Comparison between qualitative and quantitative rockfall risk methods for a hazardous road stretch

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Abstract: - In order to compare rockfall risk values characterizing road sections affected by several rockfalls, two procedures have been used: the modified Colorado Rockfall Hazard Rating System (mCRHRS) and the ROckfall risk MAnagement (RO.MA.) method. The first one is a qualitative method mainly based on a heuristic assessment and the second is a quantitative approach taking into account the occurrence probability of severe negative events. Even though the qualitative approach is not consistent with the definition of risk used in the quantitative procedure, we proved that mCRHRS ratings are comparable with risk values, expressed as probability of death of at least one occupant of a vehicle (fatal accident) exposed to the rockfall hazard per year.

Key-Words: - rockfall hazard**,** rockfall risk, quantitative risk analysis, roads, Sorrentine peninsula, southern Italy

1 Introduction

Transportation corridors in a great deal of regions are often liable to undergo rockfalls, which cause a major risk for motorists as well as a large amount of damage and injuries. Over the last two decades, several qualitative and quantitative procedures have been proposed in order to evaluate the risk and reduce the potential consequences of rockfalls on the roads.

Generally, qualitative methods use exponential scoring patterns, and the total score reflecting the risk derives from the summation of scores of factors of different categories, such as: the slope height, ditch effectiveness, traffic, geological characteristics, failure magnitude and consequence [1], [2].

In quantitative approaches, the exposure to risk is given by the annual probability of rockfall failure, the vehicle being spatially and temporally in the path of the event when it occurs, and one or more occupants of the vehicle being killed as a result [3]. The quantitative risk assessment is an essential tool for planning risk mitigation measures [4]. It is important to note that qualitative approaches are not consistent with the definition of risk used in quantitative procedures (risk = hazard × consequences), and related results can be only qualitatively compared [5], [6].

The aim of this paper is to show results obtained applying, to the some road sections, two methods: the modified Colorado Rockfall Hazard Rating System (mCRHRS) [7] and the ROckfall risk MAnagement (RO.MA.) approach [8]. The studied road sections belong to an important road linking some famous tourist resorts in the southern slope of the Sorrento Peninsula (southern Italy) such as Positano, Amalfi and Salerno, the province capital town. This road is affected by high traffic intensity because it is the only transportation corridor in this area that, due to its complex geomorphological and geo-structural setting, is sometimes affected by severe rockfalls, which cause injuries, damages and road closures.

2 The studied road

The road portion studied belongs to a very tortuous road path (Fig. 1) going along the coast (the Amalfitana state road) that was built in the middle of the 19^{th} century by the Bourbon Department of Bridges and Roads. As a result of its age and impossibility of a modern realignment (in order to preserve the environmental heritage of this area protected by UNESCO), the road is characterized by only one single lane going in each direction without an adequate hard shoulder, and a high degree of road curvature. The width of the road is 7.0 m, but it is not wide enough in most places to allow vehicles to overtake one another (especially buses and

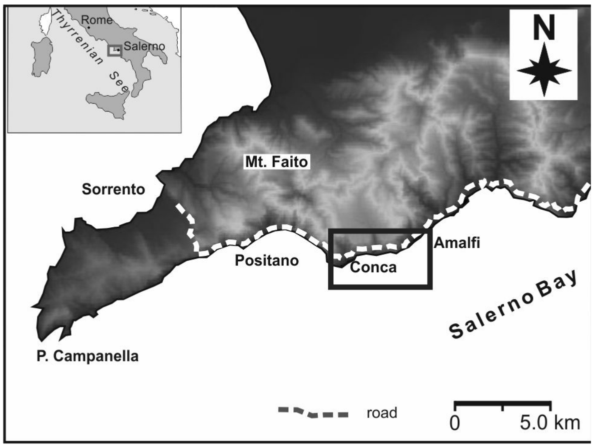

Fig. 1 – Location of the study area.

trucks). The imposed speed limit is everywhere 50 km/h.

The studied road stretch, of about 3.0 km in length and crossing the Conca dei Marini municipal territory, was chosen because it is the one most affected, in time, by rockfall events. The road has been subdivided into ten sections, with lengths varying between about 225 and 380 m, defined so as to have – as much as possible – slopes impending over the road characterized by homogeneous geological characteristics (Table 1).

Protection devices constituted by rockfall barriers, reinforced wire rope nets and mesh drapes, installed by ANAS (the national company which owns the road), are present along some slopes and cuts belonging to the studied road sections.

An analysis of traffic data recorded in the spring/summer and the autumn/winter periods of 2003, and for different sunlight conditions (day and night), allowed to ascertain that about 80% of the traffic is made up of cars and the remainder of motorcycles and tourist coaches. The vehicular flow due to commuting and business (very intense in the low season) during the spring/summer period is replaced by an equally intense tourism one. Since the traffic is mainly made up of cars, the average number of these vehicles (Nv) travelling on the road per day, amounting to 1,058 in all road sections and in the two directions (towards Positano and Amalfi), in following calculations was taken. At last, on the road crossing foot-traffic is negligible.

3 Geological setting and rockfall events

The road crosses a coastal area characterized by high reliefs lying on the northern side of the Gulf of Salerno. By means of sub-vertical cliffs and very steep slopes, in a few distance from the coast, the relief goes from the sea level until to heights greater than 600 m ASL (Fig. 2). Almost vertical slopes favour the free fall of boulders on the road, whereas in the remaining cases irregular rock faces, due to the presence of ridges or benches with lower slopes, cause launching and rebounding phenomena.

On slopes flanking the road, the cross-bedded Jurassic limestones and dolomitic limestones outcrop, sometimes dipping less than the slope or with horizontal strata. The tectonic disturbance promotes wedge and/or plane failures along the joint set intersections and stratification. Three joint sets or more, corresponding to fractures striking parallel to slopes or with mutually intersecting NW–SE and NE–SW trends, affect the outcropping rockmass. Also caves and very open joints, due to chemical dissolution of limestones in several sites are present, and karst dissolution is an active geomorphological process weakening, over time, the intact rock portions, separating the adjacent rock walls with open discontinuities.

High cuts and natural slopes give rise to rockfalls mainly due to the unfavorable layout of joints, geomorphology, climate, and joint enlargement caused by the roots of the plants. Using data by ANAS a total of 15 rockfall events were recorded, covering a time span from 1996 to 2008. If we consider the lengths of the ten road sections, mean rockfall frequency values (λf) ranging between 0 and 1.672 events yr^{-1} km^{-1} can be calculated (Table 1). Rockfalls mainly occurred in autumn/winter depending on high-intensity and short-duration rainfalls usually occurring during the months of October and November. Secondary falls of already detached boulders that are no longer supported by vegetation often resulted from summer wildfires.

4 The employed rockfall risk methods

The modified version of the Colorado Rockfall Hazard Rating System (mCRHRS) is a qualitative method developed at the Colorado Department of Transportation (CDOT) [7]. Twenty-seven parameters are grouped into four separate categories (slope, climatic, geological, and traffic characteristics). A range varying between 3 and 81 points is considered and using an exponential scoring system with a base of 3, a rating for each parameter is assigned. Then, these scores are added and the final rating which defines the risk (R) is given by:

$$R = fm + \Sigma fh + fd + \Sigma fc \, , \qquad (1)$$

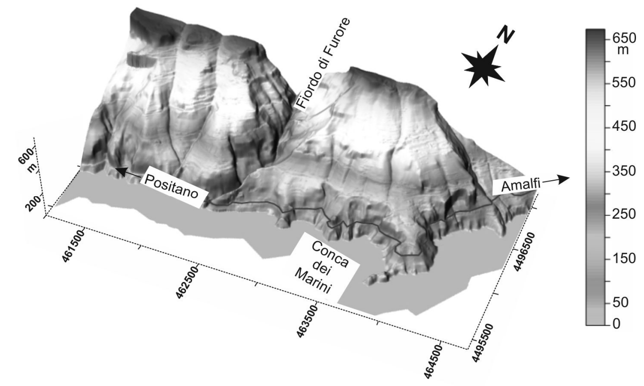

Fig. 2 – 3D map showing the topography of the studied area with the road path.

where *fm*, *fh*, *fd*, and *fc* are factors related to the estimated rockfall magnitude (*m*), the failure hazard (*h*), the ditch effectiveness (*d*), and the consequences of a possible failure (*c*), respectively.

The exponential scoring system applies to the hazard factors (slope height, geological characteristics, block size, volume of rockfall per event, climate and presence of water on slope and rockfall history) and to the consequence factors (ditch effectiveness, average vehicle risk, percentage of decision sight distance, roadway width). Some categories are described qualitatively and might lead to appraisals which might be subjective and approximate. Depending on the slope lithology, not all of the 27 parameters are used simultaneously. If sedimentary or crystalline rock masses outcrop on the slope 18 parameters must be used, whereas if the dominant lithology is the block-in-matrix material, then only 12 parameters are rated (in such a case discontinuities are obviously not present). As this study deals with sedimentary rocks, specific rating parameters pertinent to these outcropping rock masses were analyzed.

The RO.MA. method [8] was developed in order to calculate the individual fatality risk that can affects people that use the road, with and without protection measures. The first step is the definition of the number of boulders per year which can attain the road (*Nr*), defined on the basis of inventories or by means of the statistical analysis of trajectories. The identification of the elements at risk regarding cars, trucks, buses, pedestrians, etc. is also necessary. Then, using a probabilistic approach implemented in the event tree analysis, the risk of occurrence of fatal accident, non-fatal accident and no accident is evaluated. At last, the calculated risk of a fatal accident is compared with an abacus defining threshold values of unacceptable, ALARA (As Low As Reasonably Achievable) and acceptable rockfall risk [4]. This approach also allows computing the risk reduction resulting by the introduction of active and passive protection measures.

5 Results and comparison between methods

With reference to mCRHRS, the total rating (*R*) was calculated for each of the ten sections in both traffic directions (towards Positano and Amafi) and in spring/summer and autumn/winter periods (Table 1). In fact, in the same road section, due to variable Actual Sight Distance (ASD) values on the two traffic directions, total ratings may be different. The higher the rating, the greater is the risk. Since along the road there are no ditches to retain any fallen rocks, “ditch effectiveness” is the factor having the highest rating (81 points) and, consequently, the greatest percentage contribution to overall rockfall risk. Also annual precipitation and the Percentage of reduction in the Decision Sight Distance (PDSD) cause the score increasing, whereas the slope characters, as well as launching features are less important. A small contribution is supplied by the following categories: annual freeze–thaw cycles, seepage, degree of undercutting, degree of interbedding, block size, friction, and Average Vehicle Risk (AVR). The total final rating varies between about 500 (in the road section n. 7) and 843 points (in the road section n. 9). A higher number of rockfalls affected this section during the time span 1996 – 2008.

With reference to RO.MA. method, on the basis of rockfall inventory data and trajectory simulations performed by means of a dedicated software (Rocfall v. 4.0 by Rocscience inc.), the percentage of fallen blocks (*Pp*) stopping on the road was calculated. This percentage was evaluated on the total amount of 1,000 blocks (*Nb*) released during each simulation. Trajectory simulations were performed along 68 different topographic profiles, located in the ten road stretches, and for three possible rockfall hazard scenarios based on boulder volumes of 0.1, 1 and 10 m^3, respectively. Then, rockfall hazard that affects the road (i.e., the number of rocks hitting the road per year and per km) has been calculated by multiplying *Pp* by *Nb* and by the mean failure frequency (λf).

In order to consider the potential outcomes (consequences) arising from the detachment of a boulder with variable volumes, the probability that a passenger has a fatal accident depends on three possible combinations of interaction between rocks and vehicles: moving vehicle/falling rock, moving vehicle/fallen rock and stationary vehicle/falling

Tab.1 – Final ratings and probability values of a fatal accident calculated for the studied road sections (with the existing protection measures), by means of the mCRHRS and RO.MA. approaches, respectively. λ_f is the mean rockfall frequency and Nr is the number of boulders hitting the road per year.

Road section	Length of the road (m)	Rockfall events	λ_f	N_r	mCRHRS ratings				RO.MA. method
					spring/summer		autumn/winter		Fatal accident
					towards Positano	towards Amalfi	towards Positano	towards Amalfi	No. of fatalities yr^{-1} km^{-1}
1	375	1	0.205	1.02	677	677	671	677	$1.11x10^{-3}$
2	360	1	0.214	1.28	831	831	831	831	$1.43x10^{-3}$
3	225	1	0.341	2.04	795	795	795	795	$2.07x10^{-3}$
4	275	0	0	0	561	561	555	555	0.00
5	280	3	0.824	3.29	801	801	795	801	$3.60x10^{-3}$
6	310	2	0.496	1.48	783	783	777	777	$8.10x10^{-3}$
7	350	0	0	0	501	501	501	501	0.00
8	380	0	0	0	651	651	651	651	0.00
9	230	5	1.672	5.02	843	843	837	837	$5.11x10^{-3}$
10	260	2	0.591	1.18	783	783	777	783	$1.41x10^{-3}$

rock. Probability values concerning the above-mentioned interactions were inferred from literature data [8]. Furthermore, to complete probabilistic calculations, in the manner provided for the event tree analysis, it is also necessary to consider the eventuality that a rock severely damages the road paving and that from this occurrence derives an accident to a travelling vehicle, with the result that a fatal accident may occur. For these probabilities, reference was done to data inferred from Italian Institute for Statistics (ISTAT), concerning the main causes of road accidents on the whole Italian road network [9].

The event tree analysis develops along twelve different paths and the probability of occurrence of each of them can be calculated from the product of each single event that constitutes the path itself. The final consequence of each path can be classified as: (i) fatal accident, (ii) non-fatal accident, and (iii) no accident. Summing probability values pertaining to paths characterized by the same final consequence, it is possible to obtain the annual probability of a fatal accident, non-fatal accident and no accident.

Using an Excel spreadsheet, probability values associated to the 12 paths of the event tree, for the above-mentioned hazard scenarios, were calculated. The following input data were needed: the number of rocks hitting the road per year (Nr), the length of the hazardous road section (Lr), the limit speed of the vehicles (Vv), the average vehicle length (Lv), the number of vehicles travelling on the road per day (Nv), the decision sight distance (DSD), as well probability values concerning interactions between rocks and vehicles. In output, the used spreadsheet allowed to obtain probability values concerning the 12 paths of the event tree, and the annual probability of a fatal accident, non-fatal accident and no accident.

According to [8], the risk reduction of a fatal accident due to protection devices installed along the road is given by:

$$Nr' = (1 - C) \times Nr , \qquad (2)$$

where Nr' is the reduction in the number of falling rocks that may involve the road and C is the catching capacity of the structure, that is, the percentage of rocks that can be stopped by the protection device. Different C values were chosen according to literature data [8] and by means of a heuristic approach.

Finally, the risk affecting each road section, expressed as the annual probability of a fatal accident for the different three hazard scenarios and considering existing protection devices, has been assessed. For each road section, the total risk is given by the sum of partial risks related to the three hazard scenarios (Table 1). This risk ranges between 0 (road sections n° 4, 7 and 8) and $1.11x10^{-3}$ fatalities yr^{-1} km^{-1} (road section 1), whereas for the whole road stretch the computed mean value is $2.30x10^{-3}$. High risk values also affect the road section 9, with increasing risk levels as more severe hazard scenarios are assumed.

In order to compare risk values calculated by means of RO.MA. method with those concerning all car accidents resulting in almost a death in Campania, during the time span 1996-2008, available data from Italian Institute for Statistics were analysed [9]. With reference to this time interval, a mean value of about 330 fatalities/year or $3.41x10^{-2}$ fatalities yr^{-1} km^{-1} has been calculated: the length of the whole Campania road network (motorways, national and provincial roads) being about 9,652 kilometres. It is worth to note that the range of rockfall risk affecting the ten road sections is lower than the risk of car accidents on Campania road network and, even thought is unacceptable, it results higher than the real risk of fatal accident caused by rockfalls, on the basis of the fatalities recorded since the construction of the Amalfitana road ($1.65x10^{-4}$ fatalities yr^{-1} km^{-1}).

Rockfall risk values affecting the studied road also are above the acceptability limit defined for "involuntary" risk, such as rockfalls, as proposed by Geotechnical Engineering Office of Hong Kong [8]. This means that in the study area, the individual risk is not acceptable, and some actions are requested in order to lower it. It must be considered that more effective countermeasures are required such as rockfall barriers and shelters.

Comparing results provided by means of the two procedures, it is possible to observe that high mCRHRS ratings affect the road sections at the same time characterized by probability values of about 10^{-3} fatalities yr^{-1} km^{-1}. It is worth to observe that since the final rating *R* is given by the sum of several parameters, if as a result of RO.MA. method the risk of fatal accident is nil, due to the lack of rockfalls (see the road sections 4, 7 and 8), then *R* only measures the degree of potential damage along the road.

6 Conclusion

The assessment of rockfall risk, by means of the above-mentioned qualitative and quantitative methods, is affected by uncertainties and limitations that must be considered when using results for risk mitigation and planning purposes. The quality of rockfall hazard scenarios depends on various factors, including the accurate identification of rockfall sources and the correctness of trajectory simulations. Furthermore, the detachment areas of rockfalls are not always easy to identify and map precisely, and the trajectory simulation software, used in RO.MA. method, may locally overestimate run-out distances reached from boulders.

In the international literature there are no investigations concerning the main differences and similarities among the above-mentioned methods. Consequently, in order to compare results an attempt was performed on a road flanked by rock slopes characterized by complex geostructural and geomechanical layouts.

As far as the results for the mCRHRS are concerned, the rating calculated for each of the 10 sections is based on not many geological factors, qualitatively described and, therefore, are not reliable enough. Furthermore, this method is sometimes subjective and needs a good expert knowledge (heuristic approach). Partial ratings must be correctly chosen according to the effective geological setting of slopes impending over the road.

With reference to RO.MA. method, since it allows to evaluate the risk both in presence and in absence of protection devices, it is an effective tool that is able to allow an easy comparison of the effectiveness of the various choices, in terms of risk reduction.

Finally, it should be kept in mind that mCRHRS is a "first-level" characterization system useful for subsequent detailed risk analyses which can be performed with the more efficacious RO.MA. method.

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