Application of empirical rockfall classification methods to risk management in an Alpine valley road

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ABSTRACT: Mountain secondary roads often follows complex land forms with high sub-vertical rock-cuts in outcropping rock prone to rock-fall events. Geo-structural rock mass surveys and collection of discontinuity data provide the basis for rock mass characterization and enable slope stability analysis and rock-fall hazard assessment. With this aim, a multiscale approach joining the non-contact techniques to the traditional one has been carried out focusing the rock cuts of a mountain road in Elva Valley (Piamonte, Italy). Based on collected data and the field visits, two different rock fall risk assessment empirical approaches were applied, namely the Rockfall Hazard Rating System (RHRS) and the so called Rockfall Risk Assessment for Quarries (ROFRAQ), adapted to road traffic. The application of these approaches to different road sections is demonstrated in the paper. Presented results will be the base to make risk management decisions and a discussion on results is eventually provided.

Keywords: Rockfall, Risk assessment, RHRS method, ROFRAQ method.

1 INTRODUTION

Rockfalls are a major hazard, and they are extremely common events in numerous rock cuts along mountain roads. These phenomena are hardly predictable and very rapid, often causing casualties, damage to vehicles or roads, resulting in economic losses (Budetta, 2004; Palma et al., 2012; Cignetti et al. 2021). To improve the analysis and management of the consequences resulting from this type of instability, it is of fundamental importance to assess their relative degree of detachment susceptibility for all rock masses located along the road (Mineo, 2020). However, the definition of risk and/or hazard scenarios for rockfalls implies the analysis of a set of natural instability phenomena that are very complex in terms of occurrence, frequency and magnitude.

Their examination must be based on an in-depth knowledge of the rock mass by means of surveying and/or monitoring actions. Only based on this information, it will be possible to study the structure of the rock masses at the slope scale and therefore, to identify and measure the occurrence of discontinuities, their orientation and spacing, and to define the statistical distribution of the volumes of detachable blocks (Hungr et al., 1999; Volkwein et al., 2011). Furthermore, in many cases, given the extent of the problem and the inaccessibility of the rock faces under study, photogrammetric and non-contact survey methods will be necessary for reconstructing the three-dimensional morphology of the slopes and determining a range of detailed information.

In this regard, this paper describes the procedure for risk assessment with reference to the case study of the so-called “Strada del Vallone d’Elva”, located in Piedmont, NW Italy. It consist on a 9 km long road characterized by overhanging rocky walls along which significant, but localized instability phenomena and widespread and continuous rock fall events of minor magnitude have been reported since its construction (Figure 1). Geostructural rock mass surveys and collection of data related to discontinues provided the basis for the characterization of rock masses, the study of their stability conditions and risk assessment along the entire road. With this aim, a multiscale approach combining non-contact techniques to traditional approaches was carried out (Pontoglio et al., 2020; Migliazza et al., 2021).

Figure 1. Two views of road sections extensively affected by severe rockfall events.

Based on all the data collected and the field visits, some rockfall risk assessment empirical approaches were applied to the slopes in the different road sections with the aim of making decisions related to risk management along the road. Particularly, two empirical approaches have been resorted to, namely the Rockfall Hazard Rating System (RHRS) as firstly proposed by Pierson et al (1990) and the so-called Rockfall Risk Assessment for Quarries (ROFRAQ), which has been adapted in this case to the conditions encountered in mountain roads (Alejano et al, 2008).

The first approach, RHRS, is just an empirical method providing a useful initial classification of risk suitable to establish some prioritization of slopes. On the other hand, the adapted version of ROFRAQ, complemented with rockfall trajectory program calculations, is a statistically based empirical approach, which provides risk assessment in the form of an indicative probability of accident. The application of both these approaches to different road sections is explained and presented in the paper. Results will be used to make risk management decisions and a discussion is provided on results.

2 APPLIED RISK ASSESSMENT METHODS (RHRS AND ROFRAQ)

To assess the level of risk and/or hazard along the Vallone dell'Elva road, two qualitative methods (RHRS, ROFRAQ) proposed in the technical literature (Ferrari et al., 2016) specifically developed to analyze rockfall risk conditions along road infrastructures were applied. These methods analyze slope, climatic and vehicle exposure data to define levels of susceptibility, hazard or relative risk that can be used to compare different slopes to apply hierarchical approaches useful for prioritizing and planning the realization of risk mitigation works.

The first approach, RHRS, represents the first method developed for evaluating the rockfall hazard of slopes subject to such instability (Brauner & Wyllie 1976; Pierson et al. 1990) by assigning a score, varying between 9 and 900, based on 9 parameters: slope height, geological character, block size, climate and presence of water on the slope, rockfall history, ditch effectiveness, average vehicle risk (AVR), percent of decision sight distance (PDSD) and paved road width.

A score is assigned to each parameter in relation to its value. Adding up the scores for the different categories gives a final score (from 9 to 900), which is an estimate of the hazard: higher scores indicate a higher hazard and vice versa. Based on Hoek's (2000) observation, the final score obtained can be used as a tool for managing the countermeasures, considering it as a relative risk assessment along the infrastructure. Typically a value of RHRS below 300 indicates a reasonably safe slope, while a value over 500 suggests immediate action if rockfall accidents wants to be avoided.

The ROFRAQ was one of first methods to be applied in the quarrying context and concerns the statistically based qualitative assessment of rockfall hazard and risk (Alejano et al. 2008). It is an empirical method based on the definition of the following aspects: degree of fracturing of the slope (factor A, varying between 0 and 10), potential instability conditions (factor B, varying between 0 and 10), triggering causes (factor C, varying between 0 and 10), the path of the blocks (factor D varying, between 0 and 10), presence of elements exposed to rockfall risk (factor E, varying between 0 and 10) and previous cases of rockfall (factor F, varying between 0 and 1,5).

Knowing all the factors, it is possible to determine the ROFRAQ index by multiplying them. This index varies between 0 and 150 000 and provides an indicative estimate of the level of risk and the necessary mitigation action. Moreover, a rough estimate of the probability of accident in any road section analyzed is given by the value of ROFRAQ divided by 100,000. Based on this figure, the combined probability of accident on various road sections or the whole road can be computed, and these values can guide management of protection measures until an acceptable risk level is attained.

Particularly, the evaluation of factor E (elements exposed to rockfall risk) was modified to consider the specific characteristics of the exposed elements at the site under study, particularly the presence of vehicles traveling along the road at the foot of the slope (ROFRAQmod).

The E factor is calculated as (1):

$$E = a \cdot \frac{b}{100} \cdot \frac{c}{100} \cdot d \tag{1}$$

where "a" is an assigned score with respect to the block size, "b" and "c" represent respectively the time and the space probability that a vehicle may be hit by a falling block, and "d" is an assigned score with respect to the locations of the elements at risk in relation to the toe of the slope.

Specifically, parameter "b" is determined by considering Average Vehicle Risk (AVR), which is the same parameter used in the RHRS, and it is calculated as (2):

$$b = AVR = \frac{ADT \ \cdot SL/24}{PSP} \times 100 \tag{2}$$

where ADT is the average daily traffic (expressed in number of cars/day), SL is the slope length (km), 24 is the number of hours per day (h/day), and PSP is the posted speed limit (km/h).

The parameter "c" considers the space that a car occupies on the road but also the space that it needs to stop before an obstacle, and it is calculated as (3):

$$c = \frac{l_c + \ s_s}{SL} \times 100 \tag{2}$$

where l_c is the length of the car (it was taken equal to 3 m), s_s is the stopping distance (it was assumed equal to 10 m) and SL is always the slope length.

3 APPLICATION METHODOLOGY

The methods described above were applied to overhanging rocky walls of Elva valley road. For this purpose, the road was divided into 87 average 50 m long sectors based on structural homogeneity and slope of constant orientation and height. To apply the methods described above, all the necessary parameters were defined and acquired through field activities and traditional and non-contact surveys.

In particular, the DTMs obtained from the photogrammetric and topographic surveys, which reconstruct the slopes along the entire road, allowed the geometric characteristics of the slopes to be defined. The block features were defined through geostructural surveys and the definition of discontinuity systems, spacing and roughness (including tilt tests). In addition, Markland tests for the definition of kinematics allowed the parameters for block motion to be identified. In order to give indications on the possible causes of instability triggering, data obtained from various meteorological and seismic stations close to the road were analyzed.

At each sector, along vertical cross-cut sections obtained directly from the reconstructed DTM of the road, rockfall simulations were performed using the Rocfall software (Rocscience, 2022). Based on these simulations, carried out considering the detachment conditions on the wall, it was possible to define the percentage of blocks that reach and pass the road and the percentage of blocks whose trajectory or fall path endpoint was the road. Finally, data on the level of exposure of passing vehicles was estimated considering the possible conditions of the road opening, estimating the presence of approximately 100 vehicles per day (annual average), with a maximum speed of 50 km/h in pseudo-straight sections and 35 km/h in curvilinear sections.

The definition of these characteristics made it possible to assign relative scores to the specific parameters considered and, from the combination of these according to the procedures described, to define the relative risk value in terms of RHRS and ROFRAQmod in each sector.

4 RESULTS AND DISCUSSION

Through the application of the two methods RHRS and ROFRAQmod, a variation profile of the relative risk level along the all the sections of the road under scrutiny was obtained for each method (Figures 2 and 3), which can be the background for the planning of possible mitigation measures.

Since it was neither possible to define an absolute risk value, for which probabilistic analyses would be required, nor to directly compare the values obtained with the two methods, since each refers to different parameters and methodologies, each profile was analyzed individually. To this end, the range of risk variation, defined by the minimum and maximum values, associated with each method was divided into three relative risk bands: minimum, medium and maximum. It is important to remark that the RHRS method considers the sum of the scores while ROFRAQ considers the product of them. For this reason, to compare the two approaches, the scores obtained by the RHRS method are presented in normalized axis, while those obtained through the ROFRAQmod method in logarithmic axis. A qualitative example of the applied procedure is shown in Figure 2 and 3. Remark that, due to its multiplicative nature ROFRAQ values will highlight extreme values.

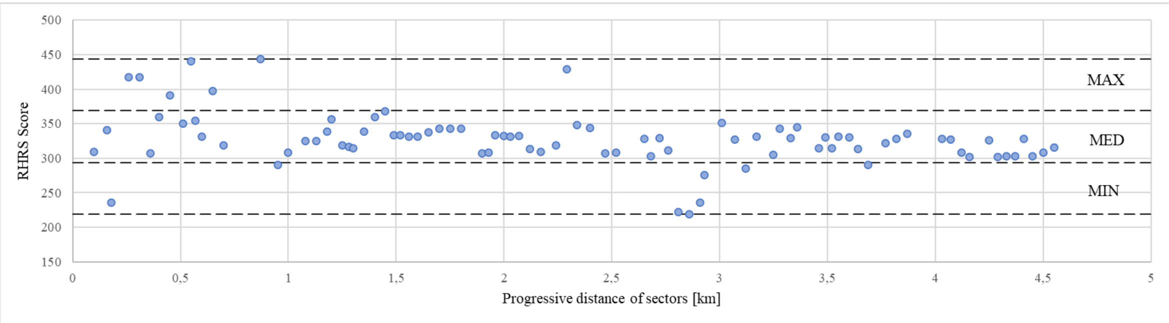

Figure 2. Graphic presentation of RHRS values all along the sections of the road analyzed.

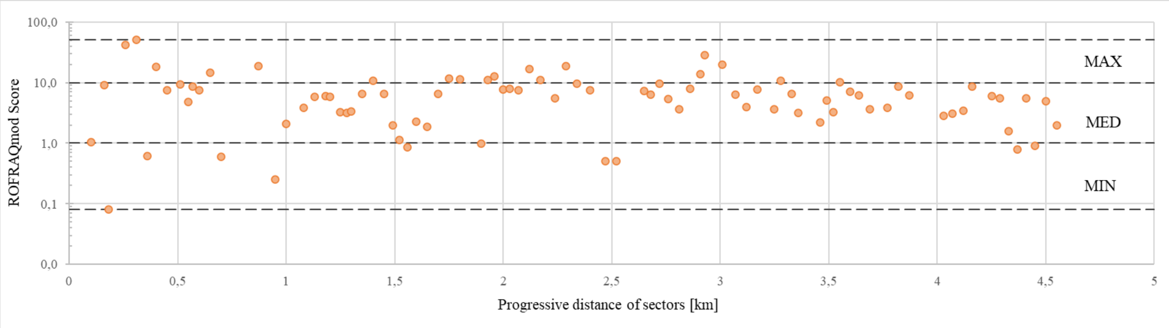

Figure 3. Graphic presentation of ROFRAQmod values all along the sections of the road analyzed.

Depending on the analysis method applied, each analyzed sector may detect the same degree of relative risk or fall into different categories, precisely because the different approaches consider and combine parameters that may be similar but not the same. Furthermore, it is not easy to identify the most suitable methodology to apply to a specific site, since the two methods were developed for different purposes and application fields.

However, the two methods matched each other well in identifying sectors with a higher, lower or medium relative risk. This is also clear in Figure 4 where the percentage distribution of roads falling into the three different classes is illustrated.

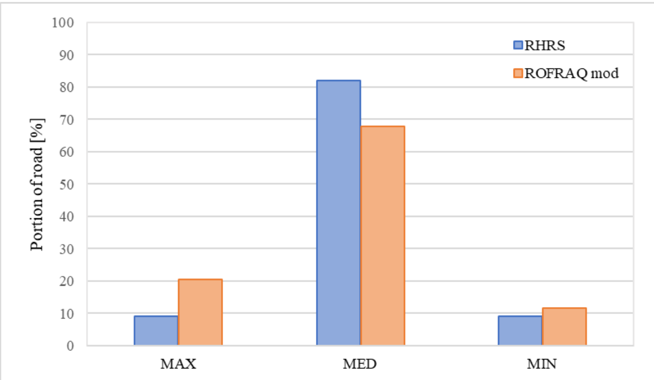

Figure 4. Percentage distribution of road sections falling into the three different risk levels.

Based on inferred probabilities derived from ROFRAQmod computed values it can be estimated a yearly probability of accident slightly over 5% for the whole road, a very high hazard value that justifies the decision of closing the road some years ago. A reasonable value to open the road will be to lower this probability to 1/1000 or 0.1 %.

According to the obtained classifications values and looking at data graphs it seems that there are 3 zones of the road where higher risk is identified (from 0.2 to 0.9 km, from 1.7 to 2.4 km and from 2.7 to 3.3 km), more relevantly based on ROFRAQmod data.

The approach to propose remedial measure will focus to identify for every section based on particular parameters of the presented classification approaches, the potentially more effective measures to control rockfall (rocksheds for very high slopes, anchored meshes in fractured rock and not so high slopes and so on).

In order to propose possible solutions, key ingredients will include the topics cited above: probability of accident, hazard assessment based on classifications and suitability of remedial measures. With these in mind, a draft report on possible measures for the 50 % more hazardous sections will be provided with budgetary estimates of its cost. In case, the cost of remedial measures to lower probability of accident to acceptable values was deemed to be reasonable, a more detailed executive project will be developed and proposed.

5 CONCLUSIONS

"Strada del Vallone d'Elva" is mountain road closed by road authorities due to severe rockfall events occurred in the area. Geostructural rock mass surveys and rock joint data collection provided the basis for the characterization of rock masses and the identification of stability conditions and potential failure modes all along the road.

Based on all the data collected and the field visits, two empirical approaches rockfall hazard approaches were applied to different road sections. Namely, the Rockfall Hazard Rating System (RHRS) and the so called Rockfall Risk Assessment for Quarries (ROFRAQ), which has been adapted in this case to the conditions encountered in mountain roads. Both approaches are deem to identify the more hazardous sections, even if the second one seems to highlight more clearly the more hazardous section, something the authors attribute to their multiplicative structure. Additionally, this second approach can estimate rough probabilities of accident, helpful for decision making.

The empirical classification rockfall hazard approaches are showing to be useful in order to guide the process of remedial measure design. They will be further used to make risk management decisions.

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