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QUANTITATIVE RISK ASSESSMENT FOR VIABLE INFRASTRUCTURES SUBJECTED TO ROCKFALL: ANALYSES OF SOCIAL AND ECONOMICAL CONSEQUENCES

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In quantitative risk assessment, the accurate prediction of the possible consequences represents a challenging aspect. Public Administrations and private owners often face difficulties in defining risk management plans, priority of interventions, and in allocating resources for mitigation works. Predicting and assessing geohazards and their effects is thus becoming urgent to create safe and resilient infrastructures, settlements and working places. Depending on the element at risk, different consequences can be considered. For infrastructures, damage analyses can be related to different aspects: social, e.g. people involved, physical, e.g. damages on the structure, economic, e.g. connected to activity/traffic interruption, and environmental, e.g. related with flora and fauna preservation.

Dealing with rockfall hazard, the present work investigates social and economic damages for viable infrastructures, e.g. high traffic roads or mountainous roads, often unique access route to remote areas. In previous works the Authors have developed an event-tree based risk assessment method to evaluate the social risk, expressed as the annual probability of having at least one victim on a road subjected to rockfall. In the present work the method is enhanced, addressing the aspects due to road closure and the economic damages. Depending on the type of infrastructure, the traffic demand and capacity, the location of the damaged part within the transport network, and its resilience, the economic risk can vary. In mountainous area the case in which two locations are connected by alternative routes all affected by rockfall hazard is possible. The closure of one of them causes a rerouting of the traffic. Beyond the economic damage, the alternative routes suffer for an increase of exposure to the hazard, hence an increase of the social risk. The method is fundamental for risk management as it provides a decisional basis for policy-makers and public Authorities.

Keywords: quantitative risk assessment, rockfall, social impact, economic damages.

1. Introduction

Over the last twenty years, significant focus has been placed on the reliability and vulnerability of road infrastructures. Reliability is defined as the ability to maintain adequate serviceability under prevailing operating conditions (Berdica, 2003), while vulnerability refers to susceptibility to incidents that can significantly restrict road network functionality (Hassan et al., 2022). Transportation systems are considered 'lifelines,' connecting different spatial areas and providing vital services for the population's survival. Both natural and man-made hazards affecting arterial roads can have extremely damaging effects on the area and population (Rupi et al., 2015). Maintaining serviceability is crucial for both system users and operators, both public and private, for social and economic reasons. To reduce network vulnerability and manage financial resources efficiently, road owners need to accurately understand potential risks in terms of human lives, network interruption time, and repair costs. Extreme weather conditions or natural calamities can disrupt transportation networks. In mountain regions, landslides are the most likely natural hazards, with rockfalls being particularly dangerous due to their unpredictability and high kinetic energies (Scavia et al., 2020). When two locations are connected by alternative routes affected by rockfall hazards, the closure of one route inevitably causes traffic rerouting. Existing risk assessment procedures generally compute damages in terms of human lives (i.e., social risk) on specific lines, neglecting the impacts on traffic redistribution and the resulting potential increase in risk on other network routes (Budetta et al., 2016). An alternative approach is generally adopted to evaluate the economic losses from road closures. The total cost is calculated by summing (i) changes in vehicle operating and occupant time costs, (ii) lost user benefits from cancelled trips, and (iii) changes in accident costs (Dalziell & Nicholson, 2001). This represents the change in the generalized cost of transport between two network nodes when a link fails, termed 'network vulnerability' (Taylor and D'Este, 2007). Strada et al. (2015) proposed a similar formulation for both direct and indirect economic damages. However, these formulas do not consider the probability of the hazardous event causing the closure.

Dealing with rockfall risk assessment on mountain roads, the present work proposes a methodology and the analytical formulae to compute the social and economic damages on a network due to the occurrence of a rockfall event on a road and its consequent disruption for a period of time. The method accounts for both occurrence probability and traffic rerouting, without entering in the specific details of generalized cost computation and all the possible indirect costs. A simple example is proposed.

2. Methodology

The damage assessment process starts with the knowledge of the characteristics of both the hazard and the elements at risk. In previous works the Authors have developed an event-tree based risk assessment method to evaluate the social risk, expressed as the annual probability of having at least one victim on a road subjected to rockfall (Marchelli, 2020; Marchelli et al., 2021). In the method, all the possible scenarios leading to a fatality are outlined and a probabilistic approach is followed. The temporal, say annual, probability that a block arrives on the *i*-th road *r*, $P_{(S:T)_{r_i}}$, or the number of expected rockfall events reaching the road per year $N_{B_{r_i}}$ is computed, knowing the expected traffic conditions in terms of number of vehicles and mean speed. Given the *i*-th road, the annual social risk $R_{s_{r_i}}$ is:

$$R_{s_{r_i}}(1y) = 1 - \left(1 - PF_{r_i}\right)^{N_{B_{r_i}}}, \qquad (1)$$

being PF_{r_i} the probability of human life loss for the certain occurrence of an event. The approach can be used also for a portion of road, only, and then integrated for all the portions constituting the same road (Marchelli, 2020; Marchelli et al., 2021). This calculation does not consider traffic rerouting, but owners can assess the priority of the interventions by knowing the risk for each individual road.

In the case of multiple roads connecting two points, it is assumed that they can all be affected by rockfall events with different $P_{(S:T)_{r_i}}$, and that the occurrence of an event necessarily implies the closure of the affected *i*-th road for the amount of time τ_i required for maintenance. The damage assessment should thus consider the increase in traffic and therefore exposure in the remaining roads. Neglecting fatalities due to vehicle accidents, the annual social risk of a network with *N* roads, in the event of closures $R_{sN}(1y)^c$, can thus be computed as:

$$\begin{aligned} R_{sN}(1y)^c \\ \cong \underbrace{R_{sN}(1y)\prod_{r_i=1}^{N}\left(1 - P_{(S:T)_{r_i}}\right)}_{(A)} + \sum_{r_i=1}^{N} \underbrace{P_{(S:T)_{r_i}} \prod_{r_j=1}^{N-1}\left(1y - P_{(S:T)_{r_{j\neq i}}}\right)\left[R_{sN}(1y - \tau_i) + R_{sN}^{new}(\tau_i)\right] +}_{(B_i)} \\ + \sum_{r_i,r_j}^{N!/(2(N-2)!} \underbrace{\left[P_{(S:T)_{r_i}} P_{(S:T)_{r_{j\neq i}}} \prod_{r_k=1}^{N-3}\left(1 - P_{(S:T)_{r_{k\neq i}}}\right)\right]\left[R_{sN}\left(1y - \tau_i - \tau_j\right) + R_{sN}^{new}(\tau_i) + R_{sN}^{new}\left(\tau_j\right)\right]}_{(C_i)} + \Omega \quad (2) \end{aligned}$$

being $R_{sN}(1y)$ the annual risk of the network with no closures, computed as the sum of the risk for each of the *N* roads $R_{s_{r_i}}(1y)$, and $R_{sN}^{new}(\tau_i)$ the risk of the network when the *i*-th road is closed, given by the sum of the risk for each remaining open road, considering the increase in traffic. The term $R_{sN}(1y - \tau_i)$ represents the risk of the network computed for the period in which no closures are applied. The term A represents the risk in case of no closure on any of the roads, where $\left(1 - P_{(S:T)_{r_i}}\right)$ is the probability of no closure, while the term B$_i$ the risk of alternately closing roads. The term $P_{(S:T)_{r_i}} \prod_{r_j=1}^{N}\left(1 - P_{(S:T)_{r_{j\neq i}}}\right)$ is thus the probability that only the *i*-th road closes. The term C accounts for closures of couples of roads during the same year. For very low occurrence probabilities, the term can be neglected. Other combinations were not added (the term Ω) because the probability of more than two independent events occurring in the same year is very low. The situation of simultaneous occurrence of events is also neglected. Comparing the B$_i$ term for each possible *i*-th road is intended to highlight the most vulnerable street from a social perspective, while network comparison should consider,$R_{sN}(1y)^c$ for each network. For very small $P_{(S:T)_{r_i}}$, Eq. (2) turns into:

$$R_{sN}(1y)^c = \underbrace{R_{sN}(1y)\left(1-\sum_{r_i=1}^{N} P_{(S:T)R_i}\right)}_{(A)} + \sum_{r_i}^{N} \underbrace{P_{r_i}[R_{sN}(1-\tau_i)+R_{sN}^{new}(\tau_i)]}_{(B_i)}. \quad (3)$$

Dealing with the economic issues, we define the change in the total cost (both direct and indirect) for the closure of the *i*-th road as $\Delta C_{r_i} = C_{r_i} - C_0$, being C_{r_i} and C_0 the total cost of the network when *i*-th road is interrupted and when all the roads function normally, respectively. These last two terms are calculated as the generalized cost multiplied by the simulated traffic volume. Neglecting the closure of more than two roads in the same year, and defining C_{rep,r_i} the reparation costs of the *i*-th road, the proposed formula for calculating the annual economic risk of the network of *N* roads considering closures $R_{eN}(1y)^c$ is:

$$R_{eN}(1y)^c = \sum_{r_i=1}^{N} \underbrace{P_{(S:T)r_i}\prod_{r_j=1}^{N}\left(1-P_{(S:T)r_{j\neq i}}\right)\left(\Delta C_{r_i}+C_{rep,r_i}\right)}_{(D_i)}$$

$$+ \sum_{r_i,r_j}^{N!/(2(N-2)!} \underbrace{P_{(S:T)r_i}P_{(S:T)r_{j\neq i}}\prod_{r_k=1}^{N-3}\left(1-P_{(S:T)r_{k\neq i}}\right)\left(\Delta C_{r_i}+C_{rep,r_i}+\Delta C_{r_j}+C_{rep,r_j}\right)}_{(E_i)} \quad (4)$$

The terms D$_i$ and E$_i$ present situations in which only one or two roads are closed for a time τ_i during the year, respectively. It should be noted that the simulated traffic volume in case of closures can slightly change by the initial situation (no closure), as some users could decide to cancel the trip if the new cost exceeds the utility derived from making the trip. The term $P_{(S:T)_{r_i}}$ allows an economic comparison among the cut of one or another road accounting for its closure probability. Neglecting this term, the case of certain event is assumed, and, in turn, closures of alternative road can be compared according to their consequences on the network vulnerability. For very small $P_{(S:T)_{r_i}}$, Eq. (4) turns into:

$$R_{eN}(1y)^c \cong \sum_{r_i=1}^{N} P_{(S:T)_{r_i}}\left(\Delta C_{r_i}+C_{rep,r_i}\right). \quad (5)$$

3. Example and Conclusions

A simple case of 3 mountain roads connecting two points is considered. A total traffic volume of 200 vehicles per hour ($N_{v/h}$) is considered, with a mean speed of 30 km/h. As stated by Yang et al. (2011), depending on the type and magnitude of the occurred landslide, roads might be closed for months. Based on the mean restoration time for rockfall events in Italy, in the present example, a one-month period of closure is assumed for all roads. Table 1 reports the traffic condition in case of closures and $P_{(S:T)_{r_i}}$ for each road. In case of no closure, $R_{s_{r_i}}(1y)$ equal to $5.75 \cdot 10^{-7}$, $5.73 \cdot 10^{-8}$ and $5.14 \cdot 10^{-7}$ for R1, R2 and R3, respectively, result from Eq. (1), and a network total risk of $1.15 \cdot 10^{-6}$. Taking closures into account, calculations are reported considering the following cases: (i) only one road closed per year, (ii) two roads closed per year (1&2,1&3,2&3), (iii) all road closed (1,2,3). Referring to Eq. (2), case (i) corresponds to A+$\sum B_i$ terms, case (ii) to A+$\sum B_i$+$\sum C_i$, while in case (iii) another term should be added (the Ω in Eq. (2)), and it is calculated to demonstrate its negligibility. Table 2 reports the terms of Eq. (2) separately and all together. A value of $R_{sN}(1y)^c = 1.18 \cdot 10^{-6}$ is obtained. It should be noted that the case presented is a severe case as $P_{(S:T)_{r_i}}$ is very high, i.e. 1 event every 10, 2.5 and 3 years, respectively. For lower values Eq. (2) provides results like the case without closure, and C$_i$ terms of Eq. (2) can be neglected.

For the economic risk, the travel time increment is considered, only (C_{rep,r_i} are neglected). Assuming in a simplified approach that closing a road can cause a 10% increase in travel time per passage, Table 3 reports the obtained increment in time for each case. It could be noted how neglecting case (iii), i.e. the closure of all roads in the same year, has no influence on the results. Comparing the B$_i$ terms, the closure of R2, i.e. the one with lower $N_{v/h}$, represents the worst-case scenario for the network, even though $R_{s_{R2}}(1y)$ is an order of magnitude smaller than $R_{s_{R1}}(1y)$ and $R_{s_{R3}}(1y)$. From economic perspective too, the closure of R2 represents the worst situation.

This simple example reveals how relevant is taking into account the occurrence probability for accurate damages prediction. To validate the method, future studies and analyses will be performed to include the network equilibrium concepts and compute direct and indirect cost more precisely.

Table 1: Traffic conditions in case of closures

Road	Length (m)	$P_{(S:T)_{r_i}}$	$N_{v/h}$			
			No closure	Closure R1	Closure R2	Closure R3
R1	947	0.1	70	-	80	140
R2	828	0.4	30	60	-	60
R3	895	0.3	100	140	120	-

Table 2: $R_{sN}(1y)^c$ in different conditions

Term (A)	Term (B_1)	Term (B_2)	Term (B_3)	Term (C_1)	Term (C_2)	Term (C_3)	Term (…)
No closure	Closure R1	Closure R2	Closure R3	Closure R1&R2	Closure R1&R3	Closure R2&R3	Closure R1,R2,R3
4.33E-07	4.71E-08	2.92E-07	2.19E-07	2.71E-08	2.37E-08	1.26E-07	1.37E-08
	Case (i): 9.91E-07			Case (ii): 1.77E-07			
				Tot= 1.1813E-06			

Table 3: $R_{eN}(1y)^c$ in different conditions

	Closure R1	Closure R2	Closure R3	Closure R1&R2	Closure R1&R3	Closure R2&R3	Closure R1,R2,R3
ΔC_{r_i} (min)	23.7	41.7	39.7	65.4	63.4	81.4	80.0
$P_{(S:T)_{r_i}}\Delta C_{r_i}$ (min)	1.0	10.5	7.5	1.6	1.3	8.8	1.0
		19.0					
$R_{eN}(1y)^c$ (min)				30.7			
				Tot=31.7			

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