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Event tree analysis 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 mountain roads. To the knowledge of the Author, limited studies focus on the quantitative risk assessment to pedestrians (hikers) 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, hikers, mountain road, vehicles.*

Analisi di rischio con il metodo dell'albero degli eventi per strade montane soggette al pericolo di caduta massi. *Tra i fenomeni franosi la caduta massi risulta essere uno dei più pericolosi e dannosi. Questo fenomeno può interessare in modo significativo le strade di montagna. Per quanto a conoscenza dell'Autore, un esiguo numero di studi si sono concentrati sulla valutazione quantitativa del rischio per escursionisti e veicoli lungo le strade di montagna a bassa intensità di traffico. Un metodo appositamente costruito per questi elementi a rischio è proposto e applicato ad un caso reale. Il metodo di calcolo si basa sulla tecnica dell'albero degli eventi (ETA), attraverso la quale vengono analizzati tutti gli scenari che possono portare a un incidente mortale o a lesioni. Un'applicazione su un caso studio nelle Alpi italiane illustra le potenzialità della metodologia.*
Parole chiave: *albero degli eventi, valutazione quantitativa del rischio, caduta massi, escursionisti, strada di montagna, veicoli.*

1. 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 (Ferrari *et al.*, 2017) 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 (Scavia *et al.*, 2020). Among the quantitative approaches, the Event-Tree Analysis (ETA) is one of the most profitable (Peila & Guardini, 2008; Macciotta *et al.*, 2017).

Due to its adaptability to different situations, ETA has been tailored for different elements at risk, e.g. strategic high traffic roads (Ferlisi *et al.*, 2012; Mignelli *et al.*, 2012; Mineo *et al.*, 2018), railway (Macciotta *et al.*, 2016), or pedestrian mountain paths (Marchelli *et al.*, under review). In this last work, the Authors proposed an ETA-based approach for a quantitative evaluation of the risk suitable for both vehicular traffic and pedestrian path. The case of a low-traffic mountain farm road (FR), viable both for pedestrians (P) and persons in a vehicle (V), is here presented and discussed. Even in the same location, P and V differ for exposure, non-unitary in both cases, and vulnerability. The behaviours of pedestrians and drivers are influenced by their velocity and by the path: pedestrians can stop for a rest and are more capable to react and avoid obstacles, while drivers do not suffer for the slope gradient and, thus, are less exposed due to their velocity, but they are more subjected to different collateral hazardous situations induced by rockfall.

In addition, a comparison between the risk on mountain pedestrian roads (PR) and on farm roads is here proposed and discussed. The required input of rockfall occurrence probability (De Biagi *et al.*, 2016) 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 through an example of application.

2. Method

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

Referring to rockfall events, the present work considers the block reaching the road 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, and two different type of mountain roads: a FR, viable for both the elements at risk, and a PR. Figure 1 shows the proposed event trees for both the elements at risk.

It is worth considering that during the year a number N_R of blocks can reach the road, resulting in N_R occurrence of the initiating event. The precise defining of this number starts evaluating the annual frequency of a rockfall event, i.e. the detachment of a block, represented by the average number of events per year N_D. This last can be assumed equal to the annual rockfall occurrence probability P_R in case of a small number of events. The probability that a block reaches a specific element at risk is $P_{(T:R)}$ and the product $N_D P_{(T:R)}$ approximates the annual frequency of blocks on the road N_R. In addition, considering that the road can be reached by the detached blocks with different probabilities along its path, N_R can be considered as:

$$N_R = \sum_k P_{(T:R)k} \ell_k N_D, \qquad (1)$$

in the hypothesis of subdividing the road in sections of length ℓ, homogeneous both for $P_{(T:R)}$ and for traffic condition.

Generally speaking, the determination of these probabilities requires the accurate knowledge of the condition of the rock mass (Marchelli *et al.*, 2019), a propagation analysis as realistic and precise as possible, as well as the estimation of the traffic condition (Mavrouli *et al.*, 2015; Marchelli & De Biagi, 2019). 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

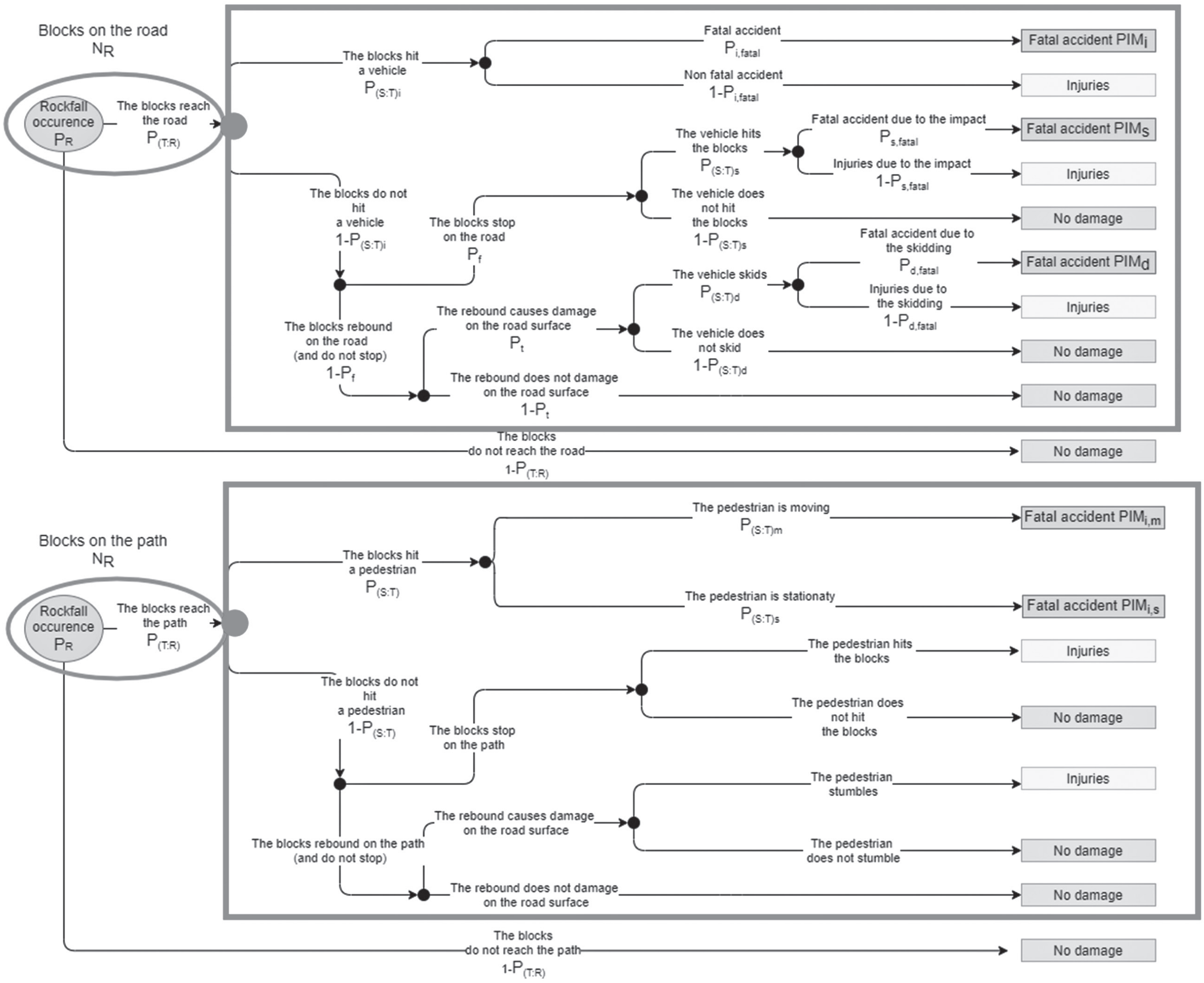

Fig. 1. Proposed ETA method for people in a vehicle on a farm road (above) and pedestrians on a farm road or on a pedestrian path (below). The large rectangles highlight the ETA structure considering the block reaching the FR or the PR as the initiating event.
Metodo ETA proposto per persone in un veicolo lungo strade poderali (sopra) e pedoni su una strada poderale o su un sentiero (sotto). I grandi rettangoli evidenziano la struttura dell'ETA considerando come evento iniziatore il blocco che raggiunge la FR (strada poderale) o la PR (sentiero).

reached a road (as a relevant susceptible element), i.e. N_R, notwithstanding the number of different possible rockfall prone zones insisting on it, the precise arrival location, and often neglecting blocks overpassing the road. In the hypotheses of performing a propagation analysis and of knowing the number of events along the whole road, for each *k-th* road portion ℓ_k the frequency of arrival N_R^k can thus be computed as:

$$N_R^k = \frac{P_{(T:R)k}\ell_k}{\sum_k P_{(T:R)k}\ell_k} N_R. \quad (2)$$

Starting from a block 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 or 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 (Mignelli *et al.*, 2012).The temporal-spatial probability of the element at risk, i.e. the spatial-temporal correspondence between the blocks and the element at risk ($P^j_{(S:T),i}$), 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. Considering a unique traffic condition, according to (Mignelli *et al.,* 2012; Marchelli *et al.*, under review), $P_{(S:T)}$ can be computed as:

$$P_{(S:T),i} = P_{(T:P)i,1} \cdot P_{(S:P)i,1} \cdot n_{\frac{v}{h}} \cdot n_h, \quad (3)$$

where $P_{(T:P)i,1}$ and $P_{(S:P)i,1}$ are the temporal and spatial probabilities that one element at risk is hit by the block, respectively, $n_{\frac{v}{h}}$ is the hourly traffic, and n_h the annual number of hours for which this traffic condition is valid.

Moreover, blocks not hitting the road can rebound (subscript *d* in Eq. (4) and in Figure 1 for V) on the path, even damaging the road surface, or can stop on the path (subscript *s* in Eq. (4) and in Figure 1 for V). For V, both the rebound or the stop of a block can cause fatality or injury, while for P, this does not lead to an accident. This last assumption is justified recognizing that, due to the low walking speed of a pedestrian, the stopping sight distance is adequate to the correspondent decision sight distance, i.e. the distance at which the hikers can recognize a hazard and perform the required action to take cover or dodge the block. The probability of stop (P_f) or rebound ($1 - P_f$) can be computed through trajectory analyses, while the probabilities of accident are computed on the bases of statistics. Refer to Bunce, 1997; Mignelli *et al.*, 2012, and Marchelli *et al.*, under review, for the formulations.

Considering the pedestrian path only, hiking trails are generally not flat and sometimes pedestrians take a rest for few minutes. For this, the proposed method differentiates between "moving" and "stopping" periods for each pedestrian along the path, considering also that a pedestrian does not hike on a mountain path only for reaching a specific destination but also for enjoying the view. As a consequence, considering Eq. (3), the spatial temporal probability of accident can be divided in stopping (subscript *s* in Eq. (5) and in Figure 1 for P) and moving (subscript *m* in Eq. (5) and in Figure 1 for P) terms. As hikers are not always aware of the hazard, a randomly choice for rest places can be considered.

For all the above considerations, it is suggested to perform this ETA for road sections, homogeneous for both reaching probability and traffic condition. Considering the properties of the ETA, for each certain event, and for each homogeneous *k-th* portion of road, adopting the nomenclature expressed in Figure 1, the probability to have a fatal outcome PIM^k is given by:

$$PIM^k = PIM_i^k + PIM_s^k + PIM_d^k \quad (4)$$

and

$$PIM^k = PIM_{i,m}^k + PIM_{i,s}^k \quad (5)$$

for FR and PR, respectively. Each term in the right parts of the equalities of Eqs. (4) and (5) can be obtained multiplying all the probability of its branches, separately for each single pathway leading to fatality. The annual probability of fatalities for the considered road is given summing the obtained value for each section. 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.

3. Result and discussion

The proposed method was applied considering both a PR and a FR in the North-Western Italian Alps. Figure 2 depicts a situation in which a rockfall prone area composed of multiple source zones insists on both a PR and a FR, both ending at 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 analysis (see Figure 2 and Table 1 and Table 2) highlighted that PR and FR are affected in different way. Different homogeneous portions were identified on the base of the reach probability (A-O for the PR and A-T for the FR in Figure 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 $N_{D,PR}$ was assumed proportional to $N_{D,FR}$, according to: $N_{D,PR} = N_{D,FR} \frac{P_{(T:R)PR,mean}}{P_{(T:R)FR,mean}}$, where $P_{(T:R)PR,mean}$ and $P_{(T:R)FR,mean}$ are the average values of the block reaching probabilities considering all the portions composing the two roads.

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 was estimated during the daily hours, only. The same pedestrian traffic conditions were assumed 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 was evaluated equal to 0.35 vehicles/hour from 16 April to 15 October.

According to the traffic limits of this road, the velocity of the vehicles was set at its maximum value of 10 km/h. Consequently, due to this low value, the probabilities that a vehicle hits a block stopped on the road and that it does not skid a damaged surface were assumed equal to 0.

Referring to the pedestrian, its

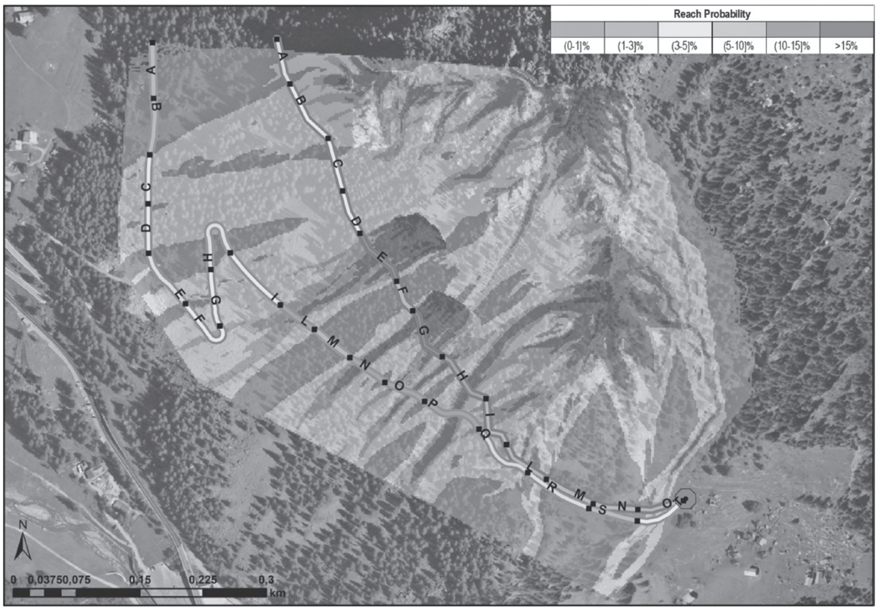

Fig. 2. FR (below) and PR (above) in the North-western Alps: aerial view of the affected area (Geoportale VDA), with the results of the propagation analysis and subdivision in homogeneous sections along the roads.
FR (sotto) e PR (sopra) nelle Alpi nord-occidentali: vista aerea dell'area interessata (Geoportale VDA), con i risultati dell'analisi di propagazione e suddivisione in sezioni omogenee lungo le strade

Tab. 1. Reach probability and annual probability of fatalities for each portion of road, for the FR for both pedestrians and vehicles.
Probabilità di accadimento spaziale e probabilità annua di fatalità per ciascuna porzione di strada, per la FR (strada poderale) per pedoni e veicoli.

FR Portion	Length (m)	Reach Probability	Annual probability of fatalities on the portion for P	Annual probability of fatalities on the portion for V
A	67	1%	2,365E-08	2,534E-06
B	68	1%	2,400E-08	2,54E-06
C	59	5%	1,041E-07	1,243E-05
D	59	5%	1,041E-07	1,243E-05
E	76	3%	8,049E-08	7,762E-06
F	87	5%	1,536E-07	1,326E-05
G	69	5%	1,218E-07	1,273E-05
H	98	3%	1,038E-07	8,156E-06
I	86	5%	1,518E-07	1,324E-05
L	50	15%	2,648E-07	3,648E-05
M	54	1%	1,906E-08	2,456E-06
N	51	15%	2,701E-07	3,657E-05
O	53	15%	2,806E-07	3,675E-05
P	77	15%	4,077E-07	3,89E-05
Q	82	8%	2,849E-05	2,099E-05
R	85	3%	2,130E-05	7,923E-06
S	59	1%	1,064E-05	2,486E-06
T	63	5%	7,095E-05	1,255E-05
PIM	1243		0,0001335	0,0002802

Tab. 2 Reach probability and annual probability of fatalities for each portion of road, for the PR for hikers.
Probabilità di accadimento spaziale e probabilità annua di fatalità per ciascuna porzione di strada, per la PR (sentiero) per pedoni.

PR Portion	Length (m)	Reach Probability	Annual probability of fatalities on the portion for P
A	56	3%	9,8E-06
B	81	5%	1,732E-05
C	66	5%	1,673E-05
D	55	5%	1,629E-05
E	74	20%	6,818E-05
F	50	1%	3,219E-06
G	70	20%	6,755E-05
H	76	15%	5,137E-05
I	68	10%	3,362E-05
L	65	10%	3,338E-05
M	62	1%	3,314E-06
N	53	1%	3,243E-06
O	56	10%	3,267E-05
PIM	832		0,0003567

velocity V_p, according to Márquez-Pérez *et al*. (2017), was estimated as:

$$V_p = 4.8e^{-5.3|0.7s + 0.03|} \quad (6)$$

where s is the mean slope of the portion. The considered a stopping time was equal to 0.08 hours, i.e. 5 minutes (Ansari *et al*., 2013), mediating between a non-stopping person, and short or medium stopping.

Following the procedure exposed in the methodology section, summing up for each traffic condition and homogeneous sections (see Table 1 and Table 2), the annual probabilities of fatality for the FR were $2.80 \cdot 10^{-4}$ in case of P and $1.33 \cdot 10^{-4}$ in case of V ($4.13 \cdot 10^{-4}$ in total), while for the PR it was equal to $3.57 \cdot 10^{-4}$. Unexpectedly, it reveals that the risk in FR is higher than in PR, even though the computed $N_{D,FR}$ was lower than $N_{D,PR}$. This is obviously due to the consideration of two types of element at risk in the same road. Moreover, in this specific case, in which only daily traffic with low velocity is allowed, the mutual interference of pedestrian and vehicle was neglected. If this assumption is relaxed the risk unavoidably increases.

4. Conclusions

The quantitative risk assessment due to rockfall events on mountain 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 was 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 portions on which performing the risk analyses. The consideration of different exposures and vulnerabilities for P and V was implemented in the method. The application on a real study case highlights the difference between two types of elements at risk and between two types of mountain roads. Further development can relate with the possibility of considering the mutual interference of pedestrian and vehicle on a farm road.

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