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Quantitative rockfall physical risk on settlements: an example

A quantitative assessment of the risk of rockfall on a local scale is a complex and challenging task since both the randomness of the natural event and the unpredictability of the behaviour of the elements at risk must be considered. From a technical standpoint, the impact of a block against a building is a phenomenon with a lot of variability, because the location of the impact point on the building (e.g. pillar, infill, roof) affects the level of damage and the possibility that the damage will spread throughout the entire structure. Similarly, impact energy can enhance the level of damage. Logic trees (or event trees) can be used to solve such problems in engineering systems. Event trees, in particular, allow a collection of probability outcomes for a given event to be calculated. As a result, if a block collides with a building, one can estimate the likelihood of hitting either a column (essential component of a concrete structure) or an infill wall (nonstructural component). Different scenarios may occur depending on the hit element, all of which can be represented using the event tree. In this technical note, an example of application of the approach is proposed to compute the physical risk on a settlement in a rockfall hazardous area.

Keywords: Event tree analysis, rockfall, building.

1. Introduction

The risk is the product of hazards, vulnerability and values of elements at risk (Scavia *et al.*, 2020). The quantification of rockfall risk on buildings is a complex task since several variables are involved (De Biagi *et al.*, 2015). On one side there is the natural phenomenon that must be correctly modelled. The quantification of the main kinematic parameters, i.e., velocity and height of the trajectory, needs specific and detailed modelling and a distribution of results rather than a single value is usually obtained as output of the propagation analyses. On the other, the physical phenomena involved when a rock boulder impacts against a structural element are non-trivial (Delhomme *et al.*, 2007; Bertand *et al.*, 2015; Ventura *et al.*, 2017).

The behavior of the construction following the impact of a falling block is the vulnerability term of the risk equation. So far, several approaches have been proposed to compute the vulnerability of

buildings. Li *et al.* (2010) proposed vulnerability curves that depend on building characteristics (construction type, material, etc.) and velocity of the landslide, with the possibility of accounting for slow and fast moving phenomena. Agliardi *et al.* (2009) analyzed the damages due to a real rockfall events on an urbanized area in North-Italy and computed a function that links block kinetic energy to the “degree of loss”. Delhomme *et al.* (2007), first, and Bertand *et al.* (2015), later, focused on the behavior of single structural components subjected to rockfall impact. Mavrouli and Corominas (2010) introduced a method to account the effects on building structure of the impact of a block against a structural member. Mavrouli *et al.* (2014) suggested the application of fragility curves to evaluate the degree of loss of buildings impacted by rockfalls. Vallero *et al.* (2020) proposed a set of calculations to evaluate the vulnerability of buildings with load bearing walls

based on the possible collapse mechanisms of structural masonry.

De Biagi *et al.* (2015) proposed an event tree risk analysis focusing on the possible failure of structural and nonstructural components of building impacted face. Differently from the previous cases, this approach considered the possibility that the impact against nonstructural components can create a harm to the occupants of the building. Although the approach allows to draw all the possible scenarios that can verify when the impact occurs, its application is still non-trivial.

The present technical note presents an example of an event-tree analysis on structural and nonstructural components of a settlement subjected by rockfalls. The physical risk, i.e., the reparation cost, is the evaluated parameter, while social and societal risks are not considered herein. The paper is organized as follows. Section 2 details the bases of event tree analysis and risk calculation, Section 3 directly jumps into the worked example.

2. Quantitative rockfall risk assessment on buildings

The adopted methodology follows the approach proposed by De Biagi *et al.* (2015). A multi-step decision

Valerio De Biagi*
Maddalena Marchelli**

* Dipartimento di Ingegneria Strutturale, Edile e Geotecnica (DISEG), Politecnico di Torino

** Dipartimento di Ingegneria per l'Ambiente, il Territorio e le Infrastrutture (DIATI), Politecnico di Torino

Corresponding author :
maddalena.marchelli@polito.it

analysis based on event-tree framework is thus considered. Event-tree is a modeling technique for scenarios derived from success and failure outcomes. The event tree starts from a single initiating event following which several possible consequences are possible. To each outcome a probability is attributed (Marchelli *et al.*, 2021). The approach accounts for the fact that a falling block can impact against a structural or a nonstructural component of the building. In the former case, the collision can engender a local damage that might propagate into a progressive collapse and causes the failure of the structure. In the latter, the damage remains local and does not propagate. The definition of the possible scenarios results from the occurrence of a sequence of events related to the local effects of the impact (local damage) and the propagation of the damage itself to the remaining part of the structure. A probability is assigned to each sub-event and the probability of each final scenario is the product of the probabilities of the events that describe it (De Biagi *et al.*, 2015).

As the vulnerability of the building depends on the magnitude of the impact, the velocity of the falling block is considered as a relevant parameter. As described in the following, a unique block mass was considered in the analysis. The total risk is thus evaluated by integrating the possible velocities with respect to their expectation, the vulnerability and the damage.

3. Case study: a settlement in a rockfall hazardous area

3.1. Description of the settlement

To illustrate the procedure previously described, a case study is herein proposed. The elements at

risk are represented by two constructions located at the foot toe of a slope along which rockfall events occur. The two buildings are part of a small trade company. Figure 1 sketches a plan view of the settlement. In the upper part, a 50 m² rectangular plan building houses the offices of the company, while a 320 m² warehouse is depicted in the bottom part.

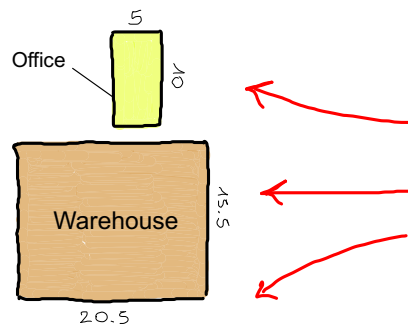


Fig. 1 – Plan of the settlement. Light grey depicts the office building, dark grey represents the warehouse. The arriving direction of the falling rocks is represented by the arrows. The sizes are in meters.

The office building is a one-floor reinforced concrete structure made of six columns (35 cm × 35 cm) disposed along a 4.8 m × 4.8 m grid, as depicted in Figure 2, and one top slab. Masonry infills are present, with a 12+12 cm thick wall. No partition walls are present in the office building. The total height of the office building is 4 m.

The warehouse is a one-floor precasted and assembled reinforced concrete structure made of six columns (50 cm × 50 cm) supporting three precasted prestressed concrete triangular beams. Roof transverse beams are hinged at the columns and the columns are hinged in the foundations. The horizontal capacity of the structure is provided by cross bracings in the cladding made of a double layer of insulating slabs with an aluminum finish. The roof is made of a lightweight steel beam grillage that supports a steel corrugated sheet. The total height of the warehouse building is 8 m at roof

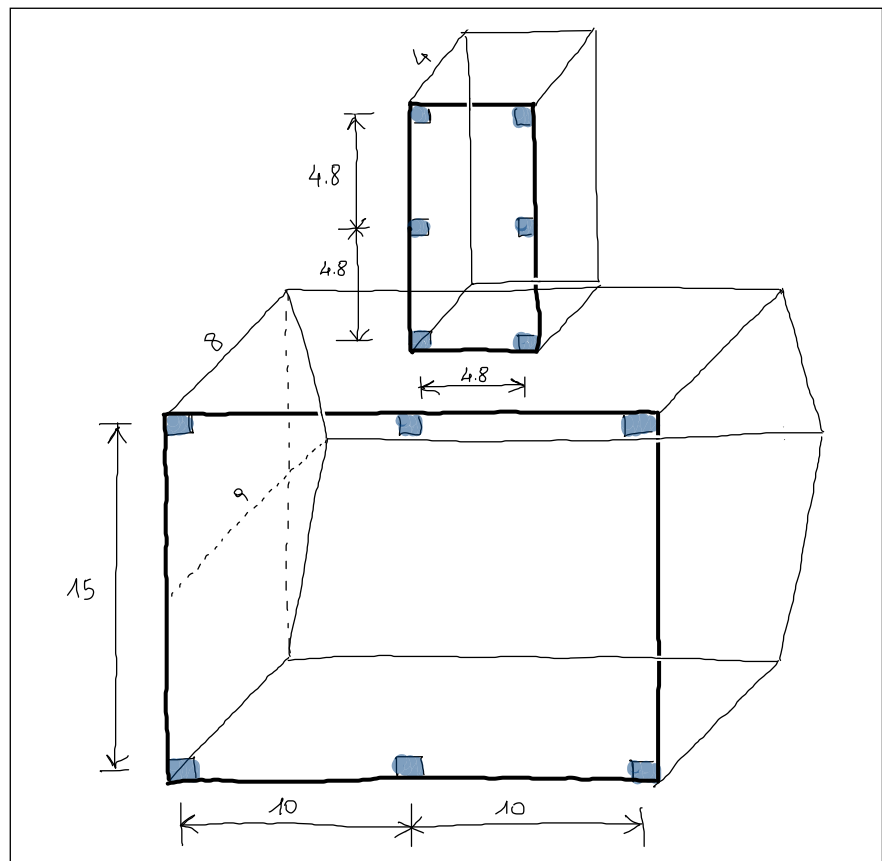


Fig. 2 – Three-dimensional view of the structures of the settlement.

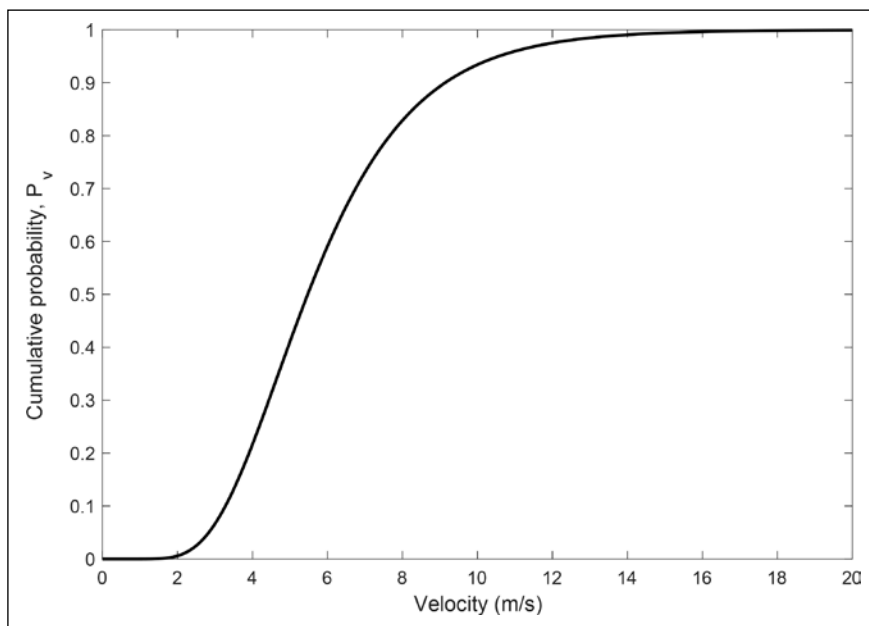


Fig. 3 – Velocity of the blocks at the settlement.

eaves and 9 m at the top of the roof.

Referring to the rockfall phenomenon, for the particular configuration of the source area, well-shaped blocks of around 0.25 m³, i.e., 500 kg, reach the inhabited area. The average frequency of the events is about 0.1 events per year. Rockfall propagation analyses provide that the cumulative distribution P_V of the velocities of the blocks at the settlement is the one represented in Figure 3.

3.2. Event tree for rockfall risk assessment

This section is devoted to the description of the event tree that describes the effects of the impact of a falling block against the two buildings. The event tree has its root on the source event, i.e., the falling block trajectory reaches the settlement. Usually, tridimensional propagation analyses provide a reaching probability or the number of simulated rockfalls that reach a particular area. Once the block arrives in the inhabited area, two possible outcomes are possible: the impact can occur on the office building or on the

warehouse. The probability that the block impacts against the office is smaller than the one that the impact occurs on the deposit since the frontal area (10 m wide) of the former is smaller than the size of the exposed face of the warehouse (15.5 m wide). Briefly, provided that the block arrives in the area, the probability of impact against the office building is $10/(10+15.5) = 0.4$, hence the probability of impact against the warehouse is 0.6.

Once the block reaches the exposed wall of the office building, it can impact against a concrete column or against an infill wall. The probability of impact against one of the two components depends on the extent of each of these along the front. The 35 cm x 35 cm concrete columns occupy roughly 10% of the face, while 90% is masonry. If the impact occurs against the masonry, depending on the kinetic energy of the moving rock, a failure of the wall is possible and the block enters and causes damages to the activity. It can be stated that when the block enters, it damages an area as wide as 4 times its diameter. On the contrary, if the falling block strikes a concrete

column, which is a structural load bearing component, depending on its kinetic energy, a failure is expected, with the possible activation of progressive collapse mechanisms. In the office building, structural system is not robust and when a column fails, half of the building collapses.

If the block reaches the exposed wall of the warehouse, it can impact against a concrete column or against the cladding. As in the previous case, the probability of impact against one of the two components depends on the extent of each of these along the front. The 50 cm x 50 cm columns occupy the 7% of the face, while 93% is cladding. If the impact occurs against the cladding, depending on the kinetic energy of the moving rock, a failure of the face is possible and the block enters and causes damages in the deposit with an extent (in width) of 4 times block diameter. If the impact occurs against a structural component, since the system is statically determined, the failure of the whole building occurs.

3.3. Damage on concrete and masonry building components

The failure probabilities of the impacted columns are computed with respect to the results proposed by Bertrand *et al.* (2015). To express the probability of failure for a given external action x , namely, the energy of the impacting block or its velocity, fragility curves can be adopted. They consist in a continuous function between 0 and 1 expressed as

$$p_f = \Phi \left[\frac{\ln(x/\mu)}{\beta} \right] \quad (1)$$

where $\Phi[^\circ]$ is the standard normal distribution, μ is the median of failure and β is the dispersion. Based on the fragility curves obtained

Tab. 1 – Parameters of the fragility curves.

Component	Building	μ (m/s)	β
Column 4 m	Office	4.0	0.17
Column 8 m	Warehouse	6.0	0.17
Infill wall (40 cm)	Office	7.5	0.12
Cladding (25 cm)	Warehouse	4.1	0.10

by Bertrand *et al.* (2015) on impacting blocks of 500 kg mass, it is possible to determine the parameters of the fragility curve for columns of different length (4 m and 8 m). Referring to masonry infills, considering the punching failure described in Vallero *et al.* (2020), the fragility curve was determined for a 40 cm thick wall ($f_c = 1\text{MPa}$). For the cladding a 25 cm thick wall was considered. The details of parameters are reported in Table 1.

3.4. Risk analysis

To estimate the physical risk of the two constructions when impacted by a rockfall, the event tree analysis was performed at various levels of velocity. Following the event tree, four damage scenarios are present:

- the block impacts against the office building, hits a concrete column causing its failure and half of the construction collapses (D1): to this scenario a physical damage of about 50 k€ is attributed
- the block impacts against the office building, hits an infill wall causing an opening (D2): to this scenario a physical damage of about 5k€ is attributed;
- the block impacts against the warehouse building, hits a concrete column causing its failure and one quarter of the construction collapses (D3): to this scenario a physical damage of about 150 k€ is attributed;
- the block impacts against the warehouse building, hits the cladding causing an opening (D4): to

this scenario a physical damage of about 20k€ is attributed. For example the damage D1 is computed as

$$D1 = 0.4 \times 0.1 \times p_f \times 50 \text{ k€} \quad (2)$$

where p_f is computed through Eq.(1) using the parameters related to “Column 4 m” component. Similarly, damages D2, D3 and D4 are evaluated. For a given velocity, the total damage is the sum of the single damages, i.e.

$$D(v) = D1 + D2 + D3 + D4 \quad (3)$$

Figure 4 depicts the values of the damage $D(v)$ at various impact velocities. Considering that a given value of the velocity is defined from the cumulative distribution determined from the propagation analysis, as

$$p_v = \frac{d}{dv} P_V \quad (4)$$

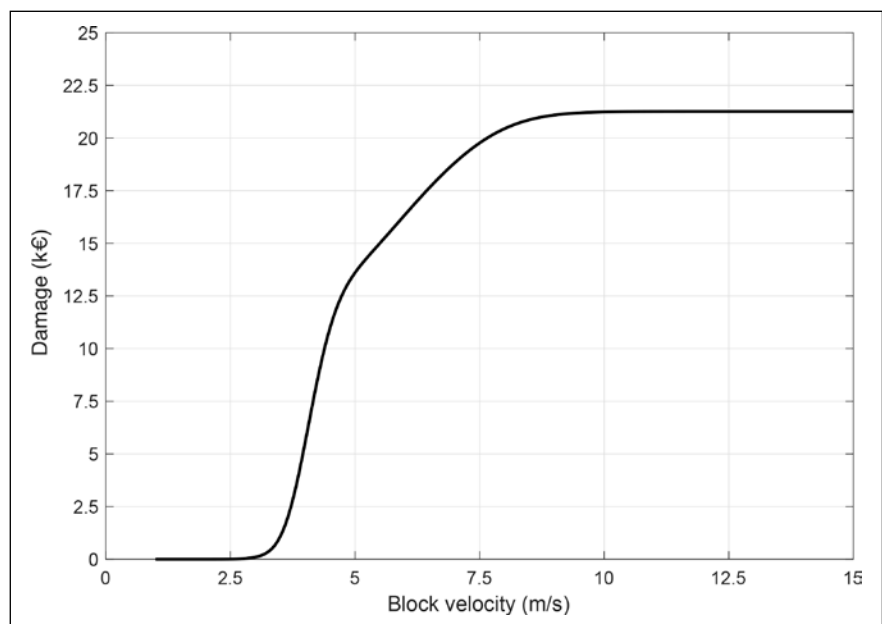


Fig. 4 – Physical damage for various impact velocities.

it results that the total risk following the occurrence an event is

$$R = \int_0^{\infty} D(v)p_v dv \quad (5)$$

In the given example, the resulting total risk is $R = 13.02 \text{ k€}$. Remembering that the annual frequency of occurrence of an event is 0.1, the annual risk is equal to 1.302 k€/year.

4. Conclusions

A quantitative assessment of the risk of rockfall on a local scale is a complex and challenging task since both the randomness of the natural event and the unpredictability of the behavior of the elements at risk must be considered. Event-tree is a logical tool that is adopted in engineered systems to understand the potential failure scenarios. Such tool, anticipated by the Authors in the quantification of rockfall risk on buildings (De Biagi *et al.*, 2015) or infrastructures (Marchelli *et al.*, 2021), has been applied to a case study. A settlement constituted of an office

building and a warehouse located in a rockfall hazardous area served as an example to show the major steps for the quantification of the risk. The proposed analysis, although simplified, shows the potentialities of the method, in particular when the structure is not simple, and structural and nonstructural components are present.

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