The influence of a heavy storm on a slope subject to rockfall phenomena: the Bazena case study

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ABSTRACT: The evolution of rockfall phenomena depends on both rock mass and slope characteristics: variations in cover, morphology or vegetation induced by intense weather events can have huge consequences. Investigating these effects is required to assess the effectiveness of existing protection structures. This study focuses on the Bazena case (Brescia, Italy), a slope subject to rockfall phenomena, crossed by a provincial road connecting two valleys. Originally the slope was covered by a coniferous forest, which was almost completely destroyed by an extremely intense storm in 2018. In this context, the ASFORESEE model was applied to understand the value of the protection provided by the forest, over a period of 25 years. The output of ASFORESEE and other evaluations here proposed show that the forest played an active role in protecting the provincial road against rockfall phenomena. This work aims to highlight the potentiality of combining nature-based solutions and flexible barriers.

Keywords: Rockfall, flexible barrier, nature-based solution, forest, ecosystem service, economic evaluation.

1 INTRODUCTION

The study of rockfall phenomena, especially through numerical models, usually requires three steps: first, the definition of the features of the rock mass where the unstable blocks are located; secondly, the quantification of one or more reference values for the falling blocks; lastly, the characteristics of the slope must be described according to the employed approach. The definition of the rock mass properties usually is derived from in situ measurements through contact or non-contact geomechanical surveys, aiming at a proper definition of the geometric properties (i.e., orientation and spacing of discontinuities), with added information related to mechanical features (i.e., friction angle and cohesion of discontinuities) that can be either derived from empirical relations or measured in laboratory tests. This step is important in defining two aspects: the kinematic possibility of a block movement and the stability of such block. The first aspect is purely geometrical and is traditionally studied through Markland's kinematic tests, which identify the possible types of movement unstable blocks can be subjected to. This process is usually performed manually employing stereographic projections: the test needs to be performed for each orientation of the rock face, making it a time-consuming approach in case of geometrically complex or articulated situations. To speed up this process, the algorithm described in Taboni et al. (2022) was employed. As it is common practice when dealing with rockfall, stability analyses were not performed; the hazard was evaluated by simulating the trajectories of a large number of falling blocks. The definition of the reference values for block volume is a crucial issue to be solved. The problem can be approached in two ways, either describing the block volume distribution measured directly below the rock face and along the slope or from previously recorded events, or deriving it from the geometric structure of the rock mass itself. Considering also that there is no consensus in the scientific literature over the choice of the representative volume (i.e., average, modal, or specific frequency percentage) (Umili et al. 2020), two values were chosen so that a significant portion of the distribution could be taken into account. Lastly, the characterization of the slope is a key feature for numerical simulations and can be subdivided into three elements: morphology of the slope, mechanical properties, and vegetation. The first parameter is readily available using Digital Terrain Models (DTMs). The mechanical properties of the slope are generally expressed in terms of restitution coefficients, the values of which are tabulated for many different types of materials. Vegetation is not considered in most cases, employing a more conservative approach that does not account for the protective effect it can provide. In this study, we tried to evaluate the positive effects of vegetation by studying a slope subjected to an extreme weather event in 2018 that removed the forest cover almost completely. The slope is located close to the Alpe di Bazena, in the Breno municipality (Brescia province, Northern Italy): the slope is crossed by a provincial road connecting two valleys, therefore of significant importance at local level. The direct effects on rockfall were quantified with and without vegetation using Rockyfor3D code (Dorren 2016), which allows for full 3D numerical simulations. The ASFORESEE model (Accastello et al. 2019) was then applied to express the economic value of the protection provided by the vegetation assuming an optimal condition of the forest.

2 MATERIALS AND METHODS

2.1 Rock mass characterization and numerical simulations

Both rock mass and slope properties were derived from an in-situ survey carried out over the entire slope. The survey provided a significant number of joint orientation measures collected along the main rock outcrops. The in-situ block size distribution (IBSD) (Wang et al. 1993 and Lu & Latham 1999) has been derived from direct measurement of blocks along the slope and the provincial road. To completely describe the curve, two values were chosen: 0,47 m^3, with a cumulated frequency of 70%, and 2,05 m^3, with a cumulated frequency of 96%. Lastly, a detailed map of the materials and features of the slope itself was compiled. Based on this map, the model for the numerical simulations was defined. By employing the algorithm proposed in Taboni et al. (2022), the main types of movements allowed by the geometrical configuration of the rock face and the location of the source areas for the falling blocks were identified, allowing for a significant level of accuracy in the simulations. Figure 1 portraits the model of the slope and its actual conditions.

The software Rockyfor3d was employed. To properly assess the features of the slope and rock faces, the code requires ten input files: a DTM for the morphology, a map of rock density, three maps describing the dimensions of the modelled block, a map describing the block shape, three maps describing the surface roughness and a last map describing the soil type. To consider the effects of vegetation, four additional input files are required, describing tree density per hectare, average and standard deviation of the tree's diameter and the percentage of coniferous trees. The software produces a large number of output files, describing in detail the dynamics of simulated rockfall: for the present work, only three were considered: the number of passages, the number of depositions, and the kinetic energy.

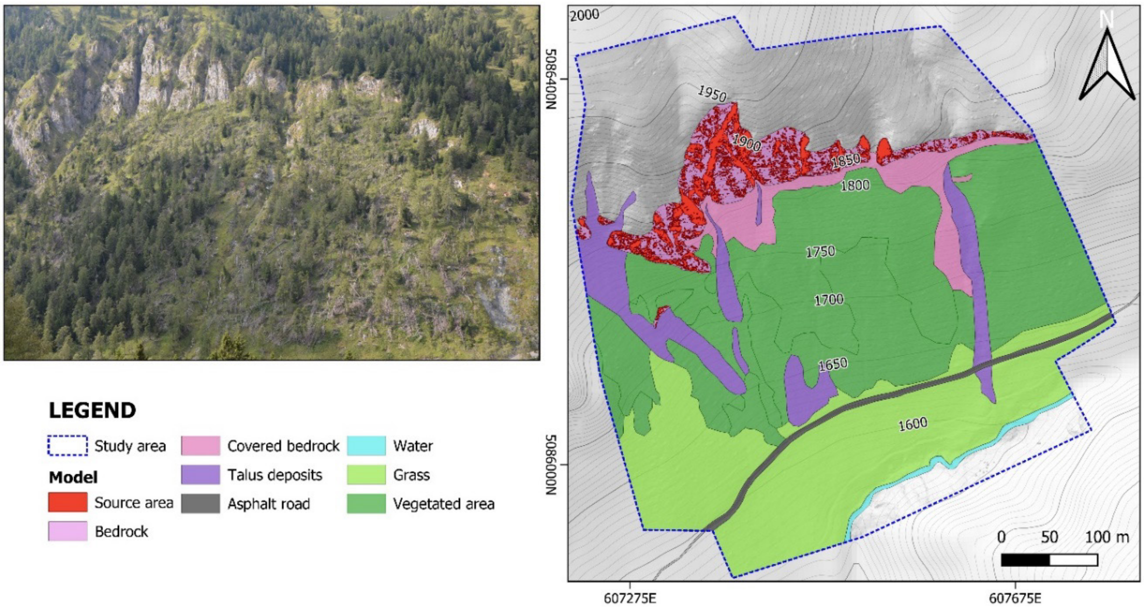

Figure 1. Slope condition after the 2018 extreme storm (left); features of the modelled slope (right).

2.2 The ASFORESEE model

ASFORESEE is a monetary economic valuation model used to assess the protection service provided by the forest against rockfall (Accastello et al. 2019). The model consists of two monetary economic methods following a deterministic approach and a probabilistic approach, respectively called Replacement Costs and Avoided Damage, both of which are based on market data available (Bruzzese et al. 2020 and Pascual et al. 2012). Specifically, the Replacement Cost method assumes that the cost of constructing artificial structures (e.g., rockfall barriers) is a proxy for the value of the protection service (Shabman & Batie 1978). The Avoided Damage method assigns a value proxy to the protection service, equal to the cost of avoided damage to infrastructures, real estate, furniture, and people, thanks to the presence of the forest (Beecher 1996). The ASFORESEE model allows for the identification of the best method for assessing the forest's protection role by considering the specific socio-economic context, the type of available input data, and the level of protection expressed by stakeholders. Figure 2 shows the working scheme of the model.

The deterministic approach was chosen for this case study because it is possible to account for the role of rockfall barriers and their construction and maintenance costs. Furthermore, the probabilistic approach is better suited for scenarios where there are multiple assets to protect and the natural risk is constant, such as in urban areas, than a provincial road with seasonal closure, where the risk is intermittent. In the Replacement Cost method, three different outputs are possible depending on whether or not the forest performs an effective protective function. In case A (Figure 2), the forest is ineffective, therefore the value considers only the forest management costs required to maintain the forest; the costs of a hypothetical defensive work are not considered. In case B, the forest is effective, but the level of protection desired by stakeholders is not satisfied, therefore the complementary presence of a smaller defensive work is required. In case C, on the other hand, the desired level of protection is satisfied: therefore, the protective value of the forest is equivalent to the hypothetical cost of constructing a defensive structure, designed neglecting the forest.

From the economic point of view, the Replacement Cost method was found to be suitable and able to estimate the value of protection role of the forest, as confirmed in a study by Bruzzese et al. (2023). Compared to other valuation methods, such as those based on stated preferences or choice experiments, this approach makes it possible to use the market prices of the selected assets to hypothetically replace the forest, minimising the subjectivity of the valuation, as stated by Notaro & Paletto (2012), while reducing the number of hypothetical data and user assumptions and ensuring its broad replicability. However, there is an inherent limitation to the application of this approach that simplifies the mechanical interaction between trees and rocks due to the need to maximise comparability with the role played by artificial structures. Although a real comparison with other studies is difficult, due to the variety of methods applied and units used to economically evaluate the role of protection, the values obtained by testing ASFORESEE on a real case study are in line with other similar experiences in the Alps, as reported in a review by Bianchi et al. (2018).

In this work, a scenario analysis was conducted to assess the effect of variations in the level of protection desired by stakeholders on the results of the economic method. In particular, the scenarios consider the risk classes reported in the National Hydrogeological Structure Plans (Autorità di Bacino Distrettuale del Fiume Po 2001), i.e., 25%, 50%, 75% and 100%, as the level of protection desired by the stakeholders.

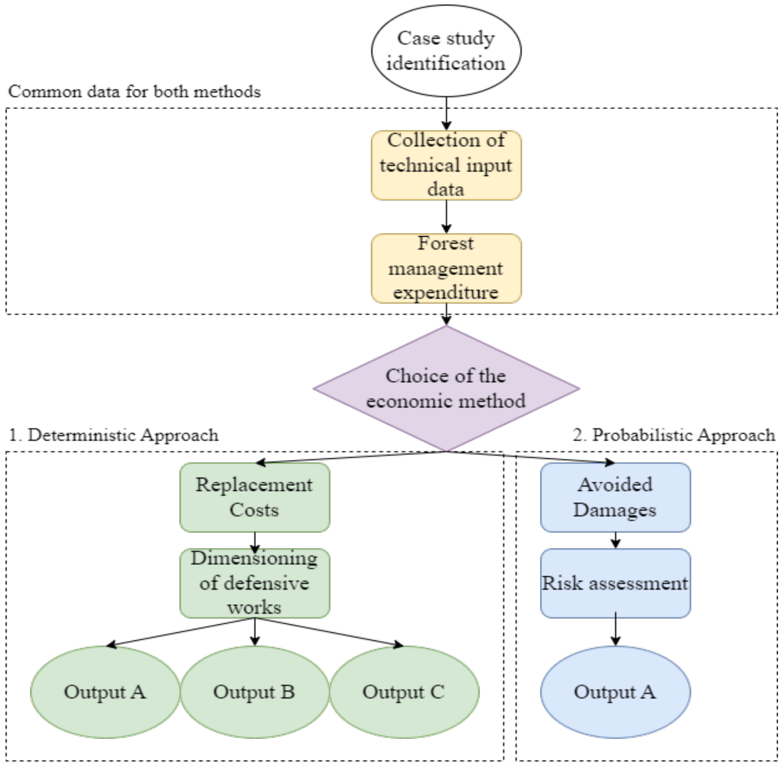

Figure 2. Functional diagram of the ASFORESEE model (modified from Accastello *et al.* 2019).

3 RESULTS AND DISCUSSION

The output files of the model without vegetation and with vegetation were compared. As shown in Figures 3 to 5, the effects of vegetation on all the three considered parameters are tangible. The diagrams describe the number of passages, deposition and kinematic energy measured directly along the exposed stretch of the provincial road. It is possible to see how, in general, the presence of vegetation produces a decrease in both the number of passing blocks and their kinetic energy, while the number of blocks stopped in the considered area increases. This is not always true, though, as in localized portions the number of passages is increased because of the morphology and the distribution of vegetated portions of the slope. For example, block trajectories tend to concentrate along two avalanche gullies where vegetation was not present even before the 2018 extreme storm, and the effects of vegetation are thus minimal. The numerical simulations performed on the Bazena slope allowed for the evaluation and quantification of the effect of vegetation on the dynamics of rockfall. It has been proven that the presence of the forest provides a non-neglectable protection effect: therefore, it can be easily seen that the consequences of the 2018 extreme storm produced a reduction in the protection provided to the road along the Bazena slope. Considering the effects of the forest, the protection contribution appears to be related to the block size: the larger the block, the less important the forest is, as the diagrams for the 96% block (2,05 m^3) testify. It is also worth noting how the modelled forest does not significantly influence the trajectories of the falling blocks.

Table 1 shows the protective value of the forest for the various scenarios assumed in different forms (overall, unit and annual). The results show that the forest effectively performs a protective

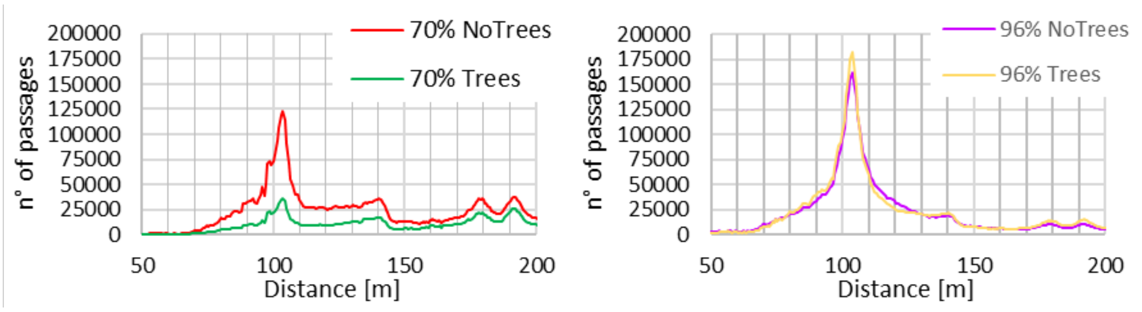

Figure 3. Distribution of the number of passages along the provincial road for the 0,47 m^3 block (left) and the 2,05 m^3 block (right).

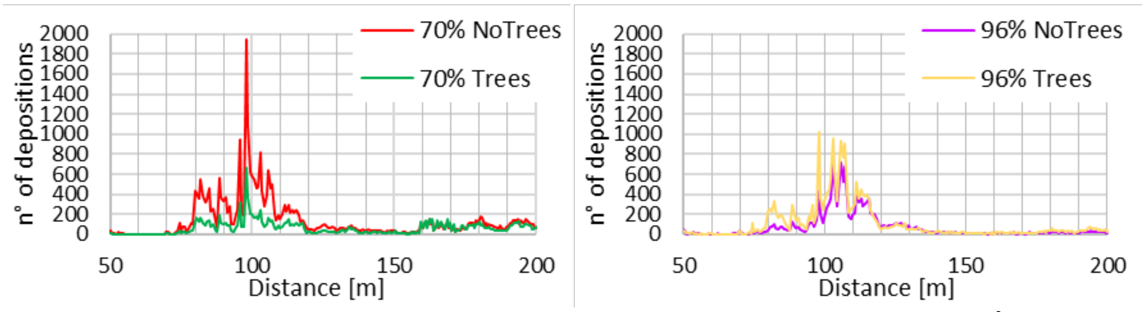

Figure 4. Distribution of the number of depositions along the provincial road for the 0,47 m^3 block (left) and the 2,05 m^3 block (right).

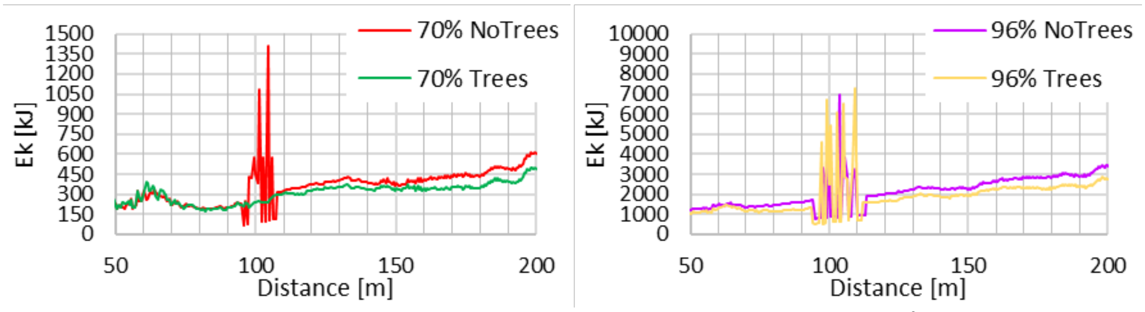

Figure 5. Distribution of the kinetic energy along the provincial road for the 0,47 m^3 block (left) and the 2,05 m^3 block (right).

function against rockfall. Given the characteristics of the element to be protected (i.e., a provincial road with seasonal frequency), the protective service provided by the forest satisfies the level of protection desired by the stakeholders for almost all scenarios, apart from the 100% scenario. In the latter case, the protective function of the forest is not sufficient, and a defensive structure (even though, undersized with respect to the one required without considering the forest effect) must be implemented, complementary to the forest. The unitary and yearly values provide more comprehensible information for decision-makers and stakeholders and highlight the high value of the service provided by the forest for the case study (about 8 ha): it reaches in both scenarios almost seven thousand euros per year per hectare, considering a duration of 25 years, approximately the estimated technical lifetime of the flexible barriers.

Table 1. Forest protection value (overall, unit and annual) of the output of the ASFORESEE model for the desired protection scenarios.

Model output	Desired level of protection [%]	Overall protection value [€]	Unitary protection value [€/ha]	Yearly protection value [€/ha/y]
C	25, 50, 75	1.823.868	223.788	6.987
B	100	1.807.072	221.727	6.922

4 CONCLUSIONS

The results obtained show the opportunity to consider protection schemes against rockfall phenomena able to integrate nature-based solutions and artificial structures. Only with such systems an adequate level of protection can be guaranteed, while reducing the use of non-renewable materials with a high environmental impact. Moreover, this choice would ensure forest management, promoting and emphasizing also other ecosystem services that support human life, such as water regulation and carbon sequestration.

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