An approach towards probabilistic design scenario for rockfall protection works

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An approach towards probabilistic design scenario for rockfall protection works

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ABSTRACT: The design of rockfall protection works relies on the evaluation of a characteristic energy value: this is usually done through 2D or 3D numerical simulations of block trajectories, from which the actual reference value of total kinetic energy at a specific location along the slope can be identified. The experience and expertise of the designers play a crucial role in the choice of the input parameters, as the process heavily depends on the choices of the reference values themselves, making the approach highly deterministic and often empirical. A possible alternative design approach would rely on the probabilistic description of the phenomenon, with distributions of the most relevant parameters instead of deterministic values. The significant advantage of this probabilistic approach lies in the rigorous statistical treatment of the parameters involved, providing in return a significantly reliable method, and the possibility to define generalized acceptable levels of residual probability.

1 INTRODUCTION

To select and properly design both active and passive rockfall mitigation works, the parameter which is usually employed as a descriptor of the process itself is the total kinetic energy (E_k), intended as the sum of both rotational and translational components. Other parameters may have significant importance in the design process of specific structures: this is the case, for example, of the bounce height of the falling block, which is required to properly identify how tall a flexible barrier or an embankment needs to be. Due to the primary importance of E_k as a design parameter, this design approach is often referred to as “Energy-based”.

The Energy-based design approach relies significantly on the expertise and experience of the designer, in virtue of how the key input parameters of the problem are described and selected. Rockfall processes are usually modeled through numerical simulations, both 2D and 3D. These simulations require the definition of a reference block volume: the choice of the value depends on the data available for the studied area (UNI 11211-3:2018; UNI 11211-4:2018). Currently, there is no standard approach regarding how to choose the reference block size value, and this responsibility falls completely on the designer. The approach is, by definition, deterministic, as only single values are identified. More importantly, the method is somewhat empirical, thus, not standardized. The most common approach consists in the measurement of a certain number of block size values, which are then averaged: this is done without even considering if a mean value has any actual meaning, or, for that matter, if a single value is enough to describe the complex nature of a real rock mass.

With these two important questions in mind, this work presents some new concepts easily implementable within the consolidated framework of the Energy-based design approach but overcoming the limitations of a purely deterministic description of the problem at hand and providing a tool for a quantitative identification of reference values.

2 MATERIALS AND METHODS

A simplified conceptual model will be introduced here. It is safe to assume that the maximum kinetic energy level a falling block will yield, if no external factor is involved, is equal to the potential energy (E_p) associated with the source area from which it detached. E_p is defined as:

$$E_p = g \cdot (\rho \cdot V) \cdot \Delta h \tag{1}$$

where g is the gravitational acceleration expressed in m/s^2, ρ the density of the material expressed in kg/m^3, V is the volume of the block in m^3 and Δh is the elevation difference, in m, between the source point and the first impact location. E_p is therefore measured in J or kJ.

In the simplest of models, g, ρ and V are constant while, if we consider only a 2D section of the slope, Δh varies in a given range depending on the position of the source area on the rockface. Source areas can be identified through the kinematic analysis of the rock outcrops. An algorithm for performing automatic kinematic analysis based on Digital Elevation Models (DEM) of the investigated area has been proposed by Taboni et al. (2022).

It is evident that this model represents an oversimplification of the real problem. In fact, if we consider a real slope as a 3D object, a range of h values is not enough to describe the real complexity of the situation. On the surface of a realistic slope, it is plausible that a given elevation value appears more than once: from this fact, it is possible to derive a histogram of frequency and, therefore, a Cumulative Distribution Function (CDF) of the elevation. Thus, it is possible to modify Eq. 1 to implement a probabilistic description of h for a given slope, replacing Δh with a CDF(h). The absolute frequency histogram is easily accessible if, for example, the slope is described as a 2.5D model, such as a raster grid of a Digital Surface Model (DSM) or Digital Elevation Model (DEM).

Similarly, a probabilistic description of the potentially detachable blocks can be performed through the concept of In-situ Block Size Distribution, or IBSD (Umili et al., 2020 and references within; Umili et al., 2023). In an IBSD, block volume is described as CDF(V), expressing the probability of not being exceeded of any given volume.

Therefore, the transition from a deterministic to a probabilistic calculation of potential energy is possible, assuming that the volume and height distributions are independent. As a consequence, the CDF of the product represented by E_p can be simply expressed as the product of their CDF, multiplied by the constants g and ρ, as follows:

$$CDF(E_p) = g \cdot \rho \cdot CDF(V) \cdot CDF(h) \tag{2}$$

In practice, the one-sample Kolmogorov-Smirnov test can be applied to find the best-fitting CDF among the hypothesized CDFs. Then, CDF(E_p) can be built through a Montecarlo simulation based on the best-fitting CDF(V) and CDF(h).

In a real case study, the reference energy parameter is not E_p, but rather E_k. Although it is true that E_k cannot be higher than E_p, the amount of energy involved in an impact event between a falling block and a defensive structure is defined by the E_k: employing E_p leads to overestimation, the degree of which depends on the processes involved along the path connecting the source area and the defensive structure, and their intensity. Friction, bouncing and fragmentation are only three major examples of energy dissipation mechanisms along the block trajectory. Although overestimating the energy involved in the impact leads to higher safety levels, it’s not a feasible design approach given how inefficient it can be. The standard practice, in fact, involves the use of both 2D and, more recently, 3D numerical simulations to quantify the design parameters. Assuming that the utilized software allows for an IBSD to be used as input, it is possible to evaluate, for a given point along a slope, the frequency distribution of E_k, and therefore its CDF, which expresses the probability of not being exceeded of E_k values.

This CDF(E_k) represents the first element of a probabilistic Design Scenario. The second element required to define key features of some specific defensive structures (embankments and flexible barriers, for instance) is the height at which the impact is expected to occur (H). Following what was done for CDF(E_k), it is similarly possible to define a CDF(H) as an output of numerical simulations. It is important to stress that this probabilistic approach works only if the reference block volume is described using an IBSD: for this reason, the IBSD is also considered as the third component of the Design Scenario.

In the following paragraph, a set of suitable synthetic examples is presented.

3 EXAMPLES AND DISCUSSION

The first and simplest model, named “case 1”, is described by Eq. 1. It has no real probabilistic components: in fact, Δh is described by n values in the interval $[h_{min}, h_{max}]$, which can be described by a uniform Probability Density Function (PDF), namely a constant probability equal to $1/(h_{max} - h_{min})$. This, in return, translates to the fact that PDF(E_p) is also expected to be uniform and CDF(E_p) a line with a slope of $(x- h_{min})/(h_{max} - h_{min})$. The resulting PDF($E_p$) and CDF($E_p$) of case 1 assuming $h_{min} = 0$, $h_{max} = 100$ m, V = 1 m^3 and $\rho = 2500$ kg/m^3 are visible in black in Fig. 1.

The second model, named “case 2”, implements Eq. 2, introducing the IBSD, described by CDF(V), while CDF(h) is equal to Δh of case 1. In particular, the IBSD was synthetically built from a Normal distribution whose mean and standard deviation are 1 m^3 and 0.2 m^3, respectively. It is worth noting that the mean corresponds to the V value used in the first deterministic case.

The introduction of this first probabilistic variable in the model removes the linearity of E_p, as now some V values are more likely to occur, as described by the IBSD. By employing a Montecarlo simulation it is possible to calculate a sufficiently large number of E_p values to describe CDF(E_p) and PDF(E_p). Clearly, a certain data dispersion has to be expected, due to the introduction of the IBSD: this second model is described by the blue curves in Fig. 1.

The third model, named “case 3”, implements Eq. 2 with both the probabilistic variables, as Δh is replaced by a CDF(h), associated with the frequency of occurrence of each h value in the Δh range on a realistic slope. In this case, CDF(h) was synthetically built based on a Gamma distribution whose mean and standard deviation are 50 m and 10 m, respectively. It is important to stress how the interval of the CDF(h) used in this third case is the same as in the original Δh of models 1 and 2. Introducing a second probabilistic variable adds to the output of Eq. 2 a higher level of dispersion, which therefore influences the shape of both the CDF(E_p) and PDF(E_p). Both are visible as red curves in Fig. 1.

As stated in the previous paragraph, using E_p to describe a rockfall scenario can lead to significant overestimation, which, although on the side of safety, leads to an inefficient design process. This problem can be overcome by employing commercially available 2D and 3D rockfall

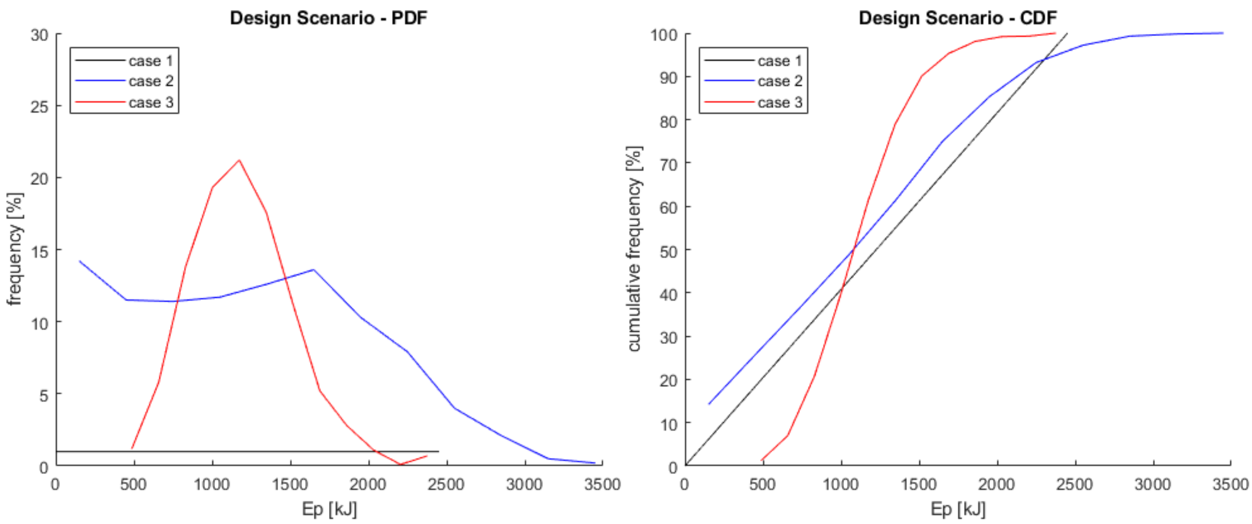

Figure 1. PDF and CDF of the three synthetic cases described: the black straight lines (case 1) correspond to a deterministic simplified description of the problem, while the blue and red lines account respectively one probabilistic variable (IBSD) in case 2 (in blue) and two probabilistic variables (IBSD and CDF(h)) in case 3 (in red).

simulation software, provided that an IBSD can be used as input. Unfortunately, this doesn't appear to be the standard.

Extracting the E_k value distribution in a selected location of the slope, it's an easy and cheap way of defining the CDF(E_k). Similarly, CDF(H) can also be produced. These two CDFs, alongside the IBSD used as input for the numerical simulations, are the three curves describing the Design Scenario of that specific position on the slope. For the third example, we identified a slope made up of a 100 m high vertical rockface, which constitutes the source area, and a 500 m long and 30° inclined lower sector. The material constituting the slope has a normal restitution coefficient (R_n) of 0.35 and a tangential restitution coefficient (R_t) of 0.85. The density of the rock is 2500 kg/m^3. Fig. 2 depicts the model, while Fig. 3 presents examples of the Design Scenario curves: the data presented here derives from numerical simulations performed with RocFall2 (Rocscience).

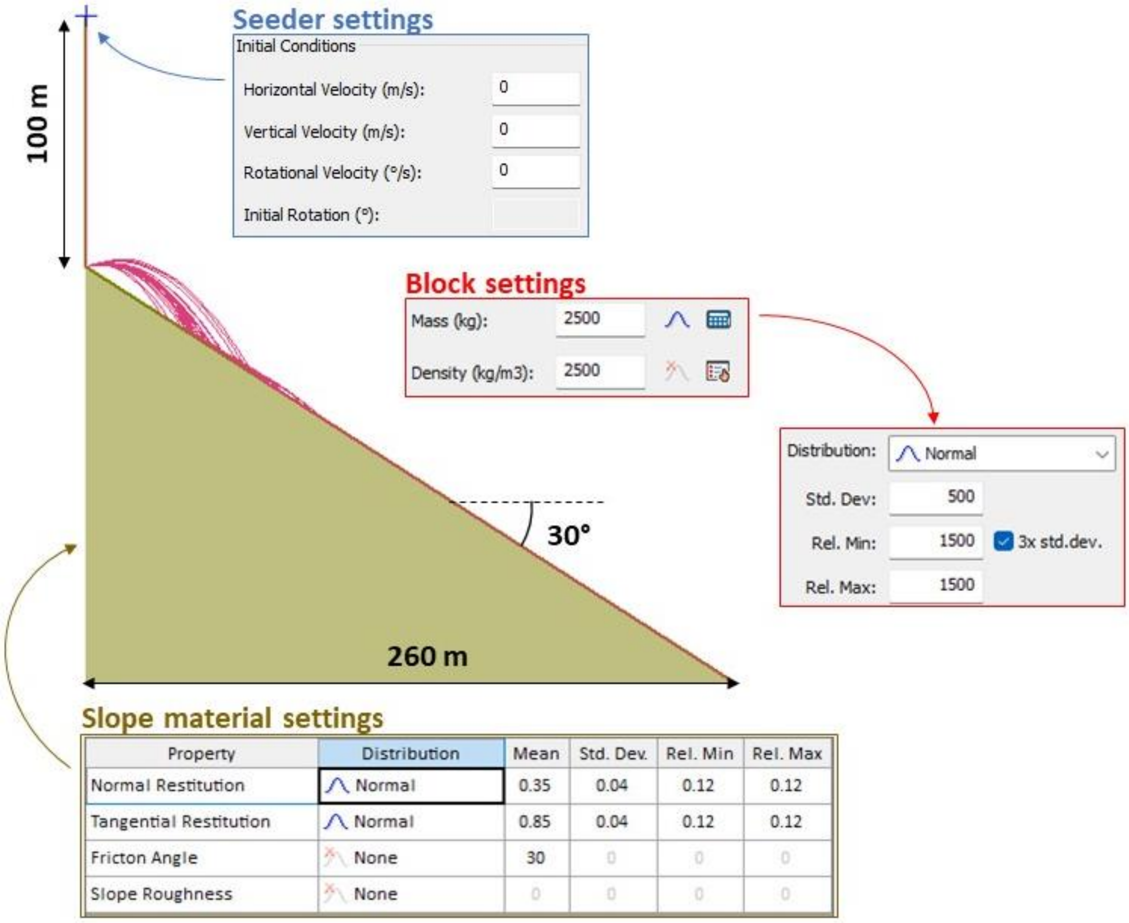

Figure 2. The simple slope model used in the third example alongside its main parameters, with some of the simulated events.

An immediate way of appreciating the usefulness of this probabilistic approach is the following: it is possible to identify the energy requirements of a defensive structure on the CDF(E_k) by setting a maximum residual probability of being exceeded, as for each probability value a corresponding E_k value can be identified. Conversely, it is also possible to evaluate quantitatively, but quickly and cheaply, the effectiveness of a given structure starting from its Service Energy Level (SEL) and identifying the corresponding probability value. In both cases, it is clear how this approach is quantitative and does not rely on empirical choices. A similar logical process can be applied in the specific case of flexible barriers or embankments, in which case the knowledge of how high a block could bounce, and therefore how high the structure is required to be, is a key design parameter. By setting a maximum residual probability of being exceeded, the correspondent H

value can be identified; conversely, the efficiency of a given design can be evaluated by identifying the probability of being exceeded associated with the height of the structure itself.

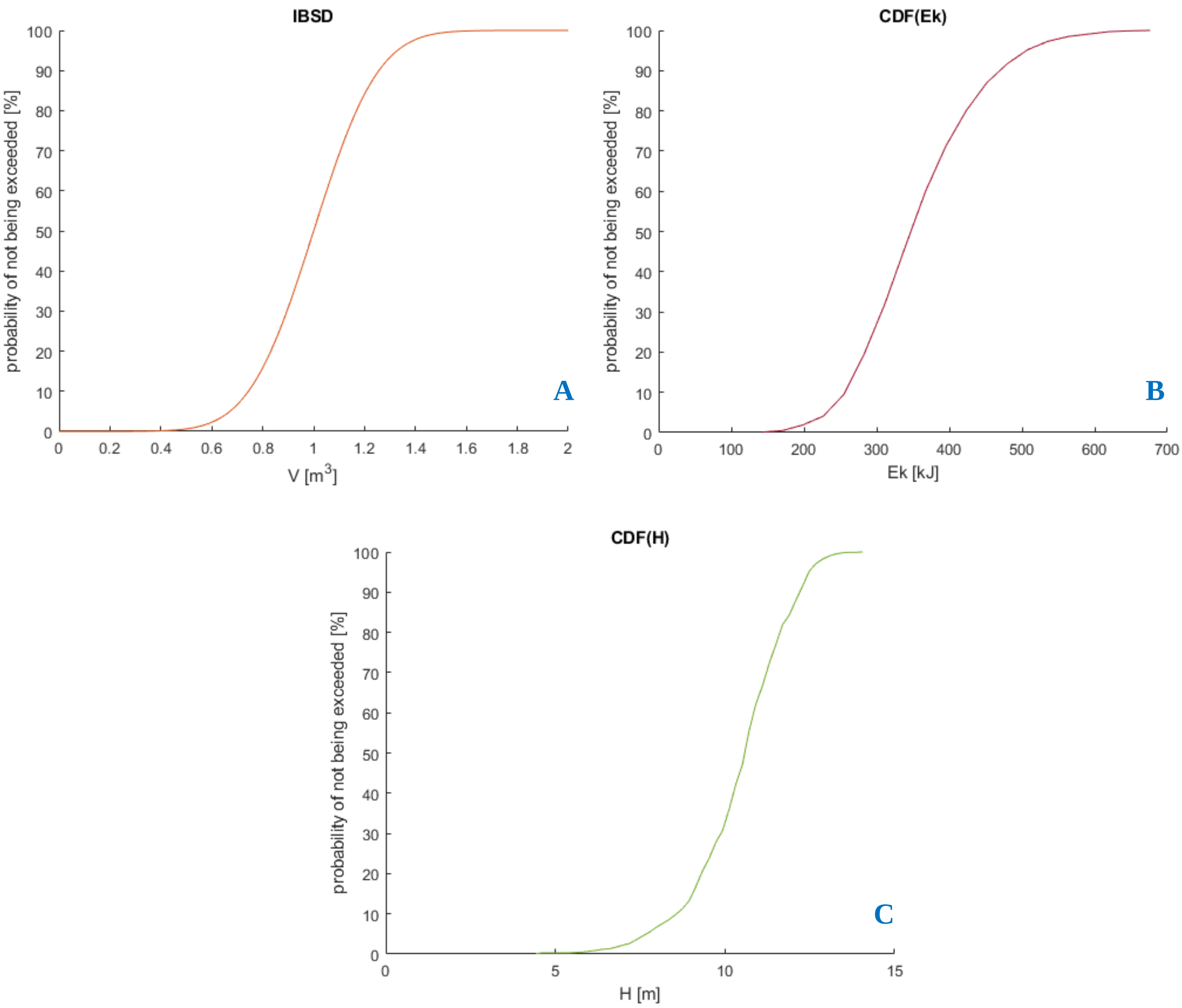

Figure 3. An example of the curves describing a Design Scenario at a certain location of the slope: the IBSD associated with the source area (A), the CDF(E_k) (B), and the CDF(H) (C). A fully probabilistic Design Scenario, such as the one here presented, provides a complete and reliable description of the problem at hand. For reference, the average block volume is equal to 1 m^3, with a standard deviation of 0.2.

4 CONCLUSIONS

The significant advantage of this probabilistic approach lies in two key features. The first one is the rigorous statistical treatment of the parameters involved, as required for the definition of the IBSD: this in return guarantees the reliability and rigor of the method, removing the need of any sort of empirical justification for the choices a designer is expected to make. Yet, the method remains simple, cheap and easily repeatable.

It is also important to note that the probability distributions of the design parameters can still be used in a traditional design approach: employing them to quantitively justify the choice of characteristic values allows for all the subsequent procedures of the traditional design approach to be performed. On the other hand, describing the phenomenon in a probabilistic way opens the possibility of employing other design methods, for example those based on failure probability.

The second advantage is the possibility to define generalized acceptable levels of residual probability, through which standardize the selection of the design parameters. In this way, the designers, who are accountable for their design choices, could be provided with a tool to deal with possible predictable consequences.

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