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Surveying existing rockfall flexible barriers to create a cartographic database aimed at the maintenance planning process

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Abstract

Rockfall risk is significantly widespread in mountain areas and can produce significant damage to infrastructures and buildings. Thus, rockfall mitigation structures along slopes or at the base of rockfaces and cliffs are equally widespread. The most common ones are the flexible barriers, which are produced as kits of many different components. Each kit features a certified resistance (i.e., its service and maximum energy levels) according to specific international regulations. The resistance corresponds to the certified one at the moment of installation. Afterward, the passing of time, weathering, rust, corrosion, and impacts from falling blocks inevitably alter the conditions of the flexible barrier and reduce its effective resistance. Moreover, the slope itself and the vegetation may change. Thus, the maintenance of these structures plays a significant role.
In this sense, having a tool that can provide readily accessible, clear, and easy-to-use information on the conditions of existing structures would be crucial. Such a tool would need to provide two levels of information: a first one, describing the position of a structure and its possible need for maintenance, and a second level detailing the conditions of the barrier and an estimate of its state of damage.
This work aims to provide the means to create a database: we have developed a survey sheet that allows for a relatively fast but complete semi-quantitative survey of existing barriers. The data gathered is then automatically analysed through an Excel spreadsheet, and a level of Concern (i.e., the need for maintenance) is provided. The damage level of the barrier is also quantified. Lastly, the data derived from the surveys is conveyed through a GIS interface and by cartographic means, making it an ideal tool for planning maintenance based on the identified criticalities and priorities.

Keywords

Rockfall protection, Risk management, Rockfall barrier maintenance, Database

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1 Introduction

Rockfall risk can be high or very high. Although, in general, rockfalls do not cause the same level of economic risk as other larger landslides, their frequency of occurrence and casualties produced are on the same level (Farvaque et al. 2022). Rockfall risk is commonly addressed by employing defensive structures, divided into passive, which will interact with a falling block and either deflect it or stop it, and active, which will exercise a stabilising force on the source rock mass (Scavia et al. 2020). Rockfall is especially common in mountain environments, where the presence of such defensive structures has become a common sight (Vallero et al. 2020). These structures are subject to several processes that result in their degradation, damage, or complete loss throughout their service lifetime. Maintenance is thus a key component, as it extends their service lifetime, and ensures their effectiveness and functionality.

Rockfall flexible barriers are very often employed due to the flexibility of the design, the range of manageable energy (from 100 kJ up to 10.000 kJ), and their cost-effectiveness (Volkwein et al. 2011). Their design is also quite simple, as they are sold in standardized kits. The total kinetic energy of the rockfall is the main design parameter of passive works (Wyllie 2015); it is thus evident that maintaining such energy level through the service lifetime and beyond is of utmost importance. Maintenance prolongs the protection provided by the barrier, counteracting the effects of weathering, corrosion, vegetation growth, and rockfall impacts (Volkwein et al. 2011).

As an increase in both the number and the frequency of rockfalls in mountain areas has been related to the changing climate (Stoffel et al. 2024; Birien et al. 2024), the need for effective defensive structures is expected to increase as well, emphasizing the importance of the proper management of risk.

The practice of managing rockfall barriers and performing maintenance is a logistically complex, time-consuming, and expensive task. This is evident if we consider that it is common for one organization, whether public or private, to be responsible for a large or very large number of structures, distributed across long infrastructures or wide territories. Moreover, rockfall mitigation structures are seldom located in easily accessible locations.

Therefore, providing useful information regarding the condition of existing rockfall barriers, in the simplest yet most complete and comprehensive way possible, is a key step required to optimally plan the maintenance process. A tool capable of providing this is, to the authors' knowledge, not present in the literature. The authors set up an Excel spreadsheet-based procedure allowing for the on-site survey of the barriers through a semi-quantitative procedure guided by a specifically set up survey sheet, the evaluation of the conditions of the surveyed structures by means of quantitative indexes, and lastly, the cartographic rendering of the gathered data. This third step provides a global view of the data in a very easy-to-read manner, accessible even to non-specialized personnel.

2 Methodology

The methodology presented here was designed to be applicable to all types of rockfall flexible barriers, old and new ones alike, as it is built around a general model of flexible barrier. By analysing and comparing the technical schemes available on the European market, it was found that, in general, the most basic components of any rockfall flexible barrier are the following: the *Posts* and their foundations and anchoring; a *Net*, with or without a secondary one; the *Ropes*; the *Brakes* or energy dissipation elements. Different types, features, and numbers of these four elements define the many different commercial products available.

The *Posts* bear the weight of the structure whilst also being able to withstand direct impacts; they consist of steel beams with an H profile or, less frequently, steel tubes. *Posts* are either anchored directly to the bedrock or a concrete foundation. The *Net* intercepts and captures falling rocks. In general, the main net is either a rhombohedral wire one or a mesh of interlocking rings, each made up of many wires. When present, the secondary wire mesh is meant to catch smaller blocks. *Ropes* connect the elements of a rockfall kit and distribute the loads exercised by the weight of the structure itself and the impact-induced stresses. We separated them into longitudinal ropes (*LR*), running along the length of the structure and anchored at its sides, retaining ropes (*RR*), bound at the top of the posts and anchored upslope, and lastly, other ropes (*OR*), additional ones found either vertically or longitudinally within the main net to ensure a higher energy performance. Ropes are kept in place by their separate anchors. Lastly, *Brakes* dissipate the impact energy transmitted through the Ropes through plastic deformation. They are found on every rope, and their shape, number, position, and behaviour differ from product to product. In addition to these four main elements, the assessment of the conditions of both the slope and surrounding area around the structure completes the picture.

To survey an existing rockfall flexible barrier means identifying and describing the conditions and features of its components and evaluating damage due to impacts, weathering, or lack of maintenance. These features are fundamental to define the type and level of maintenance required and its urgency. A semi-quantitative approach has been employed to assess the conditions of the barrier: numerical ratings have been used to qualitatively describe the conditions of the structure by means of precise criteria, definitions, and measurements. Said measurements are intended to be as simple and fast as reasonably possible, avoiding time-consuming and costly techniques in favour of an observational approach, indirectly estimating the conditions of the structure and its components. This allows for a relatively fast procedure, thus rendering the survey of large numbers of barriers feasible.

An example of a semi-quantitative survey approach for rockfall flexible barriers has been proposed by Marchelli (2020): the authors identified forty-one components to be evaluated in terms of deformation, damage, corrosion, and weathering, presence of debris, blocks or other obstacles, and vegetation. Relying on a damage matrix, the level of damage of each component is scored, and a global index can be computed. The high level of detail, though, produces a significant level of complexity and, thus, a lengthy procedure focused on surveying in detail a single barrier from a structural point of view.

The aim of this study is to provide the means to construct a geodatabase that could allow for more precise and optimised maintenance of existing rockfall flexible barriers. A critical and comparative evaluation of the structures is required: the idea is to provide the information needed to identify the priority level and properly schedule maintenance. As there is currently no possibility of certifying the residual resistance of an already installed rockfall kit, the assessment of residual resistance was not considered.

We developed a survey sheet named *Flexible Barrier Survey Sheet* (FBSS) to gather the data during the inspection of flexible barriers without requiring extensive measurements. The FBSS first page requires an identification code (ID) for the structure, the geopositioning data of the initial and ending posts, and how this data was obtained (i.e., RTK network, GPS points, etc.). As the database is designed to be coupled with a Geographic Information System (GIS) interface, these data are intended as a backup.

The second page of the FBSS introduces the previously presented schematic description of the components of the barrier. Initially, general information is requested: the ID of the barrier, the height and spacing of the posts, and the number of net panels (i.e., one less than the number of posts). For each structural element, the FBSS has a specific section that must be filled out with required information (i.e., the type of net, wire diameter, etc.) and the score assigned to each element (named *Check*). Such scores range from 0 (normal condition) to 2 (highly damaged state or complete loss of functionality). These scores are the core of the entire survey and classification. To assign a score, the operator must follow the guidelines provided for each Check. There are 41 Checks in total. In the case of optional components (i.e., other ropes, brakes, secondary net), the presence or absence of said component must be stated in a specific box with a YES or NO.

Although the FBSS does not require photographs to be taken, it is still highly advisable to do so. Photos can be employed to check the survey data at a later moment. Moreover, photographs are tangible proof of the evaluations and scores attributed to the Checks.

When the survey has been carried out, the data on the FBSS can be inputted into an automatic Excel spreadsheet, which computes all the scores and classifies the surveyed structure. The Excel spreadsheet is organised into a first sheet, which is a direct copy of the FBSS and where the survey data must be inputted (*Survey Sheet*); a second one (*Elements*), with an overview of the structural data of the surveyed barrier; lastly, a third one (*Classification*) focuses on attributing a set of three parameters to the surveyed barrier. The process performed by the Excel spreadsheet is presented in Fig. 1.

The LoC describes how critical the global condition of the flexible barrier is, both in terms of damage and need for maintenance in terms of five qualitative classes (None, Minor, Low, Average, and High) and five colours (white, green, yellow, orange, and red). The LoC classification works as follows. Each Check, if present, has a *Weight*, an integer number describing the importance of the Check but with no intrinsic quantitative meaning. The *Damage* of a Check is the product of its Weight, and the score attributed to it. Four damage classes exist: no damage (*L0*), low damage (*L1*), medium damage (*L2*), and high damage (*L3*). The maximum Damage is twice the Weight, as 2 is the highest possible score. The following Fig. 1 presents the structure of the spreadsheet in the case of the section regarding the posts. Computing the percentage of the four damage classes, the spreadsheet attributes the barrier to one of the five LoC according to the definitions presented in Table 1.

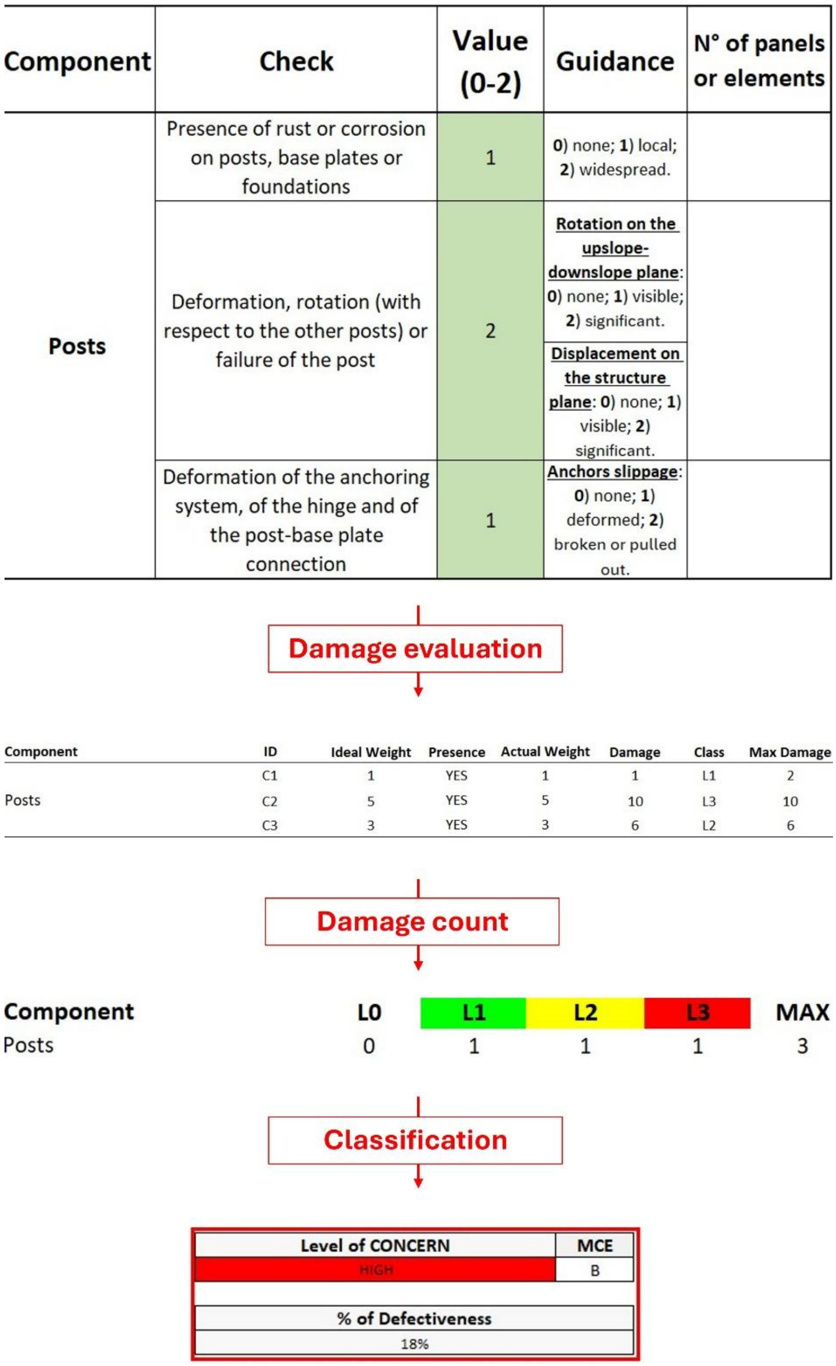

Figure 1 Example of how the Excel spreadsheet works, in this specific case regarding the posts. Once the Value is inserted into the Survey Sheet, the spreadsheet automatically computes the parameters describing the Weight and Damage associated with the element; it then counts how many Checks display each of the four damage classes and provides a classification for the surveyed barrier.

Table 1 Logical rules for the five LoC classes.

Level of Concern	Conditions
High	$L3 > 0 \cup L2 \geq n * T$
Average	$T \leq L2 < n * T$
Low	$L1 > T \cup L1 \leq L2$
Minor	$L1 < T \cup L1 > L2$
None	$L0 = 100\%$

In the equations, *T* describes the threshold between classes, whilst *n* is a multiplier factor. The operator can freely set both to adapt the classification to the required one. Default values are *T* = 33% and *n* = 2. The MCE is just a letter that details if the most critical features, i.e., those with an L3 damage level, are related either to the structural elements of the barrier (Barrier, *B*), to the general slope or environmental

conditions (Slope, *S*) or both at once (*B+S*). This was introduced to help discriminate if a High LoC barrier needs structural maintenance or just a clean-up of its surrounding area.
Lastly, the $\%_D$ is the percentage of damage calculated as the sum of the Damage values over the maximum Damage sum possible for that barrier. It can be seen as a descriptor of the working conditions of the structure: for example, high $\%_D$ describes a severely damaged, thus poorly effective structure. A newly installed flexible barrier is expected to have $\%_D = 0$. LoC, MCE, and $\%_D$ are visible in a specific table at the bottom right of the third sheet.
Once data has been collected and analysed, the actual database can be constructed. The proposal presented here takes advantage of the structure of *shapefile* and other vectorial datasets (specifically *polylines*) in a GIS (Geographic Information System) environment, which can store both the geopositioning data and additional information within an *attribute table*. Such data can then be employed to construct a cartographic rendering to better convey the informative content of the database. In our specific case, the minimum required information should describe the position of the barrier, its ID, LoC class, $\%_{D,}$ and MCE, if applicable. Graphically, the LoC class can be then used to define the colour of the polyline describing the barrier, while the ID and other indexes can be displayed as text along the polyline. The data should be plotted against a topographic rendering of the study area, a satellite image, or an orthophoto.
Of course, any other information surveyed or computed by the Excel spreadsheet can be added as well. This makes the data easier to read, even for non-specialized personnel. It also allows for the representation of large quantities of data and/or spread over a wide area, without limiting data readability. This is an optimal solution, specifically in the case of linear infrastructures, such as highways, mountain roads, and railways. The main drawback of this approach is the production of geo-referenced shapefiles: this step is potentially significantly time-consuming. A more detailed description of the structure of the database and the methodology employed is presented in Taboni et al. (2024), alongside the FBSS and Excel spreadsheet.

3 Results and Discussions

The case study presented in this section consists of a steep slope cut by a significant road connecting two adjacent valleys in the Italian Central Alps (45°55'11.6" N, 10°23'13.8" E). At the top of the slope, a 200 m high rock face overhangs the road: such rock mass is the source of frequent rockfalls and, during winter months, avalanches. The authority managing the road has installed several rockfall flexible barriers throughout the decades, to protect the most vulnerable portions of the road. Two of those existing barriers have been surveyed and analysed using the methodology presented in the previous paragraph. The first barrier is visible in Fig. 2.

The components of the first barrier feature a main net panel of rhombohedral wire mesh with 8 mm wire and a mesh diameter of 300 mm. The posts are 4 m tall H beams positioned every 6 m, supporting ten net panels for a total length of 60 m; each post is fixed in place thanks to four anchors. Along the structure, only retaining ropes (RR) can be seen, with a 15 mm diameter; on each rope there is a black box containing a braking element. Globally, the main net and the ropes feature localised patches of rust and corrosion, while the posts are almost entirely covered in rust. The foundations of the posts are working as intended and do not seem damaged. The opposite is true for the RR anchors, which are completely non-functioning and can be easily pulled out, even by hand. No information regarding the design energy capacity of this flexible barrier was available. It clearly appears to be older than the European standards imposed by ETAG 027 (EOTA 2008). The portion of the slope surrounding the barrier is characterised by pine trees, a couple of which have fallen on the barrier itself or close to it, as visible in Figure 1, but caused only limited damage. Besides this, no bushes or vines grow on the structure, and the slope beneath it is generally clear of obstacles.
The data gathered on the FBSS allowed us to classify this first barrier (Fig. 2).

Level of CONCERN	MCE
HIGH	B

% of Defectiveness
49%

Fig. 2 Photograph of the first surveyed barrier: it appears highly damaged. In some sections, it has been completely torn apart. On the right is the classification in terms of LoC, %D and MCE.

The classification highlights that the barrier must be significantly repaired and, at least in some sections, completely replaced, as pointed out by the high Level of Concern; moreover, the structure Defectiveness is very close to 50%, which means that approximately half of the structure cannot carry out its role and, thus, provide protection. The MCE is the barrier itself (B), as the surrounding area does not influence the protective performance of the structure particularly negatively. On the contrary, many elements of the barrier are heavily corroded and rusted, while most rope anchors do not work correctly.

The components of the second barrier (Fig. 3) feature a main net panel of interlocking rings with 14 mm wire and a ring diameter of 350 mm; a secondary wire mesh net supplements the main one. The posts are 6 m tall H beams positioned every 10 m, supporting seven net panels for a total length of 70 m; each post is fixed in place through four anchors and two ropes. The structure features retaining ropes (RR) and longitudinal ropes (LR), both with a 22 mm diameter; each rope is equipped with a brake. Globally, very scarce and limited patches of corrosion or rust have been identified on the ropes and posts. The foundations of the posts and the rope anchors are in perfect condition and working as intended. Along the structure, a few of the net panels have gaps beneath them, which would allow small blocks to pass through them. The main issue with this second barrier lies in the fact that four large pine trees have grown very close to the barrier itself. Additionally, close to the end of the barriers, just below one of the panels, a couple of large boulders can be found. These, alongside the trees, would significantly limit the proper functioning of the structure in the event of a rock hitting those portions of the barrier. Besides this, the portion of the slope surrounding the barrier is clear of vegetation, although bushes and vines have started colonizing the ropes and their anchors. This barrier conforms to European standards and, thus, is more recent than ETAG 027 (EOTA 2008). The data gathered on the FBSS allowed us to classify this second barrier (Fig. 3).

Level of CONCERN	MCE
LOW	/

% of Defectiveness
8%

Fig. 3 Photograph of the second surveyed barrier: it appears in very good conditions, although pine trees grow very close to the structure. On the right is the classification in terms of LoC, %D and MCE.

The classification highlights that the barrier needs only marginal maintenance, as pointed out by the low Level of Concern; the structure Defectiveness is lower than 10%, as the structure has only marginal issues related to trees and boulders too close to the barrier. No MCE is defined, as no L3 check has been identified.

The survey was performed by a trained operator equipped with a tablet. The editable FBSS Excel sheet was used to assign the score to each element. At the same time, the camera was used to acquire images of the entire barrier and details of the inspected elements. It is worth mentioning that it took approximately 20 minutes to survey each of the two barriers.
Implementing the data just described in the GIS environment yields the map in Fig. 4, where the polyline describing the shapefile of the two surveyed barriers is coloured according to the LoC class. Additional data has also been displayed. Fig. 5 presents how the data stored in the shapefile is presented when the line is interrogated.
In this specific case, we chose to show as much information as available on the map: thus, the colour of the polyline is dictated by the LoC, and for each barrier, the ID, the MCE, and the decimal value of $\%_D$. In the case of the second barrier, no MCE has been identified and isn't shown.
It is evident how immediate and intuitive it is to represent the gathered data through these means: the information can easily be understood even by non-specialized personnel. By means of such representation, it is also equally simple to identify the sites and barriers with the most urgent need of maintenance, allowing for optimal organization of the required actions.

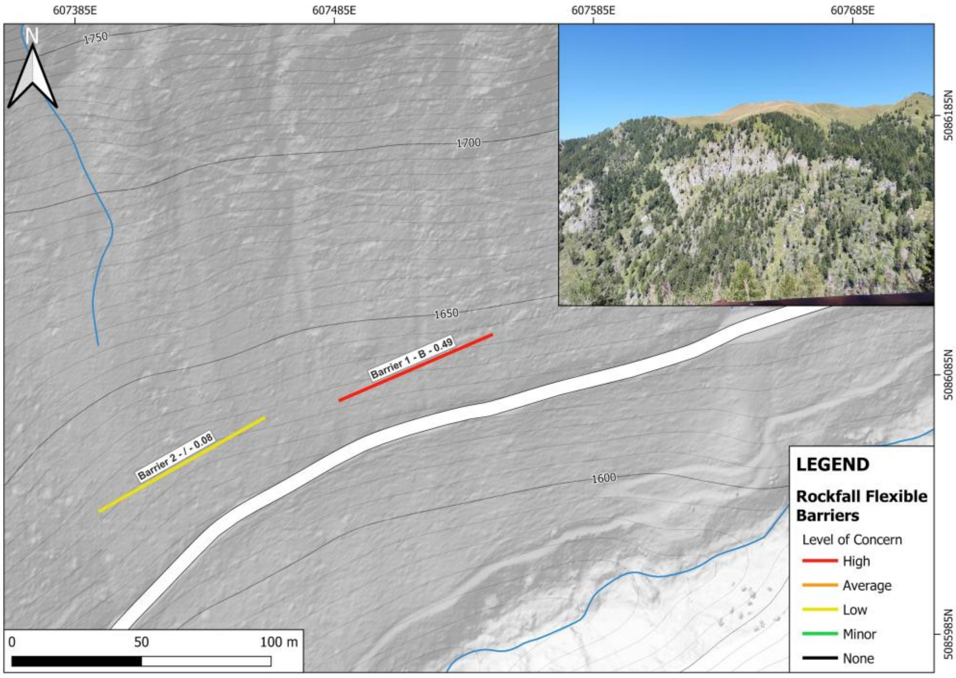

Fig. 4 Cartographic rendering of the data regarding the two surveyed barriers and a picture of the studied area.

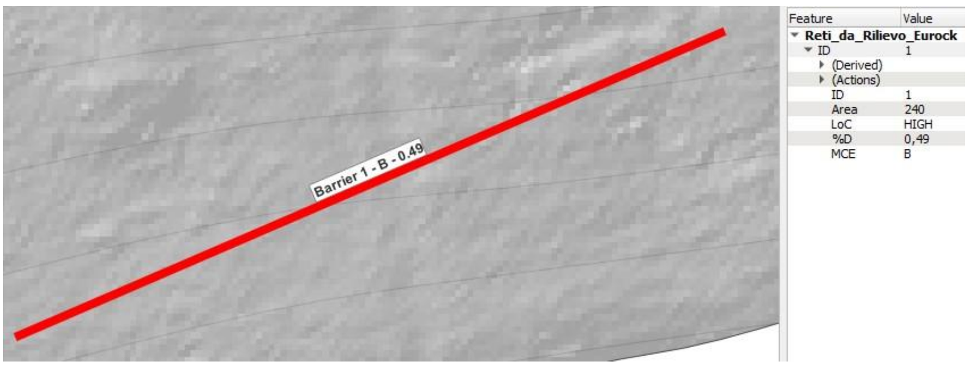

Fig. 5 Example of the information displayed when interrogating the shapefile: in this case, in addition to the information already displayed in the map, we also chose to store the total area of net (in m^2) featured by each barrier (field: Area).

4 Conclusion

This work introduces a semi-quantitative, easily reproduced, and broadly valid tool to assess the conditions of existing rockfall flexible barriers, allowing for their classification through three indexes: LoC, $\%_D$, and MCE. The procedure is automatic, thanks to a coded Excel spreadsheet. Lastly, a cartographic database can be constructed to store and convey the information, even if in large quantities or spread over a wide area. The examples provided show the efficacy of the methodology, its flexibility, and user-friendliness, which can thus satisfy the needs of infrastructure managers, municipalities, and other territorial entities. Moreover, the database can easily be updated over time.

The main strong point of the method is its simplicity and automatization. Besides the reduced time and cost, this ensures data coherence. The procedure is also quite intuitive. Lastly, cartographic rendering allows for fast and clear visualization of the data, even for non-specialized personnel.

The most significant drawback of this methodology lies in the reliance on visual inspection and manual labour. Whoever compiles the FBSS must have enough experience and training to correctly identify the structural element's conditions. Furthermore, both data management and storage rely on manual input of data and shapefile generation. It should be possible, though, to devise a fully automatic data management system. Lastly, it is worth noting that it is theoretically possible to modify the FBSS and Excel spreadsheet to work for drapery meshes as well, extending the possibilities of application of the methodology.

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