SOME REMARKS ON THE ROCKFALL STABILITY ANALYSIS

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Summary:

The aim of this paper is to discuss some aspects of the rockfall stability analysis, highlighting the difficulties in facing this widespread natural phenomenon. Rockfall often threatens roads, viaducts, buildings and many other structures and infrastructures, as well as people, causing serious damages, losses and injuries because of its high energy content. The complexity of this phenomenon is mainly due to its aleatory characteristic and a notable epistemic uncertainty on the parameters involved. Many contributions are available in literature on this natural hazard, but the research is still going on trying to define objective and quantitative methodologies for rockfall risk assessment.

In particular, some remarks on three of the most critical aspects of rockfall analysis at the local scale (slope scale) are reported, based on the author's experience. The importance of taking into account the vegetation in the runout simulations and the methods to do it are shown. Then, a methodology to estimate the characteristic (design) rock block to be used in forward-looking simulations and for defence works design is recalled. The paper ends with some observations on the buildings vulnerability estimation.

Key words:

Rockfall, rockfall runout analysis, design rock block, buildings vulnerability

1. INTRODUCTION

Rockfall is one of the most critical rock slope instabilities due to its high destructive potential and unpredictability. It is characterized by irreducible natural variability and epistemic uncertainty (lack of knowledge). The engineering interest on this phenomenon is due to the necessity to protect people, structures and infrastructures (villages, roads, etc.) from this widespread natural risk.

As well known, the risk is the product of hazard, vulnerability and value of the element at risk. The rockfall hazard is the probability of occurrence of a certain event, characterized by particular energy content, in a certain area and in a time interval. The energy level of a rockfall event depends on the velocity of the falling block in any point of its trajectory and its volume. The areal probability of occurrence depends on the topographic, topological and mechanical characteristics of the runout area, as well as the characteristics of the detachment area, like the rock mass structure, the presence of water and other indexes. The time probability of occurrence of a particular scenario (kinetic energy content) is the return period of the characteristic volume. The vulnerability of the usual elements at rockfall risk can be complex to evaluate and a lack of available methodologies to assess vulnerability is detected [10].Usually a 100% vulnerability is considered for people, regardless of the energy content of the event. For buildings, the local damage induced by the impulsive concentrated loads due to falling rocks impacts heavily depends on the impacted components: walls, columns, floors, windows, roofs, etc. Furthermore, the possibility of damage propagation with consequent global collapse has to be considered.

To reduce rockfall risk, different prevention and protection actions can be taken, mainly reducing hazard, exposure, value or vulnerability of elements at risk. To reduce hazard, stabilization interventions can be performed in the detachment areas or protection works (barriers, embankments) can be installed in the propagation area. In this case, the efficiency of works over time has to be guaranteed by taking into account ageing phenomena in the design phase. The vulnerability of buildings can be reduced by somehow increasing its resilience against dynamic impulses. Temporary road transit interruption or more drastic actions like relocation or evacuation can reduce people exposure. Use variation of structures and infrastructures can reduce their value. In any case, the effects of the protection/prevention actions on risk have to be evaluated by introducing them in the risk analyses and evaluating the residual risk.

It is clear that modelling rockfall triggering and runout is the basis for any risk analysis and management process. Velocities and trajectories of the falling blocks as well as their volume are, in particular, the required data. According to the interesting scheme proposed by Bedi [2], the optimum approach to be used to analyse the rockfall stability, at the scale of slope, is the stochastic one: the parameters are introduced with an appropriate statistical law and a probabilistic analysis is carried on. For this purpose, enough information on each parameter has to be available. Furthermore, due to the extreme uncertainty on some of the critical parameters, detailed historical data on events occurred in the past are necessary in order to validate the model by means of a back analysis. In fact, despite many studies have been devoted to improve the knowledge of the critical parameters, the validation process on the basis of a back analysis cannot be avoided, like in any numerical analysis, in order to obtain a good predictive model and not to make major mistakes.Back analysis can be performed on the basis of a well-documented historical event, trying to simulate as precisely as possible its blocks trajectories, end points and energy content (if the damages induced by the phenomenon are known).The model reliability is a function of the number of information available on the historical event. It is worth reminding that the back analysis has to be performed on a topographic profile or map referred to the conditions before the event.

In the following, some of the problems related to the analysisof this very complex rock slope instability,at a local scale,are discussed, based on the author's experience.

2. SOME ASPECTS OF ROCKFALL MODELLING

Rockfall hazard evaluation at a local scale (slope scale) requires a reliable simulation of blocks trajectories. Runout modelling allows estimating: paths of the falling blocks down the slope, runout distance and stop points (with which the invasion area can be defined), bounce height and velocity in any point along the rock path, and consequently the energy content. Different methods are available to analyse the rockfall runout, mainly classifiable on the basis of model dimension and assumptions on the representation of falling blocks.

Two dimensional approach is widely used because of its calculation speed that allows implementing stochastic analyses. In this case the analysis is performed on a 2D profile, obtained by estimating the most probable path of the falling rock block (usually the profile is a polygonal obtained by the combination of the maximum gradient lines). The side scattering is, however, missed. For this reason, a number of sections have to be analysed in order to well estimate the invasion area. Three dimensional models require a numerical representation of the topographic surface, for example the digital terrain models (DTM). The cells dimension of DTM influences the simulation results [7] [8] [19]: small cells allows a better representation of real topography, but too detailed maps (with cells size smaller than 1 m) can induce mistakes in the results, as discussed below. Some Authors [17] suggest optimal cells dimensions between 2 m and 10 m. The disadvantage of 3D modelling isthat it is time consuming, thus usually only parametric analyses can be performed. Only few codes allow, at this moment, stochastic analyses (for example, Rockyfor 3D[16]). It is also possible to perform the so-called almost 3D analyses, in which the analysis is carried on in a plane but the profile is chosen between the trajectories obtained by a previous 3D analysis on a DTM, or by using the GIS tool that allows to create the flow lines (the flow paths of water down the slope).

Apart from the approach used for rockfall analyses, the rock block can be simulated with three different methods [33]: lumped mass, rigid body and hybrid. The first assumes that the falling rock mass is concentrated in a point, so the trajectory and the velocities are independent of the mass, that is used only to calculate the kinetic energy. The rotational velocity is not taken into account. The rigid body method represents the block with a simplified shape, for example spherical [26], ellipsoidal [3], cubic and cylindrical [34]. The last method is a combination of the previous two and the rock block is considered a point in the flying phase of motion, but with a defined shape during sliding or rolling along the slope surface.

The methods can differ from each other also in the simulation of the different phases of block motion. Usually, the flying phase is calculated by means of ballistics laws, neglecting air friction, while sliding and rolling are simulated as a function of the contact friction characteristics or as a sequence of very frequent and low bounces. The impact of the block on the slope is always indirectly simulated by means of the restitution coefficients that provide the value of the velocity components of the block after impact as a reduction of the same components before impact. The velocity reduction, that simulates the energy dissipation due to a combination of different phenomena like friction, plastic deformation of slope and block, rock fragmentation, is a function of the slope surface mechanical characteristics.Many studies have been devoted to find correlations between the restitution coefficients and soil typologies (for example [29] [5] [6] [30] [34]). As these parameters are not measurable, they are affected by not negligible epistemic uncertainty, thus they have to be corrected on the basis of a back analysis.

All the available methods require a number of information, many of which are very difficult to obtain: location of the detachment area, topography, land cover, vegetation along the slope, mechanical characteristics of slope surface, rock block size (to be used in the simulations and for the design of rockfall protection works) and shape. As already asserted, a stochastic approach is required at the slope scale because of the nature of the phenomenon, in order to obtain probabilistic results. For this reason, most of the parameters have to be introduced with a statistical distribution and a number of simulations has to be performed, enough to guarantee the statistical validity of the results. The number of simulations required differs from one method to another, but in any case the correct number is that beyond which the result no longer changes.

In the following some of the critical aspects of rockfall simulations are discussed.

2.1. Slope topography and vegetation

A rock block that detaches from a steep area of a slope flies in the air or moves on the slope surface and the mechanical parameters involved in this contact are that of the surficial cover of the slope. Topography and any information on the shape of the slope surface (vegetation, obstacles, barriers, etc.) have to be obtained. The effects of the quality of topographic relief are not obvious, as anticipated before. In general, the higher is the DTM or profile resolution, the better is the quality of simulation results, but if the analysis is performed with the lumped mass method or the rigid body by considering a very little volume for the rock block, an extreme detail in the representation of slope surface roughness can lead to gross mistakes; in fact, the asperities can be seen by the block (or the point) as little, very deep segments of slope, also in reverse gradient, giving rise to incorrect trajectories.

A lot of studies have been carried on in the last years on the effects of vegetation on the rockfall propagation, with particular attention to long-trunked trees.The dissipation capacity of a forest, consisting in deviating, stopping or slowing the rock blocks, depends on the diameter and the density (the number of trees per unit area) of the trees. Few trees with big diameters are required to resist to the impact of large volumes of rock, while some researches demonstrated that very high density of trees with small diameters allows to stop, slow or deviate little volumes (between $0.001 m^3$ and $0.05\ m^3$). Furthermore, it was observed that deciduous trees (oaks, beeches, maples,etc.) are more resistant to rockfall impacts than conifers (larches, firs, pines etc.).

The dissipation due to the presence of vegetation is usually qualitatively simulated by reducing the rock block velocity by a defined percentage [14], or by varying the restitution coefficients [15] [25]. Only few codes (for example Rockyfor 3D) allow taking explicitly into account the forests. In these cases, mean value and standard deviation of trees diameters, trees density and typology (conifers or other) are required.These data can be obtained by in situ observationsand measurements or analysing a digital surface model (DSM) of the studied area. It is interesting to note thatthe part of the trunk that can dissipate the majority of the energy is that corresponding to the diameter at breast height, so the measure of tree diameter has to refer to that position [14]. Other vegetation typologies, like little shrubs or grass, are usually taken into account assuming adequate slope roughness, i.e. they are simulated as obstacles. A number of parametric analyses have been carried out to investigate the influence of explicit simulation of vegetation on trajectories, by means of Rockyfor3D code, on a very simple slope constituted by three surfaces with different dip representing the detachment (A, compact soil with rock blocks), runout (B, compact soil with rock blocks) and stopping areas (C, fine soil)[22]. Tree (conifers of 35 cm diameter) density in the runout and stop zones has been changed between 0 and 10.000 tree/ha and velocity and end points have been analysed. One cubic meter rock blocks have been considered. As shown in Figure 1, vegetation reduces the deposit area at the foot of the slope and the lateral deviation of the trajectories, increases the number of blocks stopped along the slope and considerably reduces block velocities, especially at the slope foot.

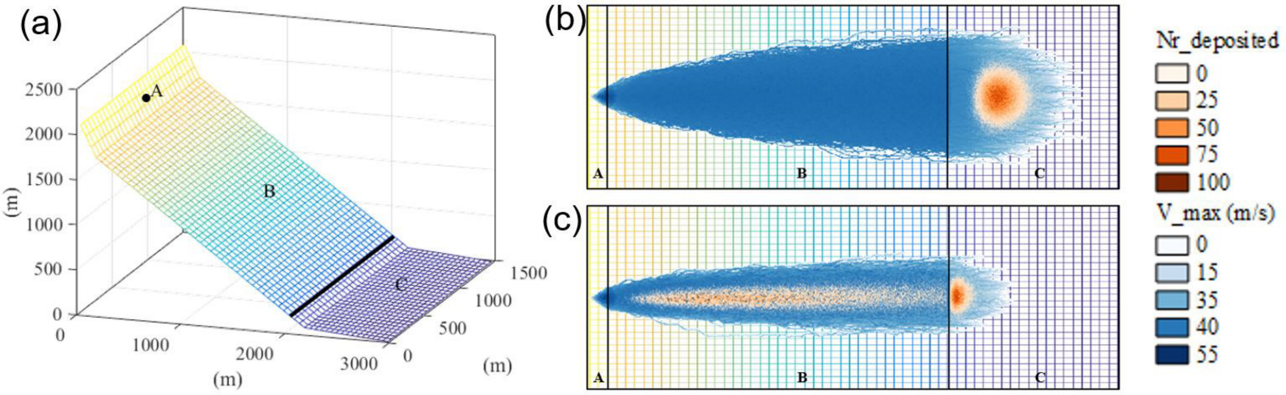


Figure 1. (a): scheme of the analysed slope. (b):maximum velocity trend and number of blocks stopped in the scenario without vegetation. (c):same parameters for the scenario with vegetation, in the case of tree density 400 trees/ha [22].

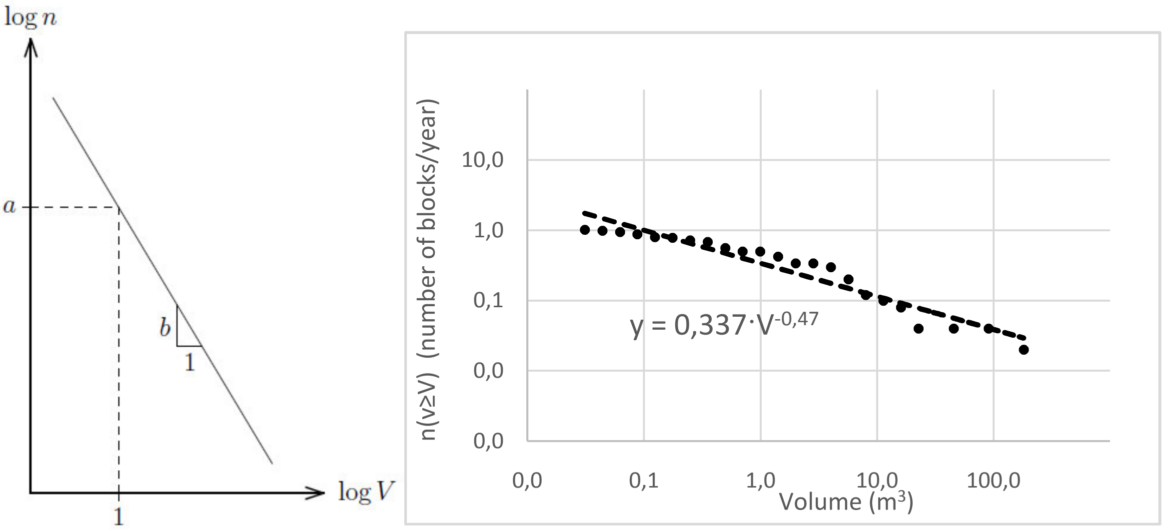
2.2. Choice of the characteristic rock block

The characteristic or design rock block is the rock volume considered in the runout modelling and in the design of protection works. It is evident that it represents the critical scenario on the basis of which the risk is calculated and the protection measures are chosen. It has also to be used for forecasting purposes. It has to represent the most probable volume that can detach from a certain slope of interest, associated to a defined return period.

Due to the difficulty to correlate rockfall events with given block volumes to a specific recurrent cause for which a return period can be defined (for example rainfalls, earthquakes etc.), historical data are fundamental for assessing the characteristic rock block. Many authors studied the possibility to correlateoccurrence probability and intensity of a rockfall event on the basis of statistical analyses of historical data distribution ([26] [20] [9] [17] [18] [1] [4] [28] [33]) founding that rock block volume and the cumulative frequency are linearly related on a log-log plotn-V (cumulative frequency versus volume) and a negative power law relationship subsists:

$$n(v \geq V) = a \times V^{-b} \quad (1)$$

where V is the block volume (in m^3), $n(v \geq V)$ is the cumulative frequency of block volume or rockfall volume (number of block of rockfall events per year, characterized by a volume higher than V), a is a constant correspondent to $N(v \geq 1)$ (cumulative frequency of block volumes larger than 1 m^3) and b is another constant representing the slope of the regression line (Figure 2 a). It can be observed that large volumes are less frequent than small ones and the power law deviates from the observed distribution for volumes smaller than a certain threshold (Figure 2b). This can be due to under-sampling of blocks with smallest volume ([4] [32]), that usually do not cause serious damages and thus are unnoticed and rarely reported in the archives.Some variability in the values assigned to power law coefficients does appear in literature.In particular, coefficient b could assume different values between 0.5 and 1.3, while coefficient a exhibits relevant variability from one site to another and is strictly linked to the number of blocks counted. This is mainly attributed to the variability in sampling procedure of the rock blocks volumes. In fact, rockfall inventories do not always contain quantitative and detailed information on historical events, thus a certain degree of uncertainty and no-homogeneity in the collected data exists. Furthermore, the interval of historical events collection can affect the recurrence volumetric distribution: in a few years records interval, for example, large volumes are underestimated.



(a) (b)

Figure 2. (a): representation of negative power law for recurrence volumetric distribution. (b): historical data and interpolation obtained for a real site in Aosta Valley (Italy)(dots are the data, dashed line is the power law)

De Biagi et al. recently proposed a novel procedure for deriving a block volume-frequency relationship in the case in which a reduced amount of data is available [11]. The methodology is based on an assumption: temporal occurrences of the falling block events are considered separatelyfrom the deposit volumesdistribution in a representative area where the rockfall phenomenonoccurs. The procedure can be summarized into five steps.

- Collecting data. For the same representative area (usually the foot of the slope), a catalogue of events, C, containing the size of the falling blocks and the corresponding date of occurrence, and a list of measured volumes, F, that may have fallen down at any time, are required.
- Defining the threshold volume. Catalogue C contains all the events recorded in a time window of temporal length t but the events are recorded after their occurrence by in situ observations and events involving small blocks are not always recorded. It is thus possible that catalogue C contains only a part of small events. To take into account this problem, the procedure introduces a threshold volume, V_t, defined as the minimum size of fallen blocks that should always been observed and recorded, after its occurrence.
- Creating a reduced data set. In both the catalogue of events and the list of measured blocks, the volumes smaller than V_t are not considered. The remaining constitute the reduced catalogue C^* and the reduced list F^*. The temporal length t is increased to t^* accounting for the fact that the decision of monitoring a rockfall prone slope usually begins after the occurrence of an event larger than the threshold volume.
- Choosing the probabilistic models. Two probabilistic models are chosen, one to describe the temporaloccurrences of the events of the reduced catalogue C^* and the other the distribution of the surveyed volumes in F^*. Poissondistribution (rare-event probabilistic law) is adopted for the former, a generalized Pareto distribution (GPD) is adopted for the latter. Poisson distribution is thus consideredfor the occurrence of the falling blocks. The probability of occurrence of n events during the observation period t^* is:

$$p(n)=\frac{e^{-\lambda t^*}(\lambda t^*)^n}{n!} \tag{2}$$

where λ is the occurrence parameter to be determined. Generalized Pareto distribution is a power like probability distribution that well fits records of list F^*. The cumulative distribution function of volume v is:

$$F_V(v) = 1 - \left(1 + \xi\frac{v-\mu}{\sigma}\right)^{-\frac{1}{\xi}} \tag{3}$$

where σ, ξ and μ are scale, shape and location parameters, respectively.

- Evaluating the parameters of the distributions.Maximum likelihood method from the reduced data sets can be used to estimate the four parameters of Poisson and Pareto distributions.Poisson distribution parameter is equal to the ratio between the number of observedevents larger than the threshold volume and t^*.The location parameter of Pareto distribution is equal to the threshold volume. Following that, the volume*v(T)* of a block corresponding to a return period T is:

$$v(T) = \mu + \left[(\lambda T)^{\xi} - 1\right]\frac{\sigma}{\xi} \tag{4}$$

and the return period, $T(v)$, corresponding to a volume v is:

$$T(v) = \frac{1}{\lambda}\left(1 + \xi\,\frac{v-\mu}{\sigma}\right)^{\frac{1}{\xi}} \tag{5}$$

Interesting applications of this procedure to case studies are reported in [11] and [12].

The described procedure can be used both for defence structures design purposes, in fact thedesign block volume can be chosen on the basis of the return period, and territorial planning, as it allows to map rockfall hazard and risk for different scenarios characterized by different characteristic volumes and correspondent return periods.However, it can be observed that in order to have a good estimation of the return period of rockfall events of the reduced catalogue, a consistent number of observations is needed. It can be asserted that this approach is affected by epistemic uncertainty, derived from the usual limited number of recorded events and surveyed blocks. In this sense De Biagi published a note on the reliability of the results obtained by the above described methodology [12], in which he estimates the errors due to missed recorded events and reduced number of measured blocks.

3. PHYSICAL VULNERABILITY

Quantify the damage induced on an inanimateelement at risk impacted by a falling rock block requires to model the impact force, as a function of the constitutive behaviour of the element and the contact law between block and element, and to evaluate the damage degree, that depends on the geometrical and mechanical characteristics of the element.In some cases, the procedure for evaluating the vulnerability is complex because two levels of damage have to be considered: local and global. Buildings, for example, are constituted of different structural elements combined in order to guarantee the global stability and robustness. The impact of a rock block can occur in any point of building (wall, window, door, roof, columns, etc.) inducing different levels of local damage. Furthermore, the possibility of damage propagation with consequent global collapse of the structure has to be taken into account.

3.1. Buildings vulnerability

As stated before, the evaluation of damage induced by rockfall on a building starts with the calculation of probability of collision. Given a number of trajectories intersecting the building, resulting from a stochastic runout analysis, it is possible to define the probability that the block impacts a component of the building through simple geometric considerations on the area of each component [10]. The impacted component can be structural (column, for example) or non-structural (windows for example). The structural component can react to the impact elastically or non-elastically, depending on its mechanical characteristics and force intensity. In the first case, the maximum stress in theelement is smaller or equal to the yielding stress of any material composing the element; in case of non-elastic response,depending on the impact forces, the element can experience a plastic behaviour or fail. This local failure can induce a propagation of damage until a global collapse, depending on the behaviour of the whole building to the localized damage.The susceptibility of a structure to global damages can be expressed in terms of fragility curves[22]. In case of damage of a non-structural component, no global failure might occur.

It is clear that the damage is strongly dependent on the structural configuration (resisting walls, frame structure) and materials (timber, concrete, masonry, steel, etc.), i.e. the effects of the interaction between an element of the building and a falling block depend on a large number of variables related both to the impact and to the impacted elements. In general, to analyse local damage, the following data must be known [10]:

- Geometry and loading conditions of each structural and non-structural element of thebuilding, in order to define a structural model of the impacted building.
- For masonry components: wall thickness and slenderness, mechanical properties of blocks and mortar, supporting conditions.
- For concrete components: cross-sectional size, length, supporting conditions, materialstrength and elastic properties, presence and type of reinforcement, structural details (e.g., nodes, stirrups).
- For other components: size, supporting conditions, material properties (strength, Young’s modulus, Poisson’s ratio, brittle vs ductile behaviour).

An interesting example of vulnerability analysis of a building exposed to rockfall is reported in [10], within a quantitative risk analysis procedure based on event tree approach.

4. CONCLUSIONS

In this paper some of the most critical problems related to the analysis of rockfall impact on people, structures and infrastructures (risk analysis), at a local scale (scale of slope) are discussed. In particular, interesting remarks are provided on the role of vegetation in the rockfall runout, the evaluation of the characteristic rock block volume for energy content evaluation and design of protection works and on the vulnerability evaluation, with particular regard to buildings. It is, in general, highlighted the extreme complexityin carrying on a quantitative reliable analysis of this rock instability, due to its aleatory character and the huge number of variables, most of which are not measurable, that influence its triggering and runout.The only reasonable approach to be used is the stochastic one, by introducing most of the parameters with a statistical distribution in a probabilistic analysis. Furthermore, runout modelling requires the validation of the model by means of a back analysis on documented events occurred in the same area in the past. To do this, a considerable number of information is needed, thus the construction of a data base of historical data as much detailed as possible is fundamental. The live interest of academic and professional communities on this natural hazard,testified by the numerous scientific papers and congresses devoted to this argument, shows that many questions are still open.Propensity to detachment of a rock mass area, simulation of existing barriers in a runout model, taking into account ageing process of each component, identification and development of damping systems to reduce buildings vulnerability, are some of the topics on which the author is working on.

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