerability, and exposure to risk. Events such as sudden rock falls, topples, or debris flows are often almost unpredictable and leave virtually no time for intervention. Assessing the risks associated with these rapid phenomena is critical to understanding their potential to cause devastating impacts. This article examines a case study occurred in Northeast Italy in early 2024 when a large portion of material suddenly collapsed, impacting a railway, initially, and then a road viaduct. The incident caused severe damage and the closure of both routes for months. Existing mitigation measures failed due to the material's volume and speed. In addition to a detailed case study description, this work also presents findings using the QPROTO plugin for QGIS, which was used to simulate the event. Finally, the consequences of the possible detachment of two other rock masses identified as unstable during an inspection following the event were assessed. Advanced modelling tools are crucial for improving risk evaluation and understanding landslide-infrastructure interactions.

*Keywords*: Rockfall, landslide risk, risk assessment, case study, infrastructure damage, structural vulnerability.

## 1. Introduction

Crossing structures serving transport infrastructures are of fundamental importance for overcoming terrain obstacles or rivers and canals. Therefore, it is essential to ensure their safety through periodic maintenance to avoid interruptions to connections and thus inconvenience to the population. In addition to structural wear and seismic risks, they may also be affected by flood or landslide events, which are often difficult to predict as, in some cases, it is challenging to identify warning signs in the area surrounding the infrastructure or on the structure itself. This complexity makes it difficult to conduct an effective risk assessment that can accurately identify and analyze landslide phenomena potentially compromising the integrity of the structure.

Among landslide phenomena, those that pose the greatest challenge in terms of prediction and timely intervention are rapid and impulsive events, such as rockfalls from a cliff face or debris flows. Numerous cases in literature illustrate the impact of rockfalls on infrastructures, such as the partial collapse of the Chediguan Bridge in China in July 2009 occurred following the impact of a 130 tonne rock mass on one of the bridge piers (He et al. 2019, Lu and Zhang 2012), and the case of the Interstate 70 in Colorado (USA), a road segment that has been affected by various rapid landslide events over the years (Arndt and Ortiz 2012). These and other cases highlight the importance of effective prevention methods for such phenomena, which, despite being relatively small in scale, can cause catastrophic events due to their high velocity. It is therefore necessary to develop risk assessment models capable of analyzing the consequences of potential rockfalls, enabling the timely implementation of preventive measures.

This study analyzes a recent rockfall case in northeastern Italy, using back-analysis to assess the potential detachment of two additional unstable rock masses identified during post-event inspections.

## 2. Description of the rockfall event

In early 2024, a large rock mass detached from a nearly vertical cliff of "Dolomia Principale" from the Norian age. The detachment surface was found to be almost flat, with a rhomboidal shape, measuring approximately 13 × 7 meters, with an average thickness of 2 meters, reaching over 4 meters at its deepest point. The event was likely caused by the significant temperature fluctuations in the preceding days, leading to freeze-thaw cycles, and possibly exacerbated by a seismic event that occurred nearby a few days earlier, which might have contributed to the fracturing of some rock bridges. The mass fell from a relatively low height (approximately 7–8 meters), partially fragmenting on impact with the ground. Large rock blocks remained intact and continued downhill, primarily rolling. A first block (5 × 4 × 2 meters) separated from the original mass, breached the rockfall barriers along its path, and stopped on a railway tunnel roof. A second block of even larger volume descended the slope unobstructed, striking firstly the railway line and then violently impacting the deck of a road viaduct, almost centrally, causing local damage and an approximately 5 cm transverse displacement with a slight rotation, before stopping on a service road at the foot of the viaduct. Following the event, both infrastructures were closed for several weeks to carry out the necessary repairs. Subsequently, the technical personnel of Rete Ferroviaria Italiana (Gruppo FS Italiane) conducted a drone-based photogrammetric survey, along with a thorough geological-geotechnical study, aimed at assessing the residual risk conditions of the rock face and designing and implementing new mitigation works directly on the slope above the infrastructure. Figure 1 shows the study area and some photographs of the event.

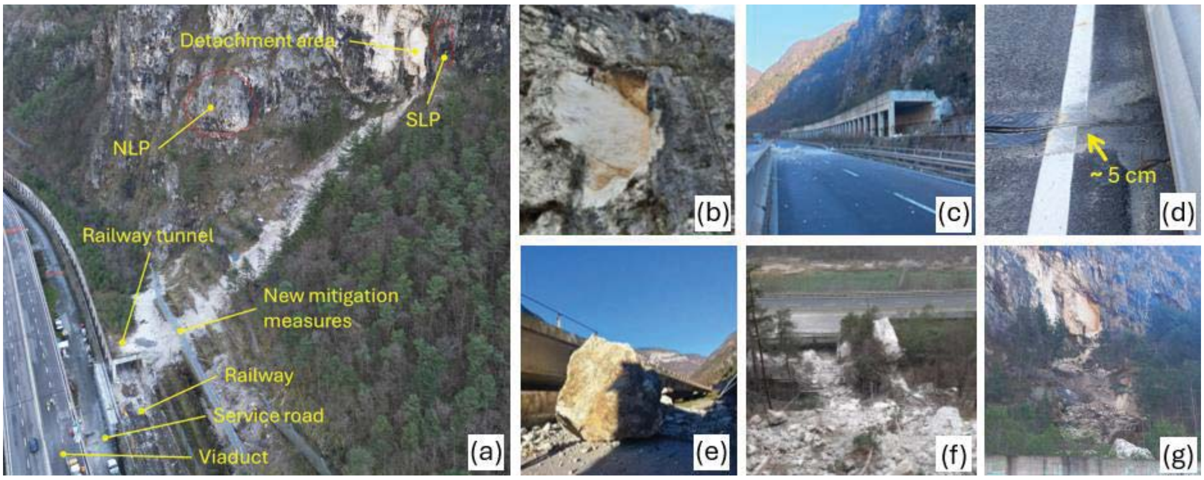

Fig. 1. a) Top view of the study area; b) detachment area; c-d-e) sign of impact on the structure; f-g) view of the first block stopped on the railway tunnel *(Source: R.F.I. - Gruppo FS Italiane and Geo-Engineering - geol. Ennio Chiesurin)*.

Although the area exhibited predisposing factors suggesting the existence of a potential risk condition, the presence of significant mitigation measures implied a reduced likelihood of interaction between potential collapses and the infrastructure. Moreover, precursor signals indicated the occurrence of sporadic and small-scale detachments, which rarely reached the railway and road networks. This case thus represents a significant example of how proper risk assessment—grounded in the evaluator's expertise, sensitivity, and sound judgment—is of fundamental and strategic importance in evaluating site conditions and determining appropriate risk management measures. In light of the events, during the post-event inspection, two additional rock masses were identified on the cliff face: the North Large Pillar (NLP), measuring 12 × 6 m with a thickness of 2–3 m, and the South Large Pillar (SLP), with a height of 20 m, a width of 10–15 m, and a thickness of 2–6 m. Preliminary and rapid analyses for risk estimation were conducted to assess the potential consequences of the detachment of these two unstable rock masses. The primary objective was to swiftly evaluate the possible impacts and, additionally, to determine whether further risk assessment operations were necessary or if the process could be concluded.

## 3. Modelling of events

To quantify the rockfall risk, it is possible to refer to three parameters: susceptibility, vulnerability, and exposure. This article focuses on the assessment of susceptibility within the framework of a risk assessment for the occurrences and of the interaction between the collapses and the infrastructures. To simulate the events, the QPROTO plugin (QGIS Predictive ROckfall Tool - https://plugins.qgis.org/plugins/qproto/) was used, implemented in the QGIS environment. This tool allows the evaluation of the visible area originating from a specific set of points, representing the detached mass or the potentially unstable one, implementing the *energy line concept* (Heim, 1932) and the *Cone Method* (Jaboyedoff and Labiouse 2011). The software is based on the idea that areas visible from a chosen viewpoint can be reached by boulders detaching from the considered sources. By overlapping the visibility cones of diffuse sources, it identifies the highest risk zones and generates a frequency map of areas most exposed to rockfall. Each point is associated with specific attributes that characterize the simulation process: the point ID, the elevation above sea level, the direction normal to the slope, the distance to which the analysis can be extended, the detachment propensity of each point (DI, Detachment Index), the mass involved, the energy line angle, and the lateral angle of the cone with its apex at the point of origin. The first angle indicates the angle between the horizontal plane and the segment connecting the detachment point to the stopping point of the element, while the second angle defines the opening of the runout cone. The simulation results using QPROTO consist of raster files with information about susceptibility, energy and velocity ranges (Castelli et al. 2021). Two analyses are considered: the first concerns the rock mass that detached from the cliff and impacted both the railway and road infrastructure, serving as a back-analysis; the second focuses on the potential detachment of the two additional rock masses identified as hazardous.

### 3.1. *Back-analysis of the actual event*

The simulation of the event considered a total detachment volume of 90 $m^3$, equivalent to approximately 243 tonne, with its centroid located at an elevation of 95 meters above the bridge. To perform the analysis, the Digital Terrain Model (DTM) provided by Veneto region was used. The energy line angle was chosen by setting the centroid of the detachment volume as the origin point and calibrating its value to replicate the actual event, resulting in an angle of 35.6°. The lateral angle was defined based on observations from the actual event, in which the opening of the runout cone was very limited. Consequently, the final value for this attribute was set at 5°. This value reflects the fact that the boulder originally detached fragmented into a few elements along its path, maintaining a very limited dispersion during propagation. Finally, the extension distance of the analysis was set to 150 meters, limiting the results to the areas considered relevant. Some of the results of the simulation are shown in Figure 2.

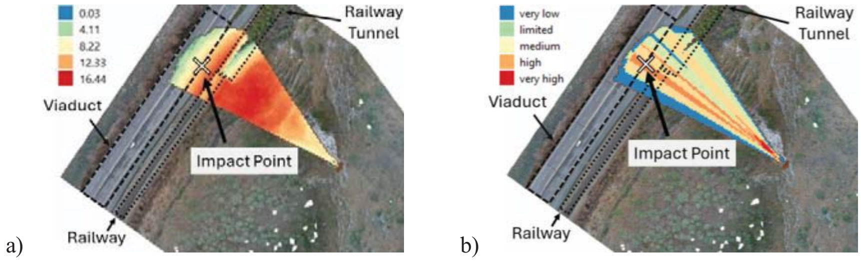


Fig. 2. Simulation results of the occurred event: maps of mean velocity in m/s (a) and susceptibility (b).

According to the simulation results, the elements reduce their speeds, eventually coming to a stop, in the area above the tunnel, matching event observations. Elements impacting the structure in the simulation had speeds of about 10 m/s. The susceptibility map highlights the areas most affected by the detachment, aligning with the actual event's outcome, and showing areas of high or very high susceptibility along the paths taken by the two main blocks.

To further support the model, a simulation of the rock mass impact with the deck was carried out using the discrete element code PFC3D (Itasca 2003), with the goal of verifying the displacement of the deck under different conditions. It was considered appropriate to perform the analysis with different values, including 3 masses, 3 speeds, and 2 friction angles between the deck surface and the bearing pad, to assess the relevance of these parameters in the simulation. The actual rock mass was approximately 110 tonne, with a speed of 10 m/s based on the QPROTO simulations results. The friction angle, based on studies in the literature (Taklas et al. 2022), was set to 35° and 40°. Post-event inspection confirmed a deck displacement of approximately 5 cm, with the rock mass penetrating the roadway by a few tens of centimeters. Results from the DEM simulation, shown in Figure 3, are aligned with these observations. Both the velocity and the impacting mass independently increase the displacement induced on the bridge deck. In all the cases, the results remain consistent with what is observed in reality.

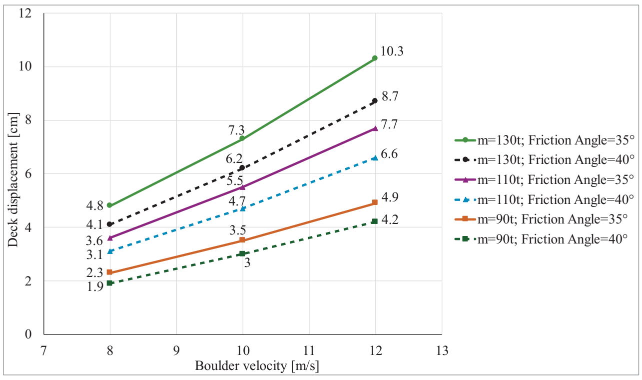


Fig. 3. Results of the impact simulations performed with the DEM.

### 3.2. *Simulation of the potential detachment of unstable rock masses*

Subsequently, it was possible to apply the tool to evaluate the consequences of other potential detachments. These additional analyses aim to preliminarily assess the risk conditions associated with the potential detachment of further rock masses, following the first documented failure. As mentioned, two large blocks were identified as particularly critical based on visual inspection. The objective of these analyses is to determine the areas potentially affected by the collapse and, most importantly, to estimate the extent of the possible interaction between the rockfall and the infrastructure. The NLP is located on the portion of the slope above the tunnel. For this mass, the same parameters of energy angle and lateral angle adopted for the simulation of the occurred event have been considered. A distance of 100 m was chosen as extension of the analysis, in order to focus the simulation on the section where the rockfall interacts with the existing railway and road infrastructures. Some results of the simulation are shown in Figure 4.

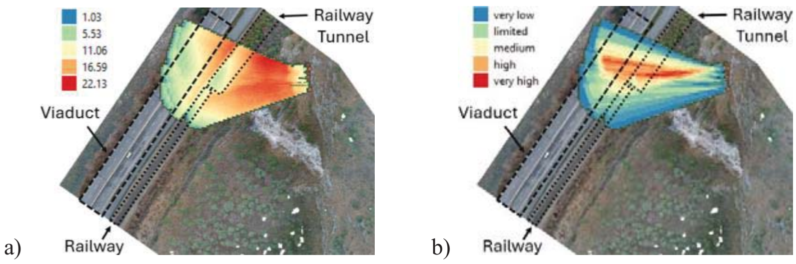


Fig. 4. Simulation results of the potential event related to NLP: maps of mean velocity in m/s (a) and susceptibility (b).

The results of the simulation show a rather high velocity in the areas adjacent to the slope, with the elements continuing beyond the railway tunnel and impacting the viaduct. In the worst-case trajectory, they reach the viaduct with a mean velocity of 16 m/s. The susceptibility map highlights the most affected area and the main trajectory followed by the elements. Subsequently, the analysis was also carried out for the SLP rock mass, located adjacent to the detached portion. The energy line angle was considered consistent with the previous cases, and a lateral angle of 10° was chosen. This parameter was slightly increased to account for greater uncertainty in estimating the mass's trajectory. The rock face near the SLP is highly fractured, making it possible that, in the event of triggering, the phenomenon could cause a greater dispersion of the elements composing the collapsing mass, thus widening the potential runout cone. As in the previous case, the analysis was conducted considering the maximum interaction distance with the existing infrastructures, set at 150 meters. Some results of the simulation are shown in Figure 5.

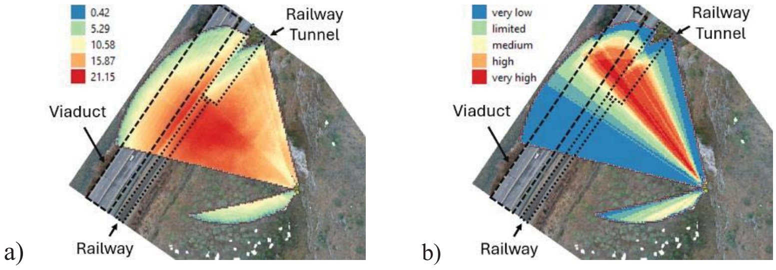


Fig. 5. Simulation results of the potential event related to SLP: maps of mean velocity in m/s (a) and susceptibility (b).

The results show speeds similar to those obtained in the simulation of the actual event, as expected, considering the corresponding position. Furthermore, it is observed that some elements may reach the structure with an average speed of about 17.5 m/s. The susceptibility map highlights the most affected area and the main trajectory followed by the elements, which appears to be directed toward the portion of the area crossed by the tunnel.

## 4. Conclusions

The study analyzed the interaction between rockfall events and a road crossing structure, with reference to a case that occurred in early 2024 in northeastern Italy. It highlighted the importance of an effective risk assessment for rapid and impulsive phenomena, such as rockfalls, which present complex challenges for infrastructure safety. Simulations performed with the QPROTO plugin in the QGIS environment helped to better understand the dynamics of the phenomenon, while the analyses conducted with DEM provided insights into its impact on the structure. Simulated scenarios considering the detachment of the other two hazardous rock masses were developed based on the calibration made from the actual event. However, the simulations did not consider the mitigation measures that were subsequently implemented by the personnel of Rete Ferroviaria Italiana (Gruppo FS Italiane). In fact, after the event, Rete Ferroviaria Italiana (Gruppo FS Italiane) implemented significant interventions on the entire portion of the slope above the railway line, introducing major risk mitigation measures. This approach allowed for the analysis of only the worst-case scenarios. Results demonstrate the potential of combining simulation tools with engineering interventions to proactively manage rockfall risks. The methodologies applied in this study serve as a reference for future risk analyses in similar contexts.

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