TXT-tool 4.034-1.1 Quantitative Rockfall Risk Assessment for Roadways and Railways

Olga Mavrouli and Jordi Corominas

Abstract

This tool presents a methodology for quantifying the rockfall risk and the consequences for vehicles circulating on roadways and railways. We present a complete and comprehensive methodology for risk assessment, using various risk descriptors, with an emphasis on the quantification of the exposure of the vehicles and the consequences from rockfall hits, in function of the rockfall frequency and magnitude. Indications on the calculation of the repair costs for damaged roadways and railways and for the indirect loss, due to their temporary closure, are also given. This methodology is useful for end-users involved in the risk management and the design of protection measures.

Keywords

Rockfalls · Risk assessment · Roadways · Railways · Vehicles

Contents

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1 Introduction

Rockfalls occur in mountain environments, coastal cliffs and cuts. Rockfalls are frequent rock instabilities that affect transportation corridors such as roadways and railways and result in the damage of vehicles and the injury of their passengers. Administrative authorities and professionals working on the protection of roadway and railway networks, are often required to consider such loss and to evaluate its potential and extent in order to prepare a rockfall management plan. Besides, the prioritization of stabilization and/or protection measures as well as the drawing of emergency preparedness plans in case of transportation corridor interruption, it requires the assessment of the rockfall risk.

Several approaches of risk analysis at site-specific and local scale for transportation routes are found in the literature (Budetta 2004; Ferlisi et al. 2012; Corominas et al. 2014). However, only few examples of rockfall risk tools, taking into account local scale data for the hazard and the consequences have been presented so far. Here, we present a tool for the quantification of the rockfall risk in roadways and highways. It can be applied at site-specific, local and regional scale. The risk calculation integrates the local data for the rockfall hazard as well as for the transportation corridors. Moreover, users can easily automatize it (e.g. using Microsoft Excel).

Risk can be defined as a measure of the probability and severity of an adverse effect to health, property or the environment (Fell et al. 2005). It is estimated as the product of probability (or frequency) of the potentially damaging event and its consequences, as given by Eq. 1:

$$\mathrm{R} = \mathrm{H} \times \mathrm{E} \times (\mathrm{V} \times \mathrm{C}) \tag{1}$$

where

H	hazard term expressed by frequency/probability of a potentially damaging event (rockfall) of a given magnitude
E	the element or set of elements at risk (property, persons) exposed to the hazardous event
V	vulnerability of the exposed element(s)
C	cost of the exposed element(s)

The quantitative rockfall risk analysis entails the evaluation of Eq. 1 and of its components in quantitative terms, using numerical scales or ranges of values to express the probability of an expected level of loss, as opposed to the qualitative methods that employ nominal ranks. The quantitative rockfall risk analysis has been gaining ground over the qualitative one for overcoming the use of ambiguous terms and for yielding reproducible, standardized and comparable results among distant locations and regions. It provides a potential tool for taking coherent criteria-based decisions and for assessing objectively their efficacy.

In this chapter, it is described how Eq. 1 can be applied for the quantification of the rockfall risk in transportation corridors, using different risk descriptors (Sect. 2) for: vehicle damage (Sect. 3), roadways and railways repair costs (Sect. 4), and indirect costs resulting from the roadways/railway temporary closure (Sect. 5).

2 Rockfall Consequences and Risk Descriptors

Rockfalls affect transportation corridors in diverse ways. Different risk descriptors are required to express the type and extent of the consequences, depending on the affected elements, the objective of the risk assessment and the work scale. Descriptors consist of parameters or combinations of parameters that provide information on the terms of Eq. 1. This tool treats the following types of consequences, which are classified into two main groups (Corominas and Mavrouli 2013, 2014):

(a) Direct consequences: (i) physical damage of vehicles and (ii) destruction of roadways/highways resulting from a rockfall impact.
(b) Indirect consequences: traffic detours resulting from the blockage of transportation corridors and the disruption of activities.

Here, the risk descriptors for expressing the risk deriving from the physical damage of vehicles (a-i) include:

- the expected annual number of the impacted vehicles;
- the expected annual repair cost of vehicles in the road/rail section;
- the return period for 1 vehicle being completely destroyed;
- the return period of 1 vehicle being impacted.

As an example of the difference in the use of these descriptors, the annual number of the impacted vehicles and the expected annual repair cost of vehicles are often solicited by administrative authorities in order to manage the rockfall risk, whereas the return period for 1 vehicle being impacted or completely destroyed, is mostly useful for insurance companies.

Additional risk descriptors can be delivered as frequency-consequence or probability-consequence pairs for given scenarios. This output is essential for evaluating whether the risk is acceptable/tolerable, after comparison with pre-established thresholds (Finlay and Fell 1997).

The destruction of roadways/highways (a-ii) is quantified in terms of the average annual cost for repair. It is taken into account that depending on the rockfall magnitude, damage may vary from small fissures on the pavement to total collapse.

Last, we show how indirect causes (b) can be assessed considering the excess expenses arising from obligatory traffic detours via alternative routes in case of route blockage. Vehicle circulating costs and lost work-hours are integrated.

3 Risk Assessment for Rockfall Impacts on Vehicles

Figure 1 shows the risk generated by the rockfalls on a rocky cliff, threatening a road. The assessment of the risk deriving from damage due to rockfall impact(s) on vehicle(s) is made by the adaptation of the Eq. 2 and the assessment of its terms. The risk equation in quantitative terms can be expressed as (modified from Dai et al. 2002; Fell et al. 2005):

$$R = \sum_{Mi} R(A) = f_a \times P(S{:}A) \times P(T{:}S) \times V_i \tag{2}$$

where:

R(A)	annual risk for every class of rockfall
f_a	annual frequency of a rockfall of a given class (non cumulative)
P(S:A)	conditional probability that a rockfall occupies partially or totally one or two lanes of the roadway
P(T:S)	conditional probability that a moving vehicle passes by the affected section at 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.

In link with Eq. 1, the rockfall hazard is expressed by two terms in the risk equation: the frequency, f_a and the conditional probability that a rockfall occupies partially or totally one or two lanes of the roadway, P(S:A). The conditional probability that a moving vehicle passes by the affected section at the moment of the failure P(T:S) expresses the exposure and the term V_i the vulnerability.

Diverse risk descriptors are evaluated by Eqs. 3–6, as adaptations of Eq. 2, introducing additionally, in some cases, the cost C of a vehicle (p.e. in €):

Expected annual number of the impacted vehicles, N:

$$N = \sum_{Mi} N(A) = f_a \times P(S{:}A) \times P(T{:}S) \tag{3}$$

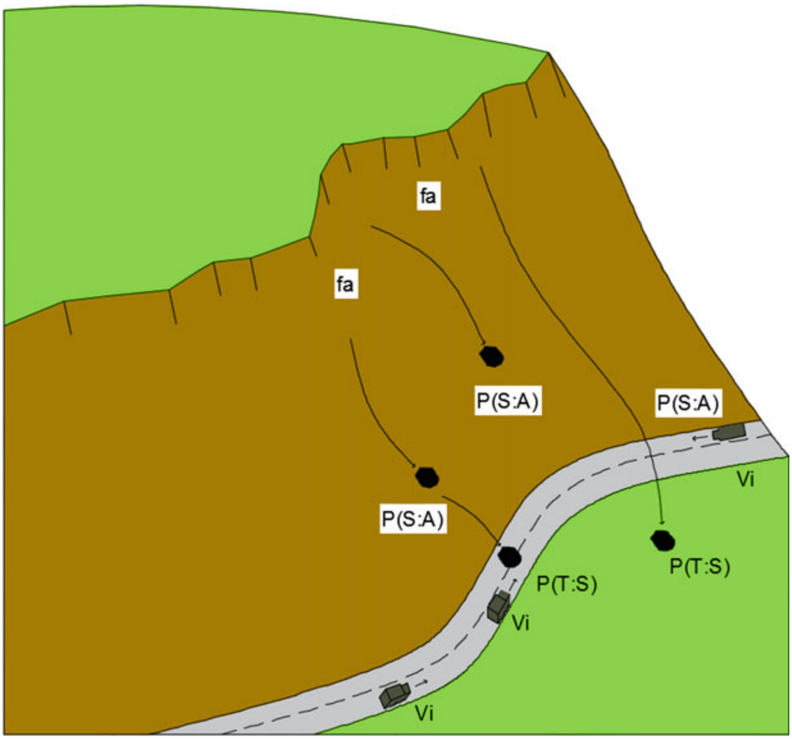

Fig. 1 Schematic representation of the rockfall risk components of Eq. 1

Expected annual repair cost of vehicles in the road/rail section, R:

$$\begin{aligned} RC &= \sum_{Mi} RC(A) \\ &= f_a \times P(S{:}A) \times P(T{:}S) \times V \times C \end{aligned} \tag{4}$$

Return period of 1 vehicle being impacted (in years), T_{imp}:

$$\begin{aligned} T_{imp} &= 1/\sum\nolimits_{Mi} N(A) \\ &= 1/[f_a \times P(S{:}A) \times P(T{:}S)] \end{aligned} \tag{5}$$

Return period for 1 vehicle being completely destroyed (in years):

$$\begin{aligned} T_{des} &= 1/\sum\nolimits_{Mi} R(A) \\ &= 1/[f_a \times P(S{:}A) \times P(T{:}S) \times V] \end{aligned} \tag{6}$$

The approaches for the risk analysis vary depending on whether it refers to a single object (i.e. road cutting), a linear feature (i.e. road/rail section) or an area (i.e. an entire municipality). Local and regional governments in charge of land-use planning and urban development are mostly interested in the spatial (areal) analysis, the outputs of which usually provide data on the spatial distribution of the risk and can be presented as maps.

The risk descriptors of Eqs. 2–6, calculated partially for single objects can be summed up to provide the risk for linear sections and in their turn for an entire transportation network. An example is presented in Fig. 2. It shows a mountain road, crossing four road cuts (A to D). The risk descriptors are obtained in function of the separate section risks (marked with the index of each section) using the afore-mentioned expressions.

Total annual risk, R_T:

$$\begin{aligned} R_T = \sum_{Mi} R(A)_A + \sum_{Mi} R(A)_B + \sum_{Mi} R(A)_C \\ + \sum_{Mi} R(A)_D \end{aligned} \tag{7}$$

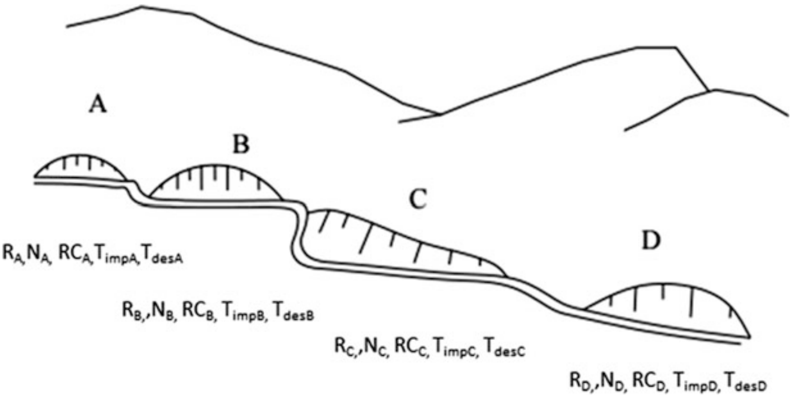

Fig. 2 Road cuts and risk descriptors for each section

Total expected annual number of the impacted vehicles, N_T:

$$N_T = N_A + N_B + N_C + N_D \tag{8}$$

Expected annual repair cost of vehicles in the road/rail section, RC_T:

$$RC_T = RC_A + RC_B + RC_C + RC_D \tag{9}$$

Return period of 1 vehicle being impacted (in years), T_{Timp}:

$$T_{Timp} = 1/N_T \tag{10}$$

Return period for 1 vehicle being completely destroyed (in years), T_{Tdes}:

$$T_{Tdes} = 1/R_T \tag{11}$$

The coverage and the scale of work as well as the amount of available data affect substantially the resolution of the analysis and the calculation of the risk components. In the following sections specific instructions are given for it.

3.1 Rockfall Frequency, f_a

For the calculation of the frequency, f_a, which usually expresses the average number of events per years, rockfall inventories are required. The most reliable sources of data come from rockfall records from maintenance units of roads and railways, park services or civil protection (Bunce et al. 1997; Hungr et al. 1999; Guzzetti et al. 2003). However, some of these inventories have some limitations. Mainly, they cover a short time-span and often deal with rockfall events of a minimum size. Ground impact features and damages to vegetation located in the rockfall paths are an alternative to prepare a series of rockfall events (Schnewly and Stoffel 2008; Corominas and Moya 2010). In some few cases, rockfall inventories may be completed by dating the features of the ancient deposits and silent witnesses.

Roberds (2005) has made a critical distinction for the evaluation of f_a: the occurrence of the rockfall may be determined either at the source or at the potentially affected area, in this case the roadway/highway. To address this, two different approaches can be followed: (a) assess the failure frequency of each slope and propagation separately, and assess in this way the frequency of the blocks reaching the road. In this case, a magnitude-frequency relation is required at each slope or land unit and, afterwards, the estimation of the run-out distance for each landslide magnitude (Corominas and Moya 2008; Algiardi et al. 2009); (b) assess the frequency directly on a roadway/railway based on statistics of past rockfall impacts (Bunce et al. 1997; Hungr et al. 1999; Dussage-Peisser et al. 2002). The latter is the most common, as data are usually inventoried for those rockfalls reaching the road/rail.

Small and even mid-sized events produce accumulation of boulders that are often indistinguishable among them and, as a consequence, some censoring takes place in the series. The censoring effect may be eliminated with a careful selection of the volume ranges and determination of the frequency of each of them. As a simple example, the frequency of small-sized events may be established based on the data gathered in the technical reports covering a time span of several tens of years. The frequency of mid-sized events might be established based on the historical data and high-resolution absolute dating techniques, such as dendrochronology.

Parameters relevant to triggering factors, such as earthquake shaking, are often used in hazard analyses, in order to investigate their correlation with rockfalls, and to establish thresholds for the failure initiation. The correlation of rockfalls with rainfall events is very weak thus the collection of rainfall data is usually a secondary priority for the quantification of rockfall hazard and risk.

Magnitude-frequency relations are fundamental for performing quantitative rockfall risk analysis. Magnitude expresses the rockfall volume. The observed magnitude-frequency distribution of rockfalls in different regions can be represented by statistical distribution laws. The most accepted is the power law (Hungr et al. 1999; Dussauge-Peisser et al. 2002; Guzzetti et al. 2003), which takes the following form (Eq. 12):

$$f_a(V) = \lambda V^{-b} \tag{12}$$

where:

$f_a(V)$	annual frequency of rockfall events of a given volume V
V	rockfall volume
λ, b	constants

The conceptual relationship between rockfall magnitude and frequency is shown in Fig. 3 (Corominas and Moya 2008). Typically, the power law relation is valid for a defined range of rockfall volumes. Malamud et al. (2004) and Picarelli et al. (2005) suggested the extrapolation of power-law magnitude-frequency relations, for a preliminary assessment of the largest events. Instead, a truncation of the afore-mentioned distributions has been suggested by other researchers (Ruiz-Carulla et al. 2015; Turcotte et al. 2002), which suggests that this extrapolation should be performed with caution.

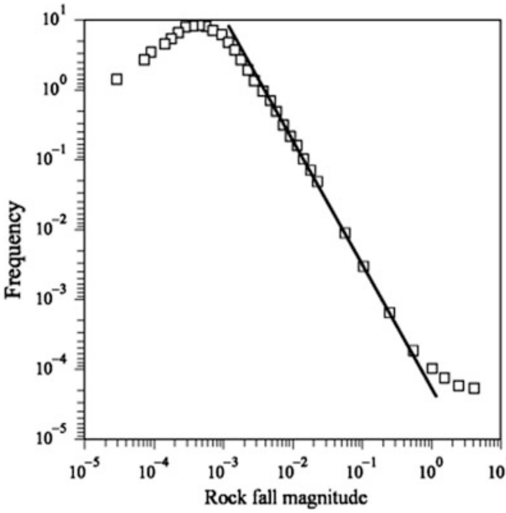

Fig. 3 Typical plot of the magnitude-frequency relation observed in landslide inventories (Corominas and Moya 2008)

The expected rockfall volumes should be ranked into different classes, as for example: 0.05–0.5, 0.5–5, 5–50, 50–500, 500–5000, >5000 (m^3). These classes should be established according to local inventory data, considering that different classes lead to different levels of damage.

3.2 Probability that a Rockfall Occupies Partially or Totally One or Two Lanes of the Roadway, P(S:A)

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 rockfalls occupy only very small parts of the road (and usually stop close to the verge of the roadway), larger rockfalls occupy its whole width. Some indicative values are given in Table 1. For wide roads, it might be considered that it varies according to the lane direction (lanes right next to the slope and lanes of the opposite direction).

Table 1 Indicative rockfall classes for a local road and values of P(S:A)

Rockfall class (m^3)	P(S:A)
0.05–0.5	0.4
0.5–5	0.6
5–50	0.8
50–500	1
500–5000	1
>5000	1

3.3 Probability that a Moving Vehicle Passes by the Affected Section at the Moment of the Rockfall, P(T:S)

The probability that a moving vehicle passes by the affected section at the moment of the rockfall is spatial and temporal. Diverse approaches exist for its calculation, depending on whether they integrate the length of the vehicle (car, truck or train) and/or the affected road/rail length by the rockfall (Nicolet et al. 2015).

The most common methods take into consideration the length of the vehicle, as in Eq. 13. This is strongly suggested for railways, where the train length is substantial.

$$P(T{:}S) = \frac{\frac{N_v}{24} \times \frac{L_v}{1000}}{V_v} \tag{13}$$

where:

N_v	circulation intensity (number of vehicles/day)
V_v	velocity (average value) (km/h)
L_v	vehicle length (average value) (m)

For rockfalls with a length significantly larger than the circulating vehicles, the affected road/rail length can be instead taken into account. This approach is less often, as in most cases rockfalls affecting small sections are the most common. Equation 14 represents the probability of the geometric centre of a moving vehicle being located in the section covered by the event.

$$P(T{:}S) = \frac{\frac{N_v}{24} \times \frac{L_r}{1000}}{V_v} \tag{14}$$

where:

N_v	circulation intensity (number of vehicles/day)
V_v	velocity (average value) (km/h)
L_r	road/rail length affected by the rockfall (m)

With this approach, P(T:S) contemplates that several cars may be hit in an affected section simultaneously. In fact, it expresses the expected number of the affected cars instead of a probability (Nicolet et al. 2015).

Information relative to the daily traffic needed for this evaluation may be found from public services for the administration of highways.

3.4 Vulnerability, V_i

For moving vehicles at roadways and railways, the kinetic energy during the impact is up to 1.4 times higher than for the stationary vehicles or impacts with the pavement, due to the velocity of the vehicle (Bunce et al. 1997). To define a relevant kinetic energy threshold, it can be considered that any rock with kinetic energy sufficient to damage the pavement could damage a vehicle and injure or kill its passengers. In that case, the vulnerability V_i would be 1.

To evaluate the risk for passengers, V_i should refer to the people instead of vehicles. For simplicity reasons, it is often conservatively assumed that every hit may lead to a fatality, thus the vulnerability of persons is $V_i = 1$ (Roberds 2005). However, real events indicate that slight injuries instead of fatalities are also possible. The vulnerability of persons due to rockfalls is a function of the magnitude of the event. In the case of a person being inside a vehicle, the protective role of the car/train shell in addition to the fact that only a part of the space inside the car is occupied by people, should be co-evaluated. Considering the difficulty in quantifying the latter, the vulnerability of the person might then, in a misuse of language, be replaced by the reduced vulnerability of the system of both the car and the person. Wong et al. (1997) have proposed a value of 0.3 for people inside the vehicles. If the vehicle is buried/crashed this value raises again to 1.

3.5 Rockfall Scenarios

Three scenario-based risk descriptors are assessed here, in terms of probability of occurrence. These are:

Scenario A: The annual probability of one or more vehicles being hit, as given by Eq. 15 (Bunce et al. 1997).

$$\mathbf{P1} = \sum_{\mathbf{Mi}} \mathbf{P(S1)} = \sum_{\mathbf{Mi}} \mathbf{1 - (1 - P(T{:}S))^{fa}} \tag{15}$$

where:

P(S1)	Probability of scenario A 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. 12.
f_a	Annual frequency of a rockfall of magnitude Mi (non-cumulative).

Scenario B: The probability of a vehicle being hit on a one-way trip, as given by Eq. 16.

$$\mathbf{P2} = \sum_{\mathbf{Mi}} \mathbf{P(S2)} = \sum_{\mathbf{Mi}} \mathbf{1 - (1 - P(T{:}S))^{fv}} \tag{16}$$

The Eq. 16 is similar to the Eq. 15 with two adaptations: (i) the annual frequency f_a is replaced by the f_v which is the rockfall (non-cumulative) frequency that corresponds to the duration of one trip through the dangerous area, as given by Eq. [17], and (ii) the probability P(T:S) is evaluated by Eq. 18.

$$f_v = \frac{f_a \times \dfrac{L_c(\mathrm{km})}{V_v\left(\dfrac{\mathrm{km}}{\mathrm{h}}\right)}}{365\,\mathrm{days} \times 24\,\mathrm{h}} \tag{17}$$

$$P(T{:}S) = \frac{L_v}{L_c} \tag{18}$$

where:

L_v	vehicle length (average value) (m)
L_c	road/rail section length (m)

Scenario C: The annual probability of a vehicle being hit on a daily two-way trip, given by Eq. 1.

$$\mathbf{P3} = \sum_{\mathbf{Mi}} \mathbf{P(S3)} = \mathbf{2 \times 365} \times \sum_{\mathbf{Mi}} \mathbf{1 - (1 - P(T{:}S))^{fv}} \tag{19}$$

P(T:S) and f_v are the same with scenario B.

4 Repair Costs for Damaged Transportation Corridors

The repair costs for damaged transportation corridors depend on the frequency of the events and their magnitude, which determines the extent of the damage. Repair costs should be established for different rockfall magnitude classes, depending on the type of roadway (i.e. local, regional or national) and railway. They can be assessed by Eq. 20.

$$RC = \sum_{Mi} f_a \times C \tag{20}$$

where

f_a annual frequency of a rockfall of a given class (non cumulative)

C repair cost for the affected roadway/railway.

The repair costs for a network are obtained by aggregation for all partial sections.

5 Indirect Loss Due to Closure of Transportation Corridors

Traffic detours due to rockfalls in a roadway occur due to temporary traffic interruption at the affected sections. The indirect loss is calculated here as the additional costs that result from the use of alternative paths (if any). This includes increased fuel costs in function of the distance difference, lost working-time costs for the commuters and toll difference costs. The expression to assess them is (Eq. 21):

$$\begin{aligned} \text{Daily loss} = {} & \Delta\,\text{Distance} \times \text{Fuel costs} \\ & + \Delta\,\text{Time} \times \text{Number of workers} \\ & \times \text{Working cost} \\ & + \Delta\,\text{Toll cost} \end{aligned} \tag{21}$$

6 Example

A5 is a mountainous road connecting a village with a city. In the past 10 years, rockfalls reaching the road have been inventoried in two sections of the roadway (1 km each). For the section K50–K1050: 15 rockfalls of 1 m^3 and 1 rockfall of 7 m^3 and for the section K1200–K2200: 11 rockfalls of 1 m^3 and 3 rockfalls of 5 m^3.

The average daily traffic density is $N_V = 3000$, the average vehicle length is $L_V = 6$ m, the average speed is v = 50 km/hr and the average vehicle cost is C = 30000 €. Consider for vehicles $V_i = 1$, for all rockfall classes. Calculate the risk related to vehicle(s) being hit by a rockfall using the proposed descriptors.

If the repair cost for roadway damage is 1500 € for rockfalls up to 5 m^3, and 4000 € for rockfalls of 5–50 m^3, calculate the expected average annual repair cost.

- Frequency assessment, f_a
  Section K50–K1050: 15/10 = 1.5 rockfalls of 1 m^3 and 1/10 = 0.1 rockfalls of 7 m^3 per year
  Section K1200–K2200: 11/10 = 1.1 rockfalls of 1 m^3 and 3/10 = 0.3 rockfalls of 5 m^3 per year
- Calculation of risk descriptors

Section	Rockfall volume (m^3)	fa	P(S:A) from Table 1	P(T:S) from Eq. 13	V	R from Eq. 2	N from Eq. 3	RC from Eq. 4	T_{imp} from Eq. 5	T_{dest} from Eq. 6
K50–K1050	1	1.5	0.6	0.015	1	0.0147	0.0147	441	68	68
	7	0.1	0.8	0.015	1					
K1200–K2200	1	1.1	0.6	0.015	1	0.0135	0.0135	405	74	74
	5	0.3	0.8	0.015	1					

For A5:

Total annual risk from Eq. 7: $R_T = 0.0282$

Total expected annual number of the impacted vehicles (Eq. 9): $N_T = 0.0282$

Expected annual repair cost of vehicles in the road/rail section (Eq. 10): $RC_T = 846$ €

Return period of 1 vehicle being impacted (in years) (Eq. 11): $T_{imp} = 35$

Return period for 1 vehicle being completely destroyed (in years) (Eq. 12): $T_{Tdest} = 35$

- Scenarios

Section	Rockfall volume (m^3)	f_a	f_v from Eq. 17	P(T:S) from Eq. 13
K50–K1050	1	1.5	3.42E−06	0.015
	7	0.1	2.28E−07	0.015
K1200–K2200	1	1.1	2.51E−06	0.015
	5	0.3	6.8E−07	0.015

Section	P(T:S) from Eq. 18	P(S1) from Eq. 15	P(S2) from Eq. 16	P(S3) from Eq. 19
K50–K1050	0.006	0.0224	2.06E−08	1.50E−05
	0.006	0.0015	1.37E−09	1.00E−06
K1200–K2200	0.006	0.016	1.51E−08	1.10E−05
	0.006	0.0045	4.12E−09	3.01E−06

Annual probability of one or more vehicles being hit, P1 (sum): 0.0449

Probability of a vehicle being hit on a one-way trip, P2 (sum): 4.12E−08

Annual probability of a vehicle being hit on a daily two-way trip P3 (sum): 3.01E−05

- Average annual repair cost for damage of the roadway

Section	Rockfall volume (m^3)	f_a	C (€)	RC from Eq. 20
K50–K1050	1	1.5	1500	2250
	7	0.1	4000	400
K1200–K2200	1	1.1	1500	1650
	5	0.3	4000	1200

For A5:

Total annual repair cost (sum): 5500 €

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