Towards Reliability-Based Design of rockfall hybrid barriers and attenuators: a focus on the actions

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Towards Reliability-Based Design of rockfall hybrid barriers and attenuators: a focus on the actions

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ABSTRACT: The conventional design approach for geotechnical structures presented in Eurocode 7 (EC7) shows limitations when dealing with rockfalls. To overcome these limitations, we propose the application of Reliability Based Design (RBD), which describes the relationship between the actions and the system's resistance. RBD is a fully probabilistic approach: each parameter is described by a Probability Density Function (PDF).
Considering the application of the RDB approach to new hybrid barriers and attenuators, this paper will focus on the description of the actions. To describe the rockfall process, two main parameters are identified: Total Kinetic Energy (E_k) and position of impact on the structure. This works shows how by employing robust statistical approach and a large set of numerical simulations it is possible to define the Cumulative Distribution Functions (CDFs) of these parameters. Then, using proper statistical tests, the best-fitting PDFs can be identified and employed in the RBD design approach.

1 INTRODUCTION

The standard design approach for rockfall defensive structures follows the precepts of Eurocode 7 (EC7) (2020), which in the general case of the design of geotechnical structures relies on the Limit State Design (LSD) approach. This method, although relatively simple to apply and use, manifests significant issues when dealing with non-standard geotechnical problems, such as rockfall, because the method does not account directly for the main parameters and descriptors of the actual phenomenon. This is especially true from the point of view of new protection works, such as hybrid barriers and attenuators, where the dynamic process of stopping or slowing down a falling block is significantly more complex in terms of design approach than in the case of a traditional flexible barrier. In fact, in the case of such new structures, the net does not catch the falling block, but guides it towards the ground whilst slowing it down as the net tail is not bound: an attenuator will not stop the block; a hybrid barrier will direct the block towards a collecting area where it will stop. A schematic representation of these new defensive structures is visible in Figure 1.

In fact, the traditional design approach for rockfall defensive works, both passive and active, revolves around one main parameter: the Total Kinetic Energy (E_k) of the falling block at a given location along the slope; this is the reason why it's usually referred to as Energy-based design approach. E_k directly dictates, for instance, the choice of the type of protection work, in the case of passive structures, as different structures or kits can manage only a specific energy range. E_k is a function of velocity (v) and mass (m) of the falling block; moreover, m is a function of its volume (V) and density (ρ). The relation is well-known and states that E_k is proportional to half of m multiplied by v^2. Therefore, it is easily seen that E_k, although an important feature of the rockfall process, is not a variable that can be measured or assessed; instead, it must be quantified through calculations and, by extension, numerical simulations. The actual initial condition is the choice of a reference block size: i.e., the *V* value employed in the calculations, defining the *m* of the falling block.

Given the fact that the detachable volume in a rock mass is function of the geometrical properties of the rock mass itself (i.e., spacing and orientation of the discontinuities within the rock mass), and considering the natural variability of such properties in naturally occurring rock masses, it can be seen how volume will behave in the same manner and show a significant degree of variability; consequently, a single deterministic value for *V* is intrinsically not sufficient to fully describe the problem. It has been shown that it is possible to describe block size in terms of a Cumulative Frequency Distribution (CDF), which in this case is specifically named In-situ Block Size Distribution (IBSD) (Umili *et al.*, 2020). The literature also shows how such a tool could be either used to quantitatively justify the choice of a reference value (Umili *et al.*, 2023; Taboni *et al.*, 2023), or directly employed as input for the numerical simulations (Taboni *et al.*, 2023). In the former case, the IBSD approach can be fully implemented within the methodological framework of the traditional Energy-based design approach, whilst in the latter case the probabilistic description of the parameter is passed on to the output of the calculations: i.e., E_k. In this paper, we will focus only on this specific instance.

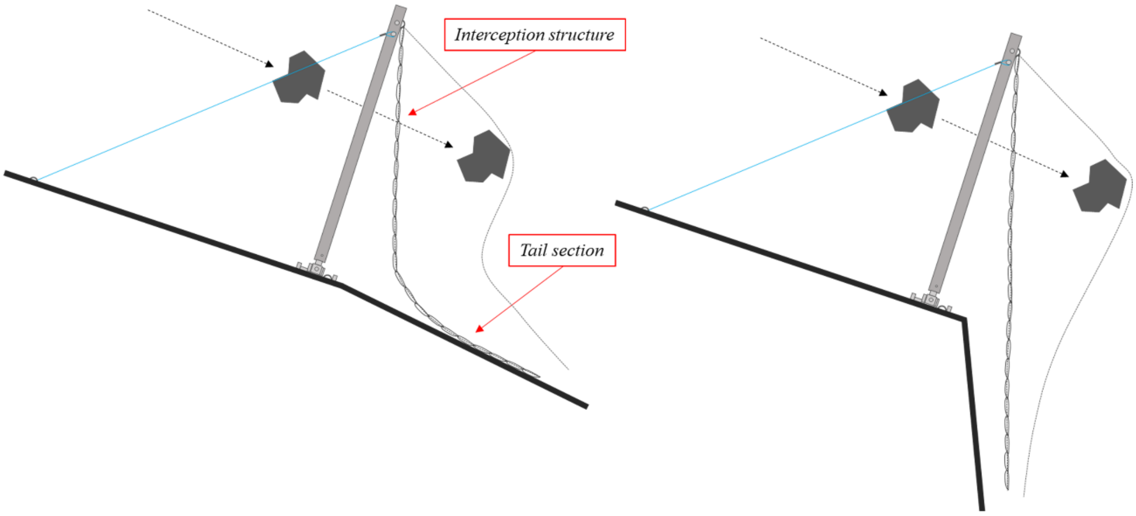

Figure 1. Schematic representation of hybrid barriers and attenuators.

As *V* was described using a CDF (the site specific IBSD), so is E_k: this poses an issue, since the standard design approach cannot account for probabilistic descriptions of the parameters, which means that in the end a single deterministic value still must be chosen. Luckily, EC7 allows for non-standard design approaches to be used: among these, the most interesting one is the Reliability Based Design (RBD) approach (Low & Tang, 1997; Low, 2007; Low, 2021), which employs probabilistic distributions of action and resistance to quantify, through an appositely defined index, the probability of failure of the protective structure. The main issue in employing such an approach lies in the fact that the inputs have to be described in terms of Probability Density Functions (PDFs), not by CDFs.

It should also be mentioned here that E_k is not the only parameter that needs to be accounted for: in the general case, the height of bounces (*B*) along the slope must be quantified to properly design passive defensive structures, as *B* is the parameter expressing where the block will hit the structure. Using a large set of numerical simulations, it is possible to construct a CDF for *B* (Taboni *et al.*, 2023).

The focus of this study is to provide a reliable, easy to repeat and rigorous method to derive the input PDFs once the frequency distributions of the actions is known. The complementary part on the resistance of a rockfall protection kit, especially in the case of new products such as hybrid barriers or attenuators, is the main topic of a paper by Carriero et al. in the Proceedings of this symposium.

2 MATERIALS AND METHODS

For simplicity's sake, in this paper we will introduce a simplified version of the rockfall problem, describing a perfectly vertical rock face, where the horizontal displacement of the falling blocks is minimal and negligible: therefore, an analytical approach is perfectly suited to describe the problem and the probabilistic description of positions is not required, since they are all considered equi-probable.

In this case, it is possible to calculate the maximum E_k as the value of Potential Energy (E_p) evaluated at a specific position (H) where a block volume (V) could detach from the rock face:

$$E_k = \rho \cdot V \cdot g \cdot H \tag{1}$$

As the rockface itself is vertical, the resulting distribution of E_k is linear for a fixed block size $\underline{V}$. Integrating the site-specific IBSD, which corresponds to CDF(V), introduces a truly probabilistic description of the problem. The CDF(V) can be obtained following its definition (Umili *et al.*, 2023):

$$CDF(V) = \frac{CDF(S_1) \cdot CDF(S_2) \cdot CDF(S_3)}{q} \tag{2}$$

where S_1, S_2 and S_3 are the spacings of the three considered discontinuity sets forming the block and q is a dimensionless number that depends only on the angles among sets.

In this way, we can construct the CDF(E_k) relative to a specific position of detachment H_i as:

$$CDF(E_k)_i = \rho \cdot CDF(V) \cdot g \cdot H_i \tag{3}$$

and repeat this operation for each H_i between the lowest and highest position of the rockfall source area. A possible way of mapping potentially unstable sectors of a rock mass is proposed in Taboni *et al.* (2022). It is worth mentioning here that outside of this simplified example, it is possible to derive the CDF(E_k) and CDF(H) for any geometry of the slope and rockface with the tools currently at our disposal: a detailed method and real case study is provided in Taboni *et al.* (2023). As the CDF(V) is built starting from a Montecarlo simulation, the same sample of volume values can be used to calculate E_k, considering different values of H. From the obtained samples of E_k it is possible to build discrete PDFs(E_k), namely histograms, and the corresponding CDFs(E_k). It is also possible to identify a distribution type (i.e., Lognormal, Gamma, etc.) and assess the parameters of the best fitting PDF(E_k). Once the best fitting PDF(E_k) is known, the application of the RBD approach is possible: employing the freely accessible spreadsheet provided by Low *et al.* (Low & Tang, 1997; Low, 2021) expressively to make the RBD approach accessible, the computational side of the method is straightforward.

3 EXAMPLES AND DISCUSSION

The proposed methodology was applied to a case study located in Bellino (Upper Varaita Valley, Piedmont Region, Northwestern Italy). The steep slope, including a large isolated rocky peak (Mt. Rocca Senghi), above a small cluster of old buildings named Grangia Cruset, was studied through a survey campaign reported in detail in Taboni *et al.* (2023).

The IBSD (Figure 2) was built by inputting in Eq. 2 the spacing distributions in Table 1, considering only a portion of the spacing database used in Taboni *et al.* (2023), and a value of q equal to 0.897. Through a Montecarlo simulation a sample of 1000 spacing values for each of the three PDF(S_i) was created, and consequently a sample of 1000 volume values was obtained with Eq. 2.

Table 1. Spacing distributions used to build the IBSD.

K1 (78/182)			**K2 (84/095)**			**K3 (39/343)**		
PDF(S_1)	μ_1 [m]	σ_1 [m]	PDF(S_2)	μ_2 [m]	σ_2 [m]	PDF(S_3)	μ_3 [m]	σ_3 [m]
Gamma	2.06	0.59	Gamma	2.10	0.48	Gamma	2.55	0.53

CDF(E_k) were then calculated through Eq. 3 considering six values of elevation H_i: 1, 10, 20, 30, 40 and 50 m (Figure 3). Subsequently, a Lognormal distribution was deemed as the more suitable type to describe the asymmetric and right skewed shape obtained. Parameters of the fitted PDFs are reported in Table 2. The comparison among the PDFs(E_k) obtained from Montecarlo samples and corresponding fitted PDFs is shown in Figure 3. Given the goodness of the performed fitting, it is possible to consider the $\mu_{lognormal}$ and $\sigma_{lognormal}$ values (Table 3) as proper descriptors of the actual PDFs. Therefore, they can be assumed as reasonable values for RBD calculation.

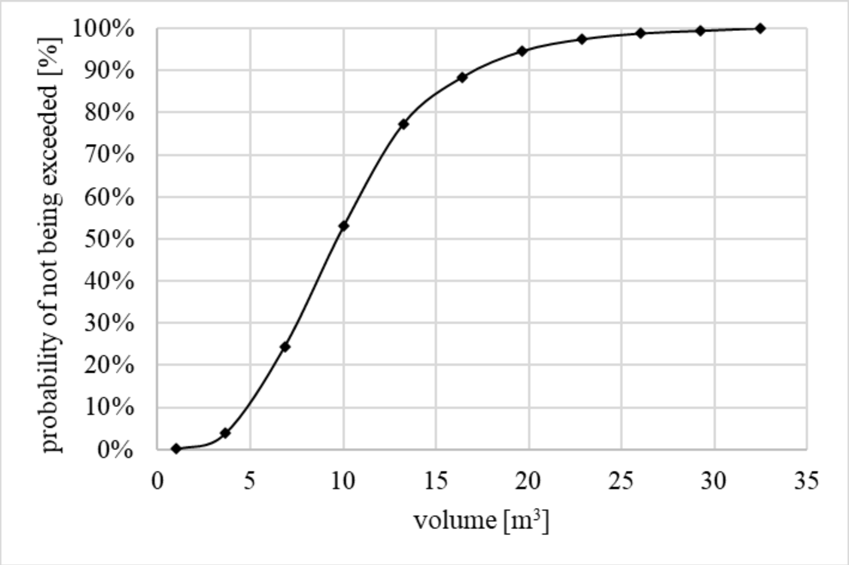

Figure 2. IBSD obtained for the case study.

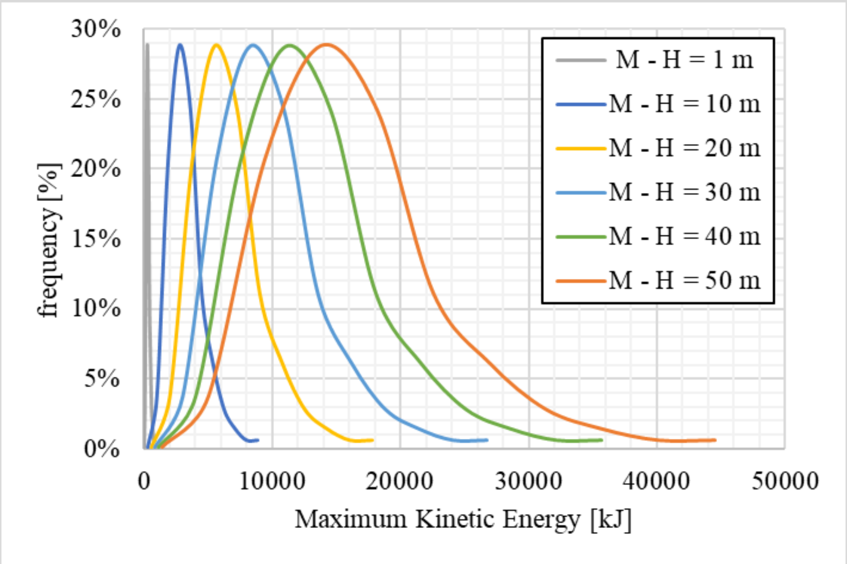

Figure 3. CDFs(E_k) calculated through Montecarlo simulation for the considered elevations H.

Table 2. Parameters of the fitted PDFs(E_k).

H [m]	1	10	20	30	40	50
μ [kJ]	331	3305	6610	9915	13220	16525
σ [kJ]	136	1362	2725	4087	5450	6812
$\mu_{lognormal}$ [kJ]	5.72	8.02	8.71	9.12	9.41	9.63
$\sigma_{lognormal}$ [kJ]	0.4	0.4	0.4	0.4	0.4	0.4

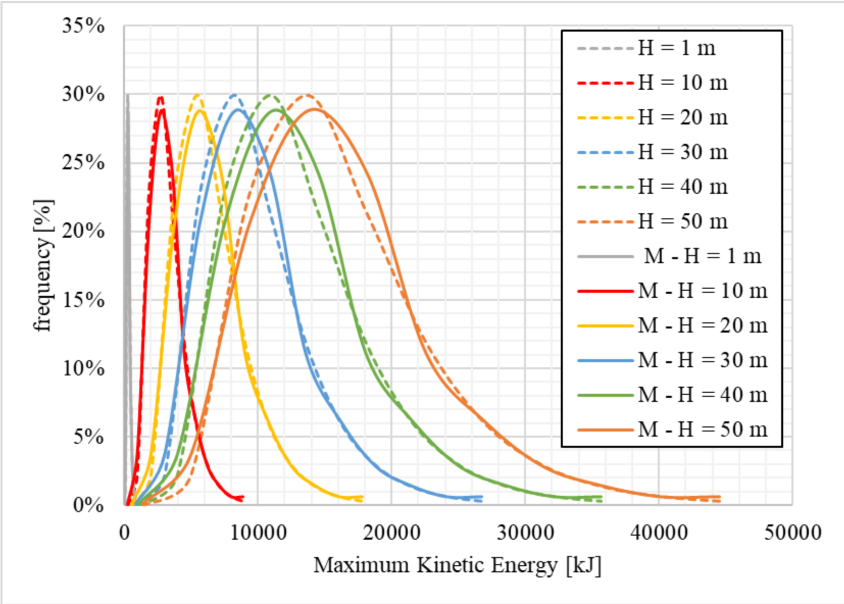

Figure 4. PDF(E_k) obtained from Montecarlo samples (continuous lines) and corresponding fitted Lognormal PDF (dashed lines) for each of the six considered fall heights H.

As it can be seen, these Lognormal PDFs fit quite well with the actual PDFs(E_k), although they tend to overestimate the probability of maximum E_k value, while slightly underestimating the peak E_k value. It should be stressed that it is always possible to quantitatively assess the fitting of a distribution employing proper statistical fitting tests, such as the Kolmogorov-Smirnov one.

Once the describing factors of the fitting PDFs are known, they can be plugged into Low's spreadsheet. As described in the Appendix of Low (2021), a Lognormal distribution of the action Q_h is accounted for through its mean ($\mu_{lognormal}$) and standard deviation ($\sigma_{lognormal}$), listed in Table 2. For the purpose of this example, to complete the inputs required to describe the resistance G_v of the hypothetical defensive structure a Lognormal distribution was employed: this distribution is described by a mean value equal to 5000 kJ and a standard deviation equal to 200 kJ. Figure 5 shows an extract from the spreadsheet, adapted to the case study, with input data and the resulting probability of failure (p_f) of the defensive structure calculated considering H = 20 m. Table 3 reports the probability of failure of the defensive structure calculated for each fall height H: as expected, p_f increases with the mean action, with a sudden growth for H above 20 m.

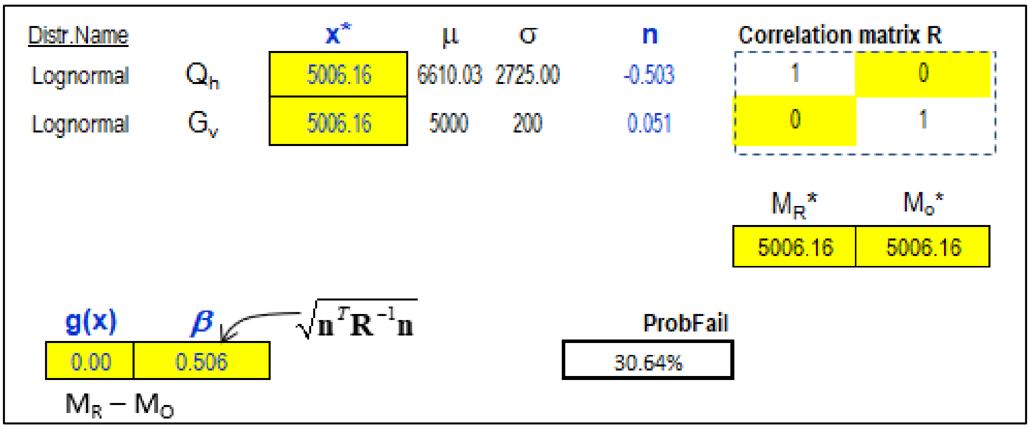

Figure 5. Extract from the Low's spreadsheet considering the case of H = 20 m.

Table 3. Probability of failure of the defensive structure calculated for each fall height H.

H [m]	1	10	20	30	40	50
p_f [-]	1.005E-12	0.108	0.306	0.936	0.988	0.998

4 CONCLUSIONS

The paper introduces a simple yet reliable and rigorous method to approach the design of rockfall protection barriers in a fully probabilistic way. The main design parameter (i.e., E_k) is described as a CDF, from which the corresponding PDF is identified employing Montecarlo simulations and fitting of proper distribution functions. The PDF is then used as input in an RBD design approach to properly introduce the effects of the rockfall phenomenon, in terms of actions exercised on the structure. Lastly, with the freely accessible spreadsheet provided by Low (2021), and assuming a simple yet realistic resistance distribution, the use of a RBD approach is presented.

The methodology here presented is simplified only in the aspects concerning the calculation of E_k: it should be noted, though, that method to properly assess the CDF(E_k) are present in literature: a real example is provided in Taboni *et al.* (2023), relying on the integration of both 3D and 2D rockfall numerical simulations.

Given the significantly higher level of complexity of the design process of new protection structures such as hybrid barriers and attenuators, the reliance on the conventional energy-based design approach is challenged by the difficulty in assessing through traditional means the effectiveness of such new structures. A RBD approach, allowed by the standing Eurocode 7, could provide a reasonable alternative.

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