Loss of life risk due to impacts of boulders on vehicles traveling along a very busy road

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ABSTRACT: The paper is aimed to describe the used approach for calculating the risk along a road stretch belonging to a very busy coastal road in Southern Italy. During the time span 1969-2013, 22 rockfalls affecting this road were inventoried. On 18th February 2014 a new rockfall happened and several boulders reached the northern lane of the road. On the basis of collected data concerning the landslide hazard and road vulnerability, a procedure for the probability evaluation of a fatal accident - for a road user - is presented, discussed in details and compared. The analysis is meant to allow the design of appropriate protection devices along the cliffs overhanging the road.

1 INTRODUCTION

Rockfalls on transportation corridors can cause casualties mainly due to direct impact on vehicles or by impact of vehicles with deposed material, as well as a large amount of economic consequences due to traffic interruptions. The rockfall risk evaluation affecting roads is a highly complex operation requiring the assessment of the hazard (triggering mechanisms and the run out parameters) and the vulnerability of vehicles on the roads along the foothills. Vulnerability mainly depends on the vehicle speed and length, the available decision sight distance, the traffic volume, the length of the rockfall risk section of the route, the number of occupants in a vehicle, and the type of vehicle. In quantitative terms, the annual probability of loss of life to an individual is given by multiplying the annual probability of occurrence of a rockfall event (of a given magnitude) by the probability of a falling rock hitting the moving vehicle, and by the vulnerability of the person given a block of size m impacting the vehicle. In order to apply this approach, the number of boulders that may hit the road must be obtained through trajectory simulations by calculating the percentage of all trajectories that could fall on the road or that are not interfering with it.

In the literature several methods concerning the Quantitative Risk Analysis (QRA) affecting roads have been proposed (Bunce et al. 1997; Hungr et al. 1999; Budetta 2002; Peila & Guardini 2008; Ferlisi et al. 2012; Mignelli et al. 2012; Budetta et al., in press). Here, we show results obtained by means of application of the ROckfall risk MAnagement (RO.MA.) method by Peila & Guardini (2008), concerning a very busy road affected by recurrent rockfalls.

Figure 1 presents a schematic operational flowchart of the RO.MA. approach.

This method develops through five steps, including (Figure 1): identification of unstable areas and the number of rocks per year that may hit the road (N_r); road vulnerability assessment; event tree analysis; risk assessment; evaluation of the efficiency of rockfall protective measures and calculation of the residual risk (Peila & Guardini 2008; Mignelli et al. 2012). The number of boulders that may hit the road or that may stop upstream (N_s), is obtained from field data or, alternatively, through trajectory simulations (Jaboyedoff et al. 2005). For the vulnerability evaluation it is need to have data concerning the length of the hazardous road stretch (L_r), the average (or limit) speed of the vehicles (V_v), the average vehicle length (L_v), and the number of vehicles travelling on the road per hour (N_v). The complete sequence of events which may result from a rockfall up to the killing of a road user (fatal accident) is evaluated by means of the event tree analysis. This analysis develops along twelve different paths (Figure 1A) 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 value of each path is given by the sum of probabilities concerning paths with the same final result (i.e. fatal accident, non-fatal accident, and no accident).

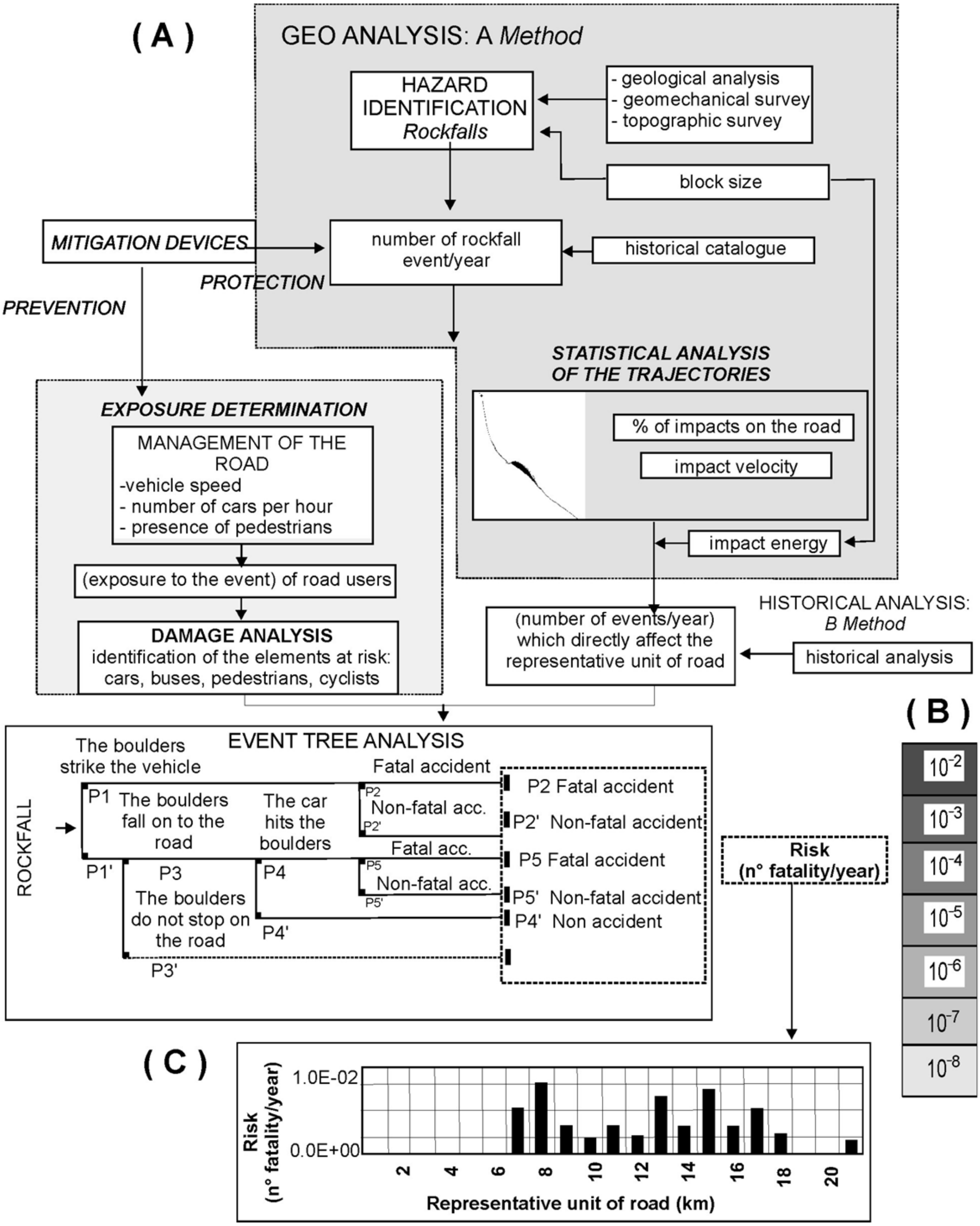

Figure 1. Procedural flow chart for ROckfall risk MAnagement assessment (A); Abacus defining the threshold values of rockfall risk. Acceptable values are lower than 10^{-5}, the ALARP band is 10^{-5}, unacceptable risk values are upper than 10^{-5} (B); histogram representing risk values versus the representative road sections (C). After Peila & Guardini (2008) and Mignelli et al. (2012) modified.

We partially modify the approach given by Peila & Guardini (2008), to calculate the spatio-temporal probability (P_{ST}) for a vehicle to be in the path of the falling boulder, when the mass falls, using both the dimension of the falling block (*We*) and the length of the vehicle (*Lv*) (Nicolet et al. 2015) as follows:

$$P_{ST} = \frac{N_V x (W_e + L_v)}{V_v} \qquad (1)$$

where P_{ST} = spatio-temporal probability; N_v = number of vehicles travelling on the road per hour; *We* = dimension of the falling block; *Lv* = length of the vehicle; V_v = average speed of the vehicles.

The probability of a fatal accident due to a direct impact of a boulder on a moving vehicle was calculated according to Bunce et al. (1997) whereas considering the impact of a block on the road surface, the probability that a travelling vehicle has an accident due to the damaged road surface was evaluated as a function of the deposed volume because generally volumes more than 0.1 m^3 may cause deep potholes (Budetta et al., in press).

Another reason for which we preferred the suggested approach by Peila & Guardini (2008) is given by the possibility to evaluate the ability of installed protection measures along the cliffs (e.g. rockfall barriers, reinforced wire rope nets, mesh drapes, etc.) to stop the falling rocks, reducing the number of those that may hit the road. The number of retained blocks (N'_r) can be calculated on the basis of the catching capacities of these devices, by means of the percentage of rocks (C) that can be stopped by the protection device. N'_r is given by:

$$N'_r = (1 - C)\, N_r \qquad (2)$$

In this way, we can compare calculated risk values (without protection measures) with those obtained taking into account the efficiency of these protections, or with risk criteria defined in the international literature. In this respect, Mignelli et al. (2012) suggested the use of an abacus defining the threshold values of acceptable and unacceptable rockfall risks (Figure 1B).

The above-mentioned approach, which has been partially modified with respect to the original one by Peila & Guardini (2008), was applied to a 350 m-long road stretch belonging to a coastal road that links the Vietri sul Mare resort with Salerno.

2 GEOMORPHOLOGICAL AND GEOLOGICAL SETTING

The studied road crosses a coastal area characterized by high reliefs lying near the harbor of Salerno (Fig. 2). Given the near vertical cliffs and very steep slopes, in a short distance from the coast, the relief goes from the sea level to heights greater than 700 m ASL. On slopes flanking the road, heavily fractured dolomites rocks outcrop. Some low-angle normal faults and several pervasive mutually intersecting joints affect the rock mass. These joints identify wedges whose lines of intersection are almost normal to the cliff face. Other randomly oriented deep tension cracks are caused by tensile stresses along cliffs. The intersections of these joints with the cross-bedded dolomitic layers result in isolated, potentially unstable boulders. Almost vertical slopes contribute to 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.

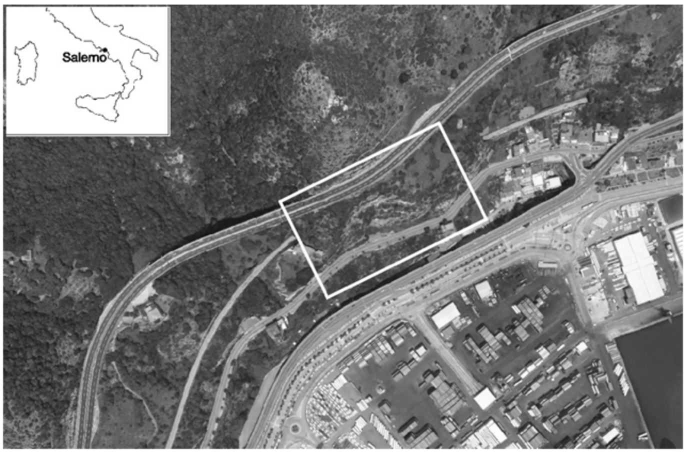

Figure 2. The harbor of Salerno and the surrounding hills. The white rectangle shows the study area.

Along the entire road stretch linking Vietri sul Mare with Salerno, between 1969 and 2013, 22 rockfalls were inventoried based on the information in the Italian Landslide Inventories (AVI and IFFI Catalogues), historical documents, and newspapers. Some rockfalls of about several cubic metres caused prolonged traffic interruptions. About 13 rockfalls occurred during the period 1993-1997, whereas only five landslide events are reported in the subsequent period up to 2013. Likely, this is due to passive devices (wire nets) which, during that time, were installed along cliffs above the road. Despite the considerable number of recorded rockfalls, there is incomplete information regarding the magnitudes as well trajectories and stopping points. On 18th February 2014, a new rockfall of about 40 m^3 affected the road at the kilometer 51+300 (Figure 3).

Figure 3. The rockfall occurred on 18th February 2014.

Several boulders falling from the overhanging cliff reached the northern lane of the road (in the direction towards Vietri sul Mare) threatening an adjacent petrol station and causing a new prolonged traffic interruption. The average volume of the deposed boulders on the road was evaluated about 65 dm^3. It is worth to observe that the collapsed cliff was already protected by wire nets which, evidently, were unfit to arrest the blocks.

3 TRAJECTORY SIMULATIONS

On the basis of deposed block volumes as well run-out distances and cliff geometries, several trajectory simulations were performed using a 3D approach in order to obtain more suitable energy restitution (normal, R_N and tangential, R_T) and rolling (friction angle, ϕ) coefficients as well kinetic energies, velocities, and bounce-height along trajectories travelled by boulders. In such a way, a detailed back-analysis of the rockfall of 2014 was performed. Trajectory simulations were performed using a three-dimensional code (AZTECROCK 10.0, by Aztec Informatica Inc. 2012) designed to analyze topographic spatial models by means of deterministic and/or probabilistic (by a Monte Carlo sampling technique that uses a normal distribution) approaches. In this code the topographic surface is generated using the Delaunay triangulation method. As the program uses a lumped-mass method, possible boulder fragmentation during the fall is not considered.

Afterward, using kinematic parameters obtained from the back-analysis, a hazard scenario concerning probable trajectories arising from other potentially unstable rockfall sources, has been prepared for falling blocks with volumes equal to 65 dm^3 (Figure 4).

The rockfall sources have been carefully chosen on the basis of the morphology of the area and the starting point for boulders were conventionally located at the highest point of each source (in most cases corresponding with the cliff top). Each simulation consisted of releasing 10,000 blocks from any potential rockfall source. In order to facilitate the reading of the map, in Figure 4 only boulder trajectories that could stop on the road or that are going beyond it have been shown. In such a way, along the total length of the road potentially prone to rockfalls (about 350 m) it is possible to measure the lengths of sections exposed to boulder impacts and more precisely calculate the probability that a moving vehicle is located in the section covered by the event when it happen (Figure 4). Excluding the effective length of the road section affected by blocks coming from the rockfall of 2014 (about 5.0 m), other calculated potential lengths range between 9.0 and 3.6 metres. It is worth noting that, at this stage, the effect of installed protection devices (wire nets) flanking the road that are able to stop and/or alter boulder trajectories, is not taken into account.

4 FATAL ACCIDENT RISK CALCULATION

In order to calculate the risk, expressed as the annual probability of a fatal accident for a road user, vulnerability concerning this stretch of the road firstly was evaluated. On the basis of traffic data furnished by the Municipality of Salerno, a mean hourly traffic density (number of vehicles travelling on the road per hour – N_v) of 4500 was established. The mean velocity (V_v) and length (L_v) of vehicles were 50 km h^{-1} and 4.5 m, respectively. The mean block diameter (W_e) inferred from field surveys was 0.5 m. Regarding other hazard data needed for risk calculation, on the basis of trajectory simulations the number of rocks hitting the road per year (N_r) was assumed equal to 1.15. According to eq. 1, the probability that a vehicle travelling on the road is hit by a falling rock (P_{ST}) is 1.87×10^{-2}. For simplicity, we assume that throughout the year the traffic is constant.

Associated with the 12 paths of the event tree (Figure 1A), the fatal accident probability value was calculated for the above-mentioned hazard scenario, using the approach by Peila & Guardini (2008). Unlike the original method, we used the calculated P_{ST} value because neglecting the dimension of the block or the dimension of the vehicle might lead to inexact results (Nicolet et al. 2015).

According to Bunce et al. (1997), probability values of a fatal accident due to moving vehicle/falling rock and moving vehicle/fallen rock interactions (Figure 1A) of 0.2 and 0.1 were assumed, respectively. Furthermore, the probability of a fatal accident due to an impact of a falling rock on a stationary vehicle was assumed equal to 0.125 (Bunce et al. 1997). Finally, the probability of serious damages on the road surface and consequent fatal accident, due to the damaged road surface, was 0.7. This value assesses the likelihood that a pothole produced by a falling and rebounding block on the asphalt is more than the wheel diameter. In other words, 70% of rebounding blocks, with volumes of 65 dm^3, result in dangerous potholes that may cause serious damage to vehicles (Budetta et al., in press).

In order to perform repeated and complex calculations, an Excel spreadsheet was prepared that uses the above-mentioned input data. In such a way, it was possible to obtain probability values concerning the 12 paths of the event tree. Finally, by the sum of values of identical outcomes, probability values of a fatal accident, non-fatal accident, and no accident were calculated.

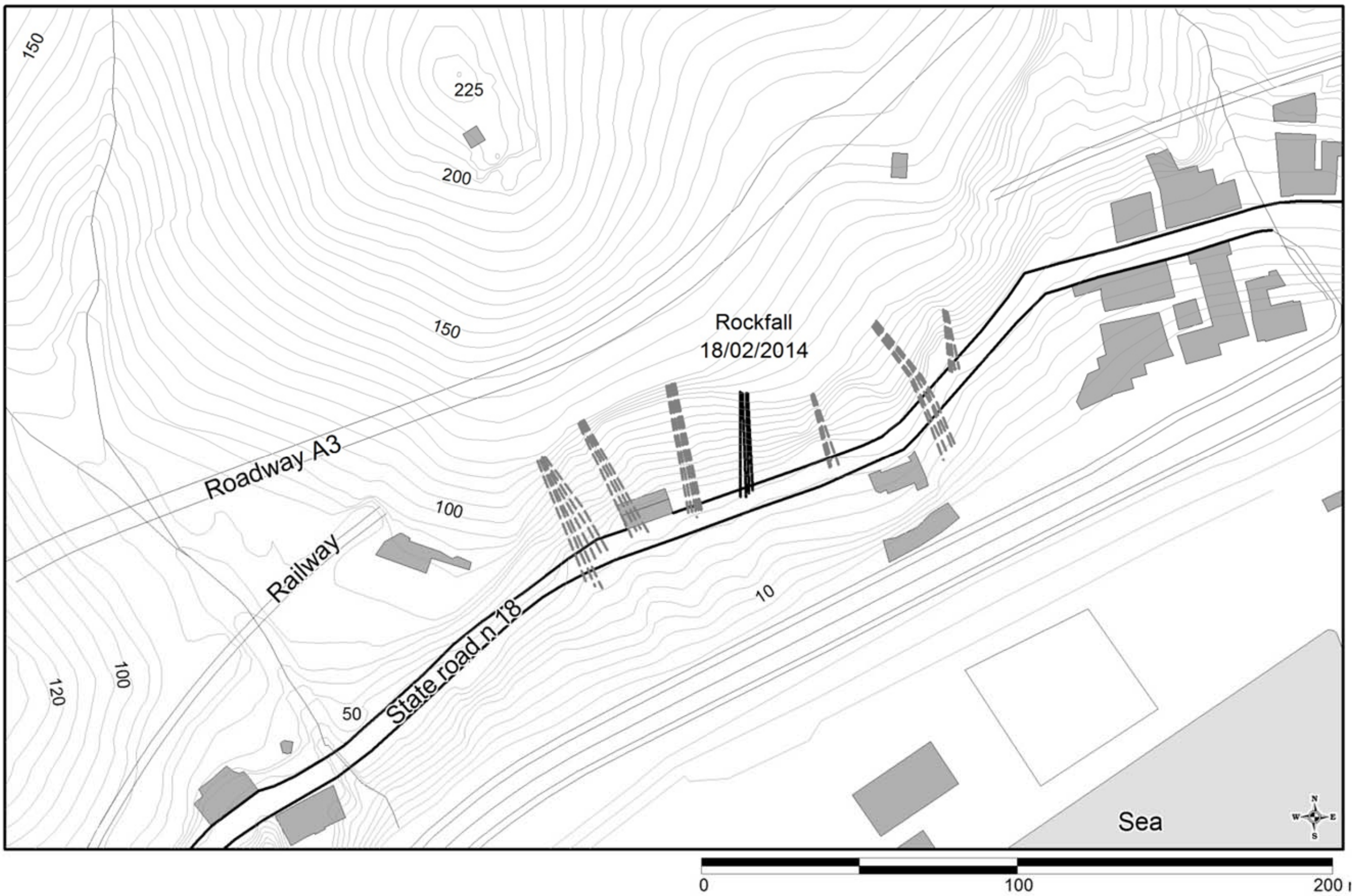

Figure 4. The trajectories that could stop on the road or that are going beyond it. With the black lines, we show the real trajectories traveled by the boulders of the rockfall of 2014. With the dotted gray lines, we show trajectory simulations obtained using kinematic parameters inferred by means of the back-analysis of the rockfall. Only trajectories that may interfere with the road are shown.

As the rockfall of 2014 already proved that the existing wire nets were unable to retain block volumes of 65 dm^3, it was not considered necessary to recalculate N'_r on the basis of the percentage of rocks (C) that can be stopped by this protection device.

Finally, for the entire road stretch potentially prone to rockfalls, the annual risk of fatal accident for a road user is $4.52\text{x}10^{-3}$. According to the abacus defining values of acceptable and unacceptable rockfall risks (Figure 1C) suggested by Mignelli et al. (2012), the individual risk is not acceptable, and some actions are required in order to lower it.

5 CONCLUSIONS

It is useful to compare the fatal accident risk value calculated by means of the modified RO.MA. method with those concerning all car accidents resulting in loss of life in Campania (the region where the studied area is located). During the time span 1996–2008, available data from the Italian Institute for Statistics (ISTAT 2014) shows a mean value of about 330 fatalities/year or $3.41\text{x}10^{-2}$ fatalities year^{-1} km^{-1}: the length of the entire Campania road network (motorways, national and provincial roads) being about 9652 kilometres. Another comparison can be done with the fatal risk caused by rockfalls on the Amalfitana road since its construction, in the second half of the 19th century ($1.65\ \text{x}10^{-4}$) (Budetta et al., in press). This state road crosses an area characterized by a geomorphological and geological layout similar to the studied one. The rockfall risk value calculated for the study area is also above the acceptability limit defined for ''involuntary'' risk such as rockfalls, as proposed by Geotechnical Engineering Office Hong Kong (1998). This means that the individual risk is not acceptable, and more effective countermeasures are required such as rockfall barriers or reinforced wire rope nets.

The rockfall hazard evaluation and the assessment of the risk performed by means of the abovementioned approach are affected by uncertainties and limitations that we must bear in mind in order to use the results for risk mitigation and planning purposes. The quality of the rockfall hazard scenario depends on the preciseness of trajectory simulations and the accurate identification of rockfall sources.

With reference to the risk analysis, major difficulties concern the assessment of more exact probability values, which must be assigned to interactions between rocks and vehicles. Sometimes the definition of these values was heuristic, and to some extent arbitrary.

Even though this quantitative risk analysis must be improved, the applied methodology demonstrates that it is possible to perform a good assessment of the expected individual loss of life, since it is based on the essential elements concerning the rockfall hazard evaluation and road vulnerability.

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