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

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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 through the definition of a reliability index. In this work, particular attention has been given to innovative rockfall protection structures such as hybrid barriers and/or attenuators. Considering the applicability of RDB approach, the paper focuses on the response of these structures to the impact of the block and their absorption capacity at different stress levels. In this context, numerical modelling represents a powerful solution to reproduce the behaviour of these structures subjected to dynamic impacts at different Kinetic Energy levels.

1 INSTRUCTIONS

The conventional design approach of any type of passive protection work aiming at reducing the risk associated with rockfall is energy-based: the total kinetic energy of the falling block in a given position of its trajectory (action, in Limit State Design (LSD) terminology) must be compared to the maximum energy absorption capacity of the protection work (resistance, in LSD terminology). The LSD approach, implemented in Eurocode 7 (EC7), shows some limitations in the case of unconventional geotechnical problems such as rockfall phenomena, since the main parameters of these systems are not considered. To overcome these limitations, one proposed solution is the application of Reliability Based Design (RBD) approaches through the definition of a reliability index, a useful and complementary tool to provide geotechnical structures with a uniform probability of failure. The RBD approach deals with the relationship between the loads that a system must sup-port and the system's ability to support those loads. This is particularly useful for 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.

This paper takes into consideration the available literature and describes, in summary, the noteworthy past experiences with full-scale experimentation, referring to the test fields described in the literature. Furthermore, the last part of the paper considers numerical approaches, which are an effective solution to reproduce the behaviour of these structures subjected to dynamic impacts at different kinetic energy levels. To this end, 2D numerical simulations were carried out with the FEM software ABAQUS, starting from simplified models to identify which parameters most influence the system's response. The objective of this study is to analyse the behaviour of hybrid barriers and attenuators subjected to different energy levels and to identify which parameters most influence the system's response. The complementary part on the analysis of the actions to which these systems are subjected is the main topic of a paper by Taboni et al. in the Proceedings of this symposium.

2 STATE OF THE ART: ATTENUATORS AND HYBRID BARRIERS

Attenuators and hybrid barriers, represent a significantly more complex object of study than traditional flexible barriers. In general, be it hybrid nets or attenuators, these systems consist of an interception structure, which dissipates most of the impact energy, and a tail section that ensures that the block is carried to the desired position (Figure 1). Specifically, these systems do not stop the block by capturing and retaining it in a deformable net, but by dissipating its kinetic energy (up to 0 for hybrid barrier) and forcing it along a trajectory close to the ground or guiding it towards a collecting area. Therefore, in ideal conditions, the block does not stop within the net itself (Cerro et. al, 2016).

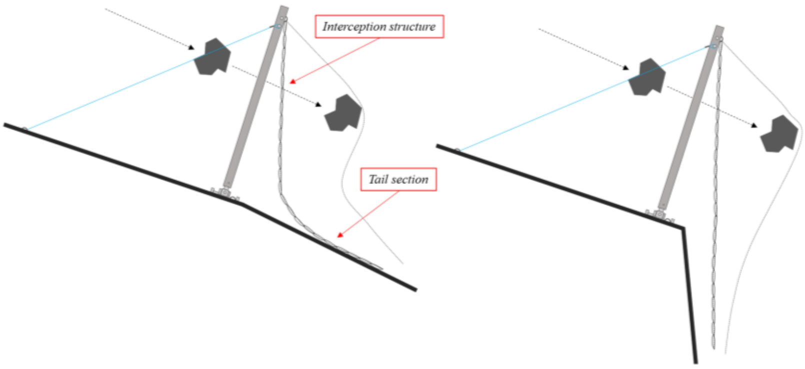


Figure 1. Schematic representation of hybrid barriers and attenuators.

Various methods and approaches are listed in the literature, both concerning the problem of the initial assessment of the behaviour of hybrid works, the study of their interaction with blocks at the time of impact and after impact, and the design phase, in which an engineer is called upon to decide shrewdly and functionally what type of work to use, how to place it, and how to size it (Glover et al. 2016; Hoffman, 2019).

Referring to rockfall structures, their design is based on the assumption that the energy retained by the block is instantaneously and completely transferred to the barrier upon impact. Consequently, this type of structure is designed with an "energy approach," comparing the kinetic energy of the falling blocks with the resistance energy of the barrier. Thus, the performance function for RBD analysis can be set as follows (3) (Vagnon et al. 2020):

$$g(x) = R_B - E_P = 0 \tag{1}$$

where R_B is the barrier resistance and E_P is the potential energy.

From equation (1) it can be seen that it is of fundamental importance to define, on the one hand, the probability distribution of the action to which the system will be subjected and, on the other hand, the probability distribution on the energy absorption capacity of the system itself.

The definition of the system resistance for structures such as attenuators or hybrid barriers is still a point of study since, although these types of structures have already been applied worldwide, knowledge of the design methodology is still lacking. Therefore, it is essential to study and analyze the response of the system through full-scale testing and numerical approaches that can highlight which parameters most affect its behavior.

A more detailed description of the application of RBD approaches can be found in the paper by Taboni et al. in the Proceedings of this symposium.

3 STUDY OF THE BEHAVIOR OF ATTENUATORS AND HYBRID BARRIERS BY FULL-SCALE TESTING

The study of the behaviour of these systems begins with full-scale testing, of which there are several examples in the literature (Arndt et al., 2009; Glover et al. 2016; Bichler and Stelzer, 2012; Hoffman, 2019). In particular, starting with the first experiments carried out by the Colorado Department of Transportation (2009) and the subsequent ones carried out in Switzerland in

2012 (Glover et al. 2016), there is significant consistency regarding several key aspects for the proper structuring of a test field that is adequate for studying the dynamics of hybrid works. Particularly, in these tests, a maximum impact kinetic energy between 250 and 500 kJ was considered by taking into account a system placed on a slope with inclinations between 35° and 50°. Both experiments highlight that a key aspect of studying the interaction between blocks and hybrid works is a non-zero rotational motion component at impact. This was achieved through configurations whereby the block rolls along a more or less inclined surface before impacting the mesh of the hybrid work. However, this approach produces significant variability both in terms of the energy associated with block motion and in terms of trajectories, and it affects the repeatability and standardization of an experimental process such as performing tests in a test field.

Other tests conducted by Bichler and Stelzer (2012) had the main objective of determining the energy absorption capabilities of the intercept structure and not the tail section. These tests considered energies of 1000 and 3000 kJ, with a slope inclination of about 45° and with the exit section constrained to the ground.. Different from the first ones, zero initial rotational energy was introduced here, and it was seen that most of the energy was absorbed during the initial impact with the interceptor structure. However, an interesting aspect recorded during the tests is the triggering of the rotational energy of the block upon impact, which therefore needs to be quantified and evaluated to analyse the energy dissipation of the system.

Lastly, tests conducted on hybrid works performed between 2015 and 2017 at a test site in British Columbia highlighted the importance of the rotational component of the rock during impact (Glover et al. 2016; Hoffman, 2019). Specifically, this site consists of a sub-vertical rock slope, about 60 m high, and the blocks are released at the top of the slope, approximately 5 meters above the ground. In these tests, a maximum impact kinetic energy between 300 and 500 kJ was considered. Analyses conducted on these tests showed that the major momentum transfer from the block to the mitigation system occurs in the initial period of impact and that the main dissipation is precisely due to the transfer of translational kinetic energy into rotational momentum upon impact with the system.

4 STUDY OF THE BEHAVIOR OF ATTENUATORS AND HYBRID BARRIERS BY NUMERICAL MODELING

Numerical modelling is a useful tool for studying the behaviour of complex structures, such as attenuators and hybrid barriers, which are made up of many elements working together under impulsive loads and dynamic conditions. Field tests are necessary to obtain a detailed idea of the behaviour of these structures, but they are time-consuming and costly, especially if each new change in the design must be studied experimentally (Escallon et al., 2015).

To analyse the influence of the variation of the different parameters (the panel's free length, constraint conditions, impact conditions, kinetic energy at impact and panel stiffness) on the response of the system, about 250 parametric analyses were carried out using a highly simplified two-dimensional model, which does not intend to reproduce the behaviour of the system, but only understand the possible influence of the panel length on deformability and actions on the structure. The analyses were performed in the explicit dynamic field (ABAQUS-Explicit), considering the elastic behaviour of the system, to evaluate the deformability conditions.

4.1 *2D model scheme*

The simplified 2D model is an equivalent model in which the panel is simulated using a two-dimensional beam element (B21). The restraint structure was considered through different constraint conditions, simulating the dynamic impact of a block, defined as a rigid body, through a 2D Shell element impacting the structure (Figure 2). The influence on the structure's response was analysed by varying several parameters: panel stiffness, constraint conditions, panel free length, impact kinetic energy, impact point and impact inclination. All the parameters considered are summarised in Table 1 below.

Table 1. Parameters considered for parametric analysis of the simplified 2D model.

Parameter		Value
Net Stiffness	S_P	Min, Med, Max
Constrain Conditions	K_{TOP} [kN/m]	10^2, 10^3, 10^4, 10^5, ∞
	K_{BOT} [kN/m]	0.5, 5, 50, ∞
Length of interception net	L [m]	12,18, 24
Impact Kinetic Energy	E [kJ]	320, 3200
Impact Point (from the top)	P_{IMP}[m]	1, 3, 5
Trajectory inclination at impact	I_{IMP}[°]	0, 20, 40

To attribute equivalent density, size and deformability to the two-dimensional element, comparable to the real one, different panels were considered, the parameters of which were derived from data present in literature [RIF PER PANNELLI]. The panels considered were identified through three levels of deformability: minimum, medium and maximum.

In addition to the deformability of the mesh panel, the deformability of the upper and lower retaining structure was also considered. The system constituting the hybrid net is completely deformable: panel, cable and supporting ropes are deformable structures, but the uprights are also connected to the base plate with a pin that allows them to rotate. The uprights, cables and load-bearing ropes have been simulated with either: a fixed constraint representing the maximum stiffness and action on the system, or with a variable stiffness elastic element to represent the deformability of the upper system from which the panel is hung. Usually, in this type of structure, the lower anchorage is limited or eliminated; therefore, the lower constraint was also simulated with a fixed constraint and a deformable constraint by reducing its stiffness. A total of four constraint schemes were considered, shown in Figure 2: the constraint system consisting of two hinges, although extremely conservative in terms of defining the structure's actions, turns out to be the most controlled numerically and in terms of the expected behaviour of the structure itself. The most representative constraint scheme of the real behaviour is certainly the one consisting of two springs, which, however, requires adequate spring calibration.

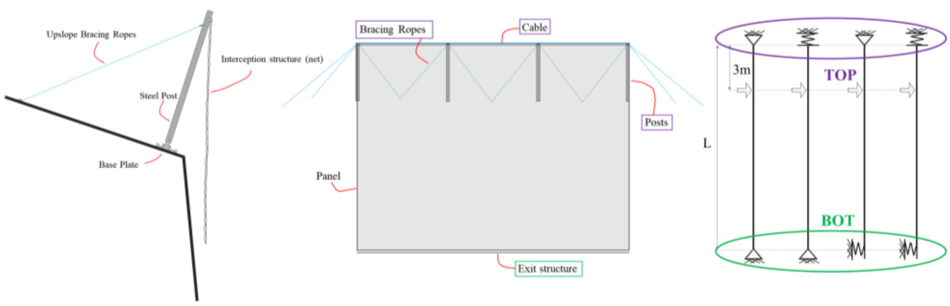


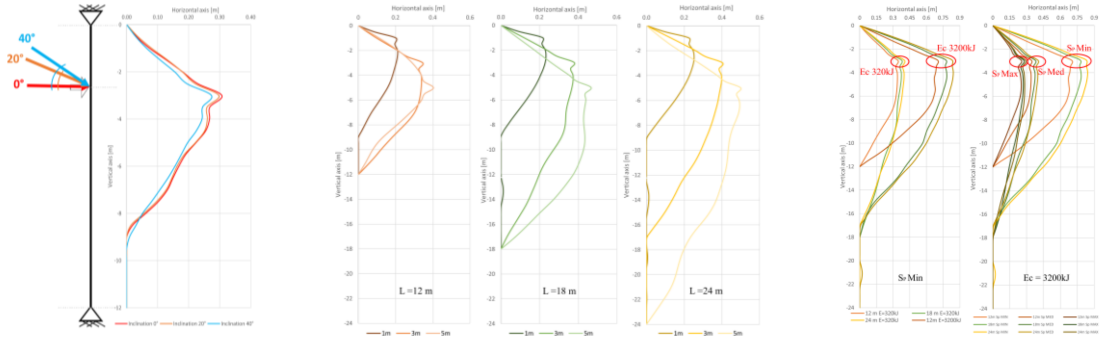
Figure 2. Scheme of the structure and representation of the constraints system used in the simplified 2D model.

4.2 *Results of parametric analysis*

To analyse the influence of the variation of the different parameters on the system's response, the variation of each parameter was analysed individually while keeping the other characteristics of the model constant.

4.2.1 *Fixed constraint system*

Firstly, the constraining system consisting of two hinges was considered, analysing the behaviour of the model under different conditions. The first aspect analysed was the impact conditions of the block, i.e. the inclination of the velocity and the position of the impact point. Figure 3a and Figure3b show the results in terms of maximum deformation, considering the three different inclinations of the velocity vector and the three different impact positions.



a) b) c)

Figure 3. Deformation of the system: a) velocity inclination b) impact position c) variation of kinetic energy and panel stiffness.

As shown in the graphs, with this simplified model, the inclination of the velocity vector does not show any significant difference in the net deformation. On the contrary, the position of the impact point affects the panel deformation: in fact, the maximum displacement is greater for impacts closer to the foot of the posts. However, this displacement variation appears to be rather small (less than 10 cm), considering impacts at 3 and 5 m. Moreover, the behaviour appears to be very similar for all lengths of 12, 18 and 24 m.

The deformation behaviour of the panel was then analysed by varying the kinetic impact energy. In this case, the panel stiffness was kept constant and equal to the minimum value. It is evident from the deformation graph (left) in Figure 3c, that larger kinetic energy values produce substantial changes even for panel lengths greater than 6 m. However, considering greater panel stiffnesses these variations are substantially reduced (Figure 3c, right).

4.2.2 *Deformable constraint systems*

The model consisting of fixed constraints is not properly representative of the deformation behaviour of the structure. In fact, the real upper and lower anchorage systems are both deformable, which is why it is necessary to analyse the influence of the latter on the maximum displacement at impact. Two conditions were analysed: the first considering a deformable constraint at the upper end and the second at the lower end, varying the stiffness. For the constraining scheme consisting of spring and hinge, analyses were carried out to evaluate the effect of spring stiffness and the effect of free length. As can be seen in Figure 4 (left), the spring stiffness has a strong influence on the action transmitted to the structure and the deformation as the length varies. For this reason, it is very important to try to evaluate this stiffness value, but it is extremely difficult to calibrate it without having full-scale test results on the structure. In contrast, Figure 4 (right) shows the results of the stiffness variation of the lower spring, which has no significant influence on the action on the structure.

Finally, the behaviour of the model with two springs was analysed by considering the influence of the panel stiffness for the three stiffness values. From Figure 5, it can be seen that, considering high kinetic energy values, the net deformation changes considerably depending on the free length: the 12 m model completely loses the dissipative effect that the panel has on the block, while from 18 m upwards the deformation returns to be similar to that expected. However, stiffer panels significantly reduce the net deformation.

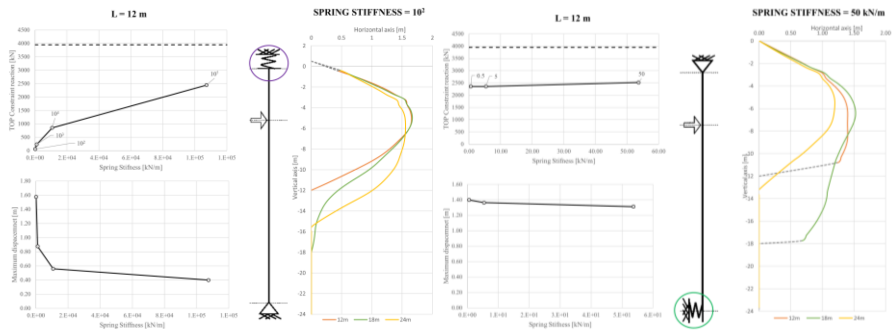


Figure 4. Result of varying upper spring stiffness, lower spring stiffness and panel length.

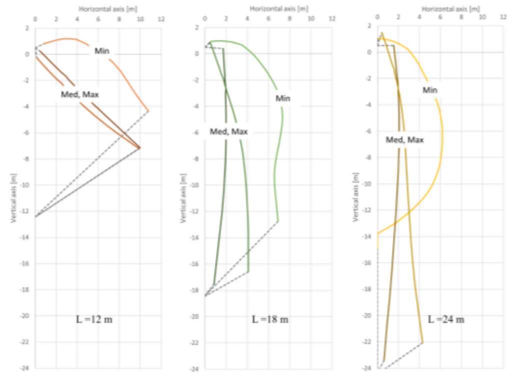


Figure 5. Variation in panel stiffness, constant impact kinetic energy of 3200 kJ.

5 CONCLUSION

The aim of this study was to analyse the behaviour of hybrid barriers and attenuators subjected to different energy levels and identify which parameters most influence the system's response. As can be seen from the results of the simplified 2D numerical analyses, the stiffness of the system and the length of the mesh panel particularly affect the response, so it is essential to carefully evaluate and define these parameters. Starting from the results of these modelling, it will be possible to define a 3D model capable of accurately reproducing the behaviour of the system.

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