Event tree analysis and comparison for mountain roads under rockfall hazard

EVENT TREE ANALYSIS AND COMPARISON FOR MOUNTAIN ROADS UNDER ROCKFALL HAZARD

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Rockfall is one of the most hazardous and dangerous landslide phenomena, which can significantly affect mountainous roads. To the knowledge of the Authors, limited studies focus on the quantitative risk assessment to pedestrians and vehicles along mountain little traffic roads. A method tailored to these elements at risk is herein presented and applied to a real case. The calculation method is based on the Event-Tree Analysis, through which all the scenarios which can lead to a fatality or injuries are investigated. An application on a study case in the Italian Alps illustrates the potentialities of the methodology.

Keywords: event tree, quantitative risk assessment, rockfall, pedestrians, mountainous road, vehicles

INTRODUCTION

Among the natural hazards, transport infrastructures in mountainous areas are particularly susceptible to rockfall, which can cause injuries or even death to roadway users, both drivers and pedestrians [1]. In the perspective of hazard management and risk mitigation plans, a quantification of the risk in terms of number of fatalities per year is often required by the Authorities. Among the quantitative risk assessment (QRA) methods, the Event-Tree Analysis (ETA) is one of the most profitable [2]. Due to its adaptability to different situations, ETA was tailored for different elements at risk, e.g. strategic high traffic roads [3]–[5], railway [2], or pedestrian mountainous paths [6].

Nevertheless, despite its relevance, a QRA on mountainous farm roads (FR), viable both for pedestrians (P) and persons in a vehicle (V) due to rockfalls has not yet been performed. Even in the same location, P and V have different non-unitary exposure and vulnerability. Furthermore, a deep comparison between the risk on mountainous pedestrian roads (PR) and on farm roads have not been realized. The required input of rockfall occurrence probability can be derived from recorded past events and adapted to both road typologies. In this perspective, two event tree analyses specifically designed for P and V in case of PR and FR are herein introduced and compared and an example of application is proposed.

METHOD

The ETA is a logical procedure in which both success and failure response are evaluated, starting from a single initiating event and defining all the possible alternative pathway options which can occur. The nodes serve as transition from one position to another one along the event tree, defining binary mutually exhaustive scenarios. The end points identify a unique outcome, whose probability is given by the conditional probability along their own pathway. The probability of more outcomes is given by the sum of the probabilities of each outcome.

The present work considers a rockfall as the initiating event, evaluating all the possible scenarios leading to a fatal accident as outcome. Two elements at risk have been considered: P and V,

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and two different type of montainous roads: a FR, viable for both the elements at risk, and a PR. Fig. 1 shows the proposed event trees for both the elements at risk. The annual frequency of occurrence of the initiating event is the average number of events per year N_D, which can be assumed equal to the annual occurrence probability P_R in case of small number of events. The probability that the rockfall reaches a specific element at risk is $P_{(\mathrm{T:R})}$ and the product $N_D P_{(\mathrm{T:R})}$ approximates the annual frequency of rockfall on the road N_R. Generally speaking, the determination of these probabilities requires the accurate knowledge of the condition of the rock mass, a propagation analysis as realistic and precise as possible, as well as the traffic condition. Due to the complexity and the uncertainties related to these data, the definition of the occurrence probability is often based on statistics of past events. In general, the available and recorded data refer to events which had reached a road (as a relevant susceptible element), notwithstanding the number of different possible rockfall prone zones insisting on it, the precise arrival location, and often neglecting blocks overpassing the road. Considering this aspect, N_R can be considered as $N_R = \sum_k P_{(\mathrm{T:R})_k} \ell_k \ N_D$, in the hypothesis of subdividing the road in sections of length ℓ, homogeneous both for block reaching probability $\mathrm{P}_{(\mathrm{T:R})}$ and for traffic condition.

In evaluating the blocks reaching the road (FR or PR), two scenarios can develop: the blocks can hit the element at risk (P or V) or not. The vulnerability, fundamental in evaluating the outcomes, function of the type of motion and of the characteristics of the elements at risk, differs in case of P and V. The method assumes that any block of any size or velocity hitting a P causes a fatality while, in case of V, it can cause fatality or injury. It means that the vulnerability of P is assumed unitary, while, in case of V, it is function of the speed of the vehicle as well as the ratio between the decision and the stopping sight distances, as proposed in [4]. The temporal-spatial probability of the element at risk, i.e. the spatial-temporal correspondence between the blocks and the element at risk ($P^j_{(S:T)}$), is function of the *j*th traffic condition on the road in this specific time and it can be computed as the temporal-spatial probability for *a single element* multiplied for the total number of element in this traffic condition during the year. For all the above considerations, it is suggested to perform this ETA for road sections, homogeneous for both reaching probability and traffic condition. Blocks do not hitting the road can rebound on the path, even damaging its surface or stopping on the path. For P, this does not lead to an accident (see [6]), while for V, both the rebound or the stop of a block can cause fatality or injury. The probability of rebound or stop can be computed through trajectory analyses, while the probability of accident is computed on the bases of statistics.

For the property of the ETA for each homogeneous section, the annual probability of fatalities can be obtained multiplying, separately for each single pathway leading to fatalities, all the probability of its branches and then summing the resulting values. The annual probability of fatalities for the considered road is given summing the obtained value for each sections. In case of a FR the total risk is given summing up the one of P and the one of V, meaning that the interaction between a pedestrian and a vehicle has not been considered in the present work. This is justified by the generally small velocity allowed in this type of road.

RESULT AND DISCUSSION

The proposed method has been applied considering both a PR and a FR in the North-Western Italian Alps. Fig. 2 depicts a situation in which a rockfall prone area composed of multiple source zones insists on both a PR and a FR, ending both to a mountain hut. The PR (832 m of length), is located at a mean altitude of 1870 m s.l.m., while the FR (1243 m of length), is below the pedestrian road with an altitude ranging from 1800 to 1860 m s.l.m. The trajectory analyses (see Fig. 2) highlights that PR and FR are affected in different way. Different homogeneous sections have been identified on the base of the reach probability (A-O for the PR and A-T for

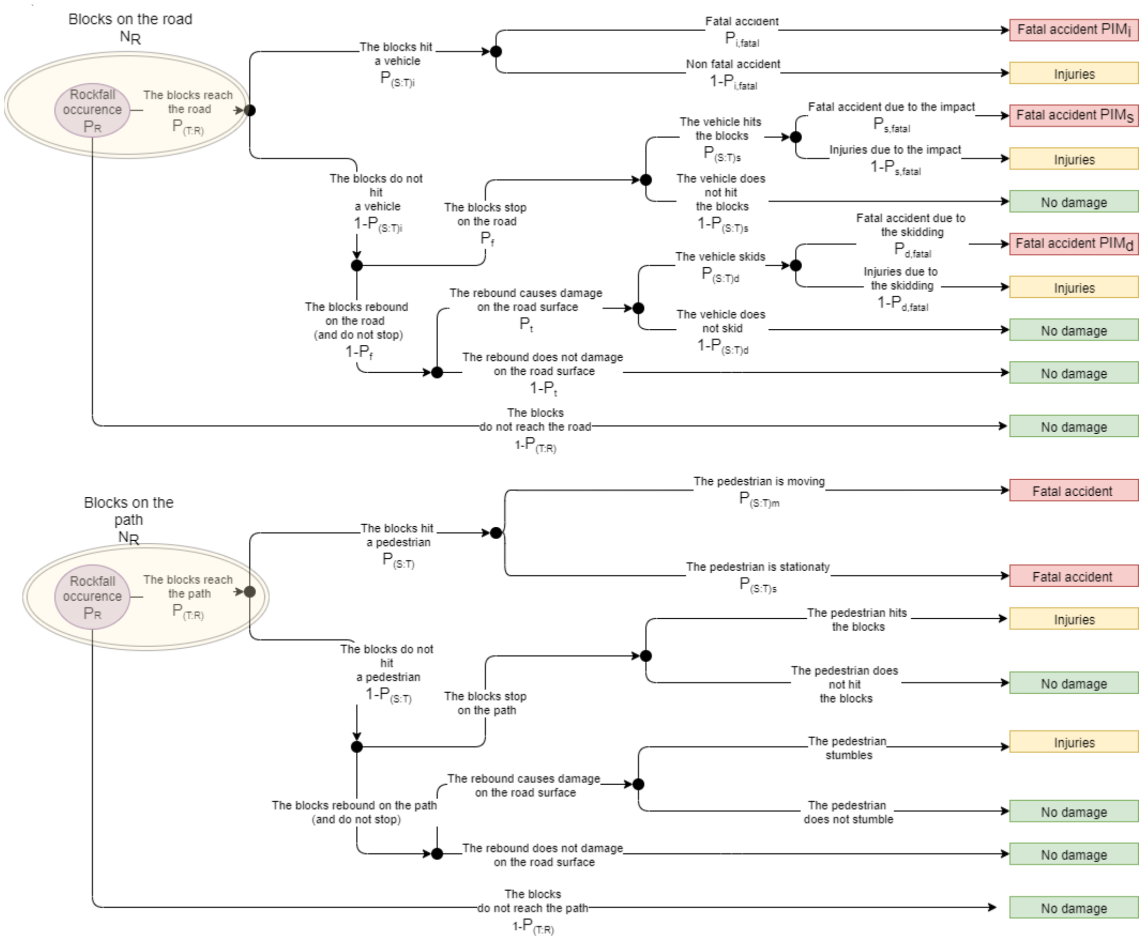

Fig. 1 Proposed ETA method for persons in a vehicle on a farm road (above) and pedestrians on a farm road or on a pedestrian path (below).

the FR in Fig. 2). The land register reports 3 rockfall events in the last 15 years on the FR, without any precise location and a conservative estimation of $N_{D,FR}$ is 0.2. For the PR, in absence of further information, the number of event $N_{D,PR}$ is assumed proportional to $N_{D,FR}$, according to: $N_{D,PR} = N_{D,FR} \frac{P_{(\mathrm{T:R})_{PR,mean}}}{P_{(\mathrm{T:R})_{FR,mean}}}$, where $P_{(\mathrm{T:R})_{PR,mean}}$ and $P_{(\mathrm{T:R})_{FR,mean}}$ are the average values of the block reaching probabilities. Considering the exposure to snow and freezeing, these roads are unviable during the winter period, i.e. from December to April. Even though the pedestrian transit is not forbidden (while it is for vehicles), a traffic of 1 hiker/h is estimated during the daily hours, only. It is assumed the same pedestrian traffic condition for both the PR and the FR. Considering the vehicle traffic, a total of 2196 hours/year of use have been computed, and, on the basis of statistics of frequentation of the mountain hut, the mean annual number of transits has been evaluated equal to 0.35 vehicle/hour from 16 April to 15 October. Following the procedure exposed in the methodology section, summing up for each traffic condition and homogeneous sections, the annual probabilities of fatality for the FR are $2.80 \cdot 10^{-4}$ in case of P and $1.33 \cdot 10^{-4}$ in case of V ($4.14 \cdot 10^{-4}$ in total), while for the PR it is equal to $3.57 \cdot 10^{-4}$.

CONCLUSIONS

The QRA due to rockfall events on mountainous roads, both PR and FR, is a crucial issue for Authorities, due to the increasingly touristic traffic, especially during summer. A novel method, based on ETA, tailored for pedestrians or persons in a vehicle has been introduced and applied to a real case. Starting from the recognition of rockfall prone source area, the annual frequency of rockfall is computed on the basis of recorded past events on FR and then adapted for PR. The performed reaching probability analyses, as well as the study of the traffic conditions, allow identifying different homogeneous path sections on which performing the risk analyses. The consideration of different exposure and vulnerability for P and V has been implemented in the method. The application on a real study case highlights the difference between different elements at risk and different types of mountainous road. Further development can relate with the possibility of considering the mutual interference of pedestrian and vehicle on a farm road.

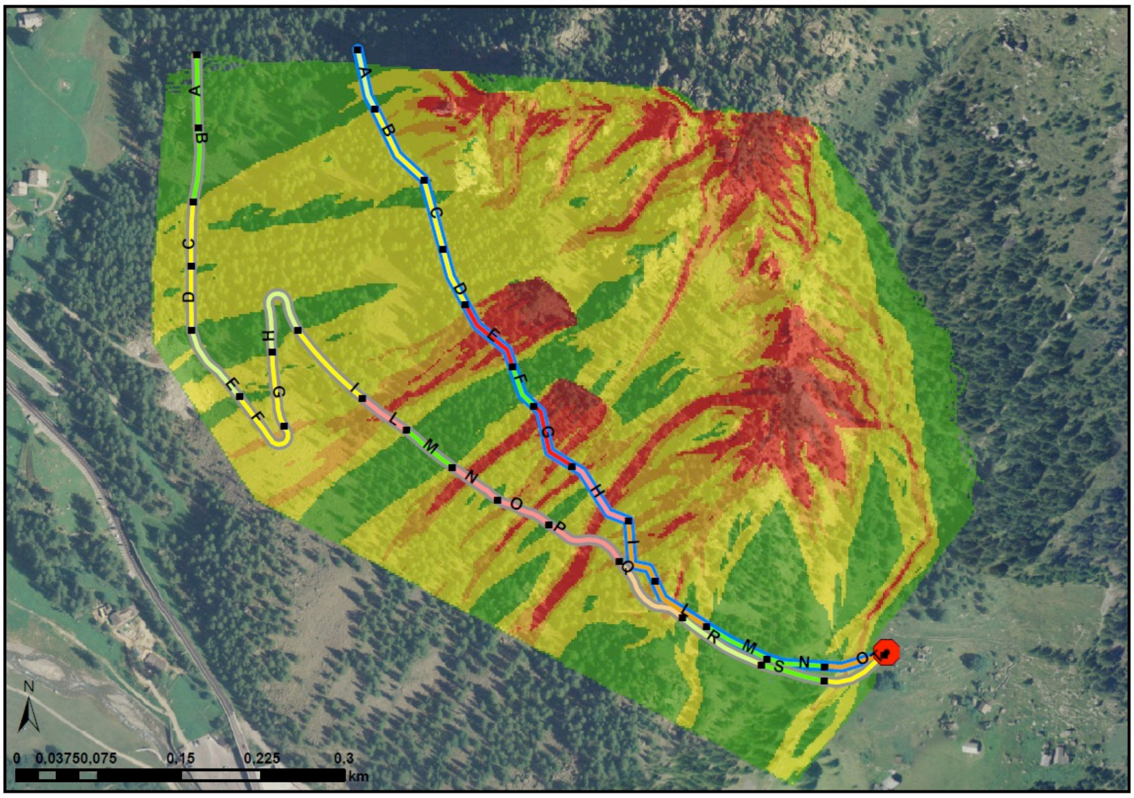

Fig. 2 FR(below) and PR (above) in the North-western Alps: aerial view of the affected area (Geoportale VDA), with the results of the propagation analyses and subdivision in homogeneous sections along the roads.

REFERENCES

[1] F. Ferrari, A. Giacomini, and K. Thoeni, “Qualitative Rockfall Hazard Assessment: A Comprehensive Review of Current Practices,” *Rock Mech. Rock Eng.*, vol. 50, no. 5, pp. 1365–1365, 2017.

[2] R. Macciotta, C. D. Martin, D. M. Cruden, M. Hendry, and T. Edwards, “Rock fall hazard control along a section of railway based on quantified risk,” *Georisk*, vol. 11, no. 3, pp. 272–284, 2017.

[3] S. Ferlisi, L. Cascini, J. Corominas, and F. Matano, “Rockfall risk assessment to persons travelling in vehicles along a road: The case study of the Amalfi coastal road (southern Italy),” *Nat. Hazards*, vol. 62, no. 2, pp. 691–721, 2012.

[4] C. Mignelli, S. Lo, and D. Peila, “ROckfall risk MAnagement assessment : the RO . MA . approach,” pp. 1109–1123, 2012.

[5] S. Mineo, G. Pappalardo, M. Mangiameli, S. Campolo, and G. Mussumeci, “Rockfall analysis for preliminary hazard assessment of the cliff of taormina Saracen Castle (Sicily),” *Sustain.*, vol. 10, no. 2, pp. 1–18, 2018.

[6] M. Marchelli, V. De Biagi, and D. Peila, “An event-tree based approach for the quantitative risk assessment for pedestrian in mountain environments subjected to rockfall hazard,” in *Proceeding in the Intrapraevent International Symposium (11th-14th May 2020)*, pp. 1–5, *under review*.