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Abstract

Although many works on the quantification of the rockfall hazard and exposure of vehicles in roadways exist, few practical examples that include detailed consequences analysis have been presented so far. We respectively present a complete and comprehensive methodology with an emphasis on the quantification of the consequences in function of the rockfall frequency and magnitude. The developed methodology was programmed using Microsoft Excel. Its application in a given section of the roadways of Gipuzkoa, Spain is presented.

Keywords

Rockfalls • Quantitative risk • Exposure • Roadways

321.1 Introduction

In many mountain and coastal terrains, rockfalls are a major hazard as social and economic factors often impose the presence of infrastructures in rockfall prone areas. A significant fraction of the rockfall quantitative risk assessment QRA involves the assessment of the risk for vehicles circulating in transportation routes and of their passengers. In the literature there are such practical examples of risk assessment at site-specific and local scale for vehicles and people inside them (Corominas et al. 2013 and references therein). However few practical examples of rockfall risk tools, taking into account local scale data for the hazard and the consequences have been presented so far. An interesting methodology for multi-risk analysis in the roadways of Switzerland was suggested by FEDRO (2012),

In this context we present a comprehensive methodology for the quantification of the risk in roadways which offers a complete list of risk descriptors. The methodology takes into account the local characteristics of the roadway, the population and the traffic. The procedure for the calculation of the

consequences is automatic using Microsoft Excel spreadsheets. An application is presented for data corresponding to specific coastal roadways of Gipuzkoa, Spain.

321.2 Study Area

The study area is the coastal corridor of the road N-634 that connects the cities of Zarautz and Getaria in the province of the Gipuzkoa in the Basque Country (Spain) as it is shown in Fig. 321.1. The path of road considered has a length of 5.4 km. The road follows the sinuous profile of the coast, which justifies the presence of several closed curves. The studied section has a large volume of traffic, which increases significantly during the touristic summer months. It is affected by frequent instability phenomena.

Geologically, the study area forms part of the coastal mountains of Gipuzkoa. The latter are strips of material of Tertiary well-stratified prevalently sandstones, limestone and shales (Flysch formation). The main landslide types are rockfalls, debris flow and in a lesser extent translational/rotational landslides. Blocks may reach some thousands of cubic meters. In 1969 a major rockfall of 20,000 m³ occurred involving the closure of the roadway for several months. Events of thousands of cubic meters also occurred in 2008 amongst other smaller ones in the last decades.

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Fig. 321.1 Satellite photo of the study roadway (N-634) and alternative paths for the calculation of the indirect cost: (green) along the highway A-8, road N-631, N-634 and (orange) along the roads GI2633 and GI3391

321.3 Hazard Data

A database was compiled to retrieve information on the type, magnitude and frequency of the rockfall events, in particular. First, it was necessary to extract data from the records of landslides, depurate, elaborate, interpret and validate them. The database includes in total 225 rockfalls for the studied path, between 1884 and 2009. The data from 1994 to 2005 were provided by the road maintenance office on paper format, those from 2006 to 2008 in Microsoft Excel spreadsheets (digital format) record, and the others were obtained from local and national newspapers. The observed rockfall magnitudes (in terms of volumes) were ranked into different classes, leading to different levels of damage

(Table 321.1). The class F was established for events of high magnitude that have not been observed during the inventoried period and the frequency of 0.0028 was attributed to it by extrapolation of the data.

321.4 Consequences

A significant part of this work was focused on the quantification of the consequences. We distinguish between direct and indirect cost. The direct one is calculated with respect to the number of the affected vehicles, with a view to calculate the number of persons who could be harmed. The indirect one refers to the economic cost due to traffic detour in case of interruption of a roadway.

Table 321.1 Rockfall magnitude classes and their respective frequencies for the roadway N-634 between Zarautz and Getaria

Class	N° of events	Period (years)	Years	Frequency f_a (events/year)	Magnitude (m^3)
A	104	1994–2009	15	6.933	0.05–0.5
B	91	1994–2009	15	6.067	0.5–5
C	24	1994–2009	15	1.600	5–50
D	5	1960–2009	49	0.102	50–500
E	1	1884–2009	125	0.008	500–5000
F				0.003	>5000

321.4.1 Direct Cost

The total direct risk in terms of loss which is due to the impact of a rockfall on moving vehicles was calculated using Eq. (321.1):

$$R = \sum_{M_i} R(A) = f_a \times P(S:A) \times P(T:S) \times V_i \quad (321.1)$$

where:

- R(A) Annual loss expressed as the expected number of fully damaged vehicles
 f_a Annual frequency of a rockfall of a given class (non cumulative)
 P(S:A) Probability that a rockfall path affects the whole road width
 P(T:S) Probability that a moving vehicle passes by the affected section the moment of the rockfall
 V_i Vulnerability of the vehicle for the magnitude M_i
 M_i Magnitude range corresponding to the rockfall class

The probability that a rock block path affects the whole width of the roadway, P(S:A) is evaluated judgmentally in function of the magnitude of the event; while small rockfall occupy only very small parts of the road (and usually stop close to the verge of the roadway), larger rockfalls occupy its whole width. The values assumed here are shown in column 4 of Table 321.2. For wide roads it might be considered that it varies according to the lane direction (lanes right next to the slope and lanes of opposite direction). The probability P(T:S) is given by:

$$P(T:S) = \frac{N_v \cdot L_v}{24 \cdot 1000 \cdot V_v} \quad (321.2)$$

where:

- N_v Circulation intensity (Number of vehicles /day)
 V_v Velocity (average value) (Km /h)
 L_v Vehicle length (average value) (m)

The daily traffic intensity is 4,260 vehicles per day, the average velocity of 60 km/h and the average vehicle length is assumed equal to 5.4 m.

The vulnerability of the vehicles was also evaluated empirically in function of the rockfall magnitude (column 6 of Table 321.2).

Summarising the results of Table 321.2, the expected annual number of impacted vehicles is 0.1247 vehicles and of fully damaged vehicles is 0.1056/year. The return period of a vehicle being impacted is the inverse of the former and equal to 8 years. If the average value of a vehicle is 30,000 €, the annualised repair cost is the product of the risk with this value and it is 3,168 €/year. The afore-mentioned calculations refer to the collective expected loss. Further risk descriptors may be calculated in terms of probability, for three specific scenarios. The following calculations involve just their probability. The risk can be calculated by multiplying the obtained probability with the respective vulnerability. For these scenarios, on the safety side, it is assumed that rock blocks of all magnitudes may affect all the width of the roadway, thus P(S:A) = 1.

The first scenario refers to one or more vehicles being reached by a rockfall. Its annual probability is given by Eq. (321.3) (Bunce et al. 1997):

$$P1 = \sum_{M_i} P(S1) = \sum_{M_i} 1 - (1 - P(T : S))^{f_a} \quad (321.3)$$

where:

- P(S1) Probability of scenario 1 for every class of rockfall M_i
 P(T:S) Probability that a vehicle is found on the roadway section that is affected by the rockfall given by Eq. (321.2)
 f_a Annual frequency of a rockfall of magnitude M_i (non-cumulative)

The second scenario refers to a vehicle being hit by a slope failure during a single trip, P2. It is given by Eq. (321.4), which is similar to (321.3), with two

Table 321.2 Direct risk per expected rockfall magnitude and total

Class	f_a	P(T:S)	P(S:A)	Impacted vehicles/year	V	Risk R(A)
A	6.933	1.60E-02	0.4	4.43E-02	0.7	3.10E-02
B	6.067	1.60E-02	0.6	5.81E-02	0.9	5.23E-02
C	1.600	1.60E-02	0.8	2.04E-02	1.0	2.04E-02
D	0.102	1.60E-02	1.0	1.63E-03	1.0	1.63E-03
E	0.008	1.60E-02	1.0	1.28E-04	1.0	1.28E-04
F	0.003	1.60E-02	1.0	4.53E-05	1.0	4.53E-05
Total				0.1247		0.1056

adaptations: (i) the annual frequency f_a is replaced by f_v which is the rockfall (non-cumulative) frequency that corresponds to the duration of one trip through the dangerous area and (ii) the probability $P(T:S)$ is here given by Eq. (321.5).

$$P2 = \sum_{M_i} P(S2) = \sum_{M_i} 1 - (1 - P(T : S))^{f_v} \quad (321.4)$$

$$P(T:S) = \frac{L_v}{L_c} \quad (321.5)$$

where:

L_v Length of the vehicle (average value)

L_c Length of the roadway

The third scenario describes the annual probability of a given commuting vehicle travelling twice per day being hit by a rockfall. It is:

$$P3 = \sum_{M_i} P(S3) = 2 \times 365 \times \sum_{M_i} 1 - (1 - P(T:S))^{f_v} \quad (321.6)$$

The probability $P(T:S)$ and the frequency f_v are the same with scenario 2.

The probabilities $P(T:S)$ are 0.015975 for scenario 1 and 0.001 for scenarios 2 and 3. The probabilities $P1$, $P2$ and $P3$ are 2.26E-01, 1.51E-07 and 1.10E-04, respectively.

321.4.2 Indirect Risk

Traffic detours due to rockfalls in the studied roadway occur often. Two alternative paths exist (Fig. 321.1), for which we calculate the indirect risk: (1) along the highway A-8, road N-631 and N-634 and (b) along the roads GI2633 and GI3391. It includes the costs that are summed up when a detour is forced due to the traffic interruption of a roadway. This implies increased fuel costs in function of the distance difference, lost working time costs for the commuters and toll difference costs. The used expression is:

$$\begin{aligned} \text{Daily loss} &= \text{Distance difference} \times \text{Fuel costs} \\ &+ \text{Time difference} \times \text{Number of workers} \\ &\times \text{Working cost} + \text{Toll cost difference} \end{aligned} \quad (321.7)$$

Table 321.3 Indirect risk

	Annual risk (Euro)
Alternative path 1	38032
Alternative path 2	9717

The parameters that enter in the calculations are: worker cost 15 €/h; 2 persons/vehicle; workers: $0.70 \times 6,390$ motorists; velocity at A8: 120 km/h; velocity at the rest of the roadways: 60 km/h; gasoline cost: 0.45 €/Km; diesel cost 0.95 €/Km. The alternative path through A8 and N-634 includes toll cost of 0.9 € for light vehicles and 1.5 € for trucks. The multiplication of the daily loss with the expected annual frequency and duration of detour, for the events of magnitude C (duration of detour 6 h), D (1 day accordingly), E (5 days accordingly) and F (20 days accordingly) yields the total expected annual cost. The values presented in Table 321.3 exclude repair costs of the road.

321.5 Conclusions

It is possible to quantify the expected loss due to rockfalls in roadways, using a variety of risk descriptors. These results can be used for cost-benefit analysis in order to prioritise protection measures. In the studied roadway, the annual probability that a given commuting vehicle travelling twice per day being hit by a rockfall, $P3$, is high according to the tolerability thresholds for personal risk of the order of 10^{-4} which are proposed in the literature (AGS 2000). This implies the necessity of protection measures.

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