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Impact identification on flexible rockfall barriers: on site test of a wireless monitoring system

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Abstract. Flexible rockfall barriers represent an effective measure to mitigate hazard related to falling boulders. The monitoring activity of these protection structures is essential to guarantee their functionality, and usually aims to verify the barrier conditions and to identify any impact on the net. The system here presented, called D-Fence, was specifically developed for the real-time monitoring of flexible rockfall barriers. It consists of a series of separate battery-powered devices installed on the uprights of the monitored structure and transmit data to the elaboration center through a wireless local network. Each module includes a 3D tilt sensor, allowing the near real-time monitoring of the rotation of the uprights, while the integration of a shock sensor makes it possible to measure in real-time the accelerations experienced by the barrier. The on-site test of the D-Fence system involved the installation of four modules on a prototype barrier located in a pilot site in Northern Italy. Each device was placed on a different upright and was connected to a local Wi-Fi network. In this configuration, two different concrete boulders were dropped on the barrier in order to test the D-Fence ability to measure the tilt variation of the uprights and identify the overcoming of a predefined acceleration threshold.

1. Introduction

Rockfalls can be defined as a detachment of one or more rock blocks from a vertical or sub-vertical cliff, followed by a series of downslope motions including free-falling, bouncing, rolling, and sliding phases [1]. They are a widespread phenomenon in mountainous areas, and are usually classified as very rapid events characterized by high kinetic energies and relevant damaging capabilities. These features, together with the difficulty of identifying early signs of instability and detachments, make the protection of people and infrastructures against these phenomena a considerably challenging task [2,3]

Among the different approaches to mitigate the risk related to rockfall events, flexible protection barriers have proven to be a versatile and effective measure to arrest falling rocks and boulders. Their capacity is typically quantified in terms of kinetic energy which the structure is able to withstand, and their dimension and components can vary according to the specific case study [4–7].

Due to the capital importance of these structures in the risk mitigation process, it is fundamental to guarantee their operativity and functionality over time. In fact, the efficiency of these protection structures can be affected by several factors such as damages caused by previous impacts, debris accumulation on the nets, and ageing phenomena induced by the exposure to natural elements [8–10]. In this context, the monitoring activity of the protection structures plays a central role in the assessment of the structure conditions and planning of maintenance works. Moreover, thanks to the possibility of integrating automatic procedures for data acquisition and elaboration, it is possible to design monitoring systems able to detect an impact on the barrier and transmit relevant information in near-real time for early warning purposes [11-13]. Nonetheless, despite the importance of this topic, there is a lack of scientific literature regarding the development and testing of monitoring equipment for these structures. Notably, most studies involving this matter address the instrumentation from a commercial point of view, presenting very few scientific details and insights.

2. Materials and Methods

2.1. D-Fence monitoring system

This paper presents a monitoring system, called D-Fence, specifically designed for real-time control of flexible rockfall barriers. Developed and produced by ASE S.r.l. (IT), its main component is represented by a series of battery-powered wireless elements, called DFC modules, that are installed on the uprights of the monitored structure. They are able to transmit sampled data via a Wi-Fi or LoRa-based local network, created through appropriate devices located on-site and powered by a photovoltaic panel. Each module integrates two different sensors, namely a 3D MEMS accelerometer to monitor the rotation of the uprights at predefined time intervals, and a Shock Sensor designed to identify in real-time any impact on the barrier and activate predefined alert procedures. Due to its modular nature, the D-Fence system can be customized according to the barrier features and dimensions, in order to obtain an appropriate description of the structure behaviour. Additionally, the system allows the integration of a remote camera to acquire images of the monitored barrier at defined intervals, or in correspondence of an event detection. The authors described a similar configuration in another study, focused on the control of debris flow barriers [14].

After successfully sending the sampled values to the elaboration centre, the raw data (already expressed in physical units) are saved in a dedicated database. Then, an automatic software applies a series of statistical controls on the monitoring outcomes in order to recognize and correct any spike and/or inconsistency detected in the available dataset. Moreover, the software integrates a routine to check the potential exceeding of any predefined alert threshold. The outcomes of the elaboration process are stored in a separate section of the database. Finally, it is possible to browse the final results on an interactive web-based visualization platform, accessible from any device with an internet connection (Figure 1).

Figure 1. Structure of the D-Fence monitoring system.

2.2. Pilot site description

On September 2021, two tests were carried out on a full-scale rockfall barrier installed in a pilot site, with the objective to analyse the effectiveness of the D-Fence system. The tests involved the investigation of several aspects and components of the proposed monitoring approach, with particular attention to the following elements:

- The Wi-Fi network reliability in environmental conditions similar to a real on-site application

- The performance of the MEMS sensor in terms of measuring the inclination of the individual upright, as well as resolution, repeatability, and instrumental noise
- The ability of the Shock Sensors integrated in the D-Fence to an impact on the structure, with particular attention to different installation positions
- The effectiveness of the module assembly in resisting impacts on the barrier and transmitting the signal after the event

The apparatus used to perform the tests involved a prototype barrier designed for energy impact levels up to 4000 kJ. The structure was installed horizontally in a configuration with 4 uprights spaced 10 meters apart, for a total of 3 panels. For what concern the monitoring system, it was decided to install a single DFC module on each upright, with two slightly different configurations depending on the upright number, as detailed in Figure 2. Specifically, the sensors on the uprights M1 and M2 were placed with the X axis in the horizontal direction (i.e., parallel to the net and the upright), while the devices placed on the uprights M3 and M4 were installed in the vertical direction (i.e., perpendicularly to the net and the upright). This choice was aimed at investigating the possible variation of sensitivity in the measurement of the inclination of the upright, as well as the effectiveness of the activation of the Shock Sensor.

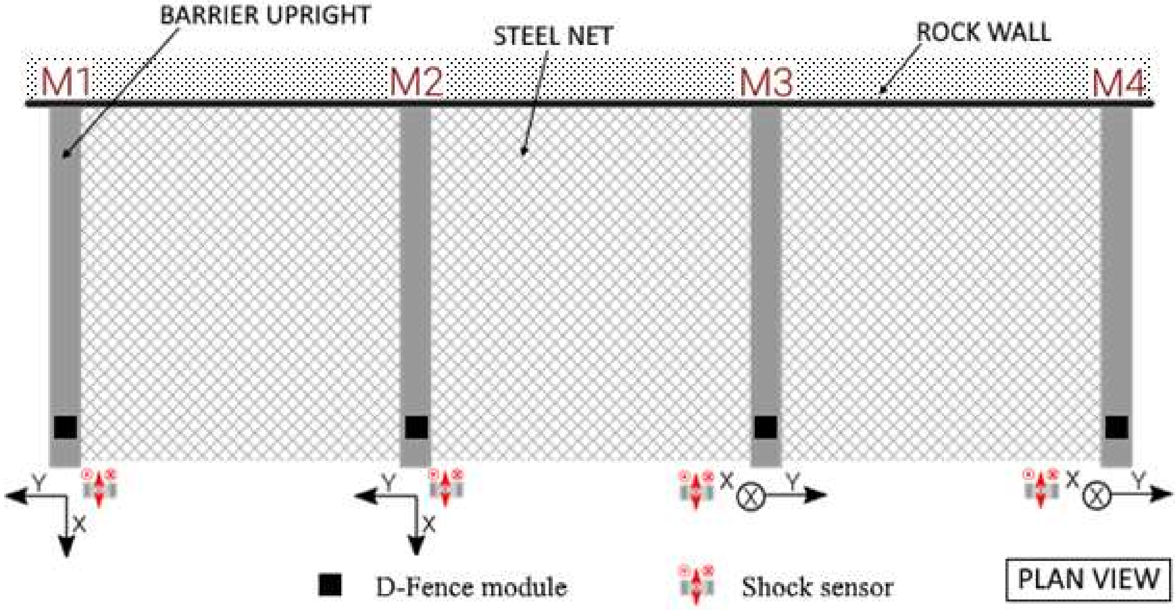

Figure 2. Configuration of the barrier and the monitoring system, with details regarding the installation of all DFC modules on the uprights.

3. Results and Discussion

The installation of the monitoring devices was planned for the day before the text execution, in order to assess the sensors stability in normal conditions. This operation was performed by evaluating the average tilt variation between two consecutive measures sampled by the MEMS accelerometer before performing the test. In this phase, all DFC modules were set to a sampling frequency of 15 minutes, sending the acquired data to the elaboration center through the Wi-Fi connection created by two UMTS routers located on-site. The outcome of this operation evidenced a positive result in terms of signal stability, obtaining an average tilt variation of approximately 0.002°.

The tests performed on the barrier involved the release of two boulders featuring different masses and energy levels, as summarized in Table 1. Since the barrier is installed horizontally, boulders fall freely until impact. After the first test the boulder was cleared, and no operation was performed on the prototype barrier before the execution of the second part of the test. The exact date and time of the impact was determined thanks to the Shock Sensors integrated in each DFC modules, which were able to detect and report the sudden acceleration experienced by the barrier.

Table 1. Features of the boulders used for the test.

Test	Date [dd-mm-yy HH:MM]	Boulder mass [kg]	Kinetic Energy [KJ]
1	21/09/21 09:44	533	160
2	21/09/21 10:21	5350	1600

The following graphs summarize the outcome of the test execution, displaying the differential tilt data of each single DFC module, highlighting also the instants related to the impact on the barrier. In particular, Figure 3 presents the tilt variation measured along the vertical direction, while Figure 4 shows the same physical quantity recorded in the transversal direction. It should be noted that the module positioned on the upright M4 was unable to provide monitoring data during the tests, due to a faulty component that started malfunctioning after the installation on the barrier.

The two central modules showed a significant downward tilt variation in correspondence of each impact. In particular, as evidenced in Figure 3, DFC-M2 recorded more significant variations during the execution of the first part of the test, while DFC-M3 shows a notable movement of the upright in correspondence of the impact of the second boulder. According to collected data, after the execution of both tests, uprights M2 and M3 showed a downward tilt variation of 0.631° and 0.802° respectively (Table 2). Moreover, it is possible to observe the presence of a tilt variation recorded by DFC-M3 before the test execution, arguably induced by work operations performed on the barrier. On the other hand, the module installed on the upright M1 did not show any meaningful variation of its position along the vertical direction.

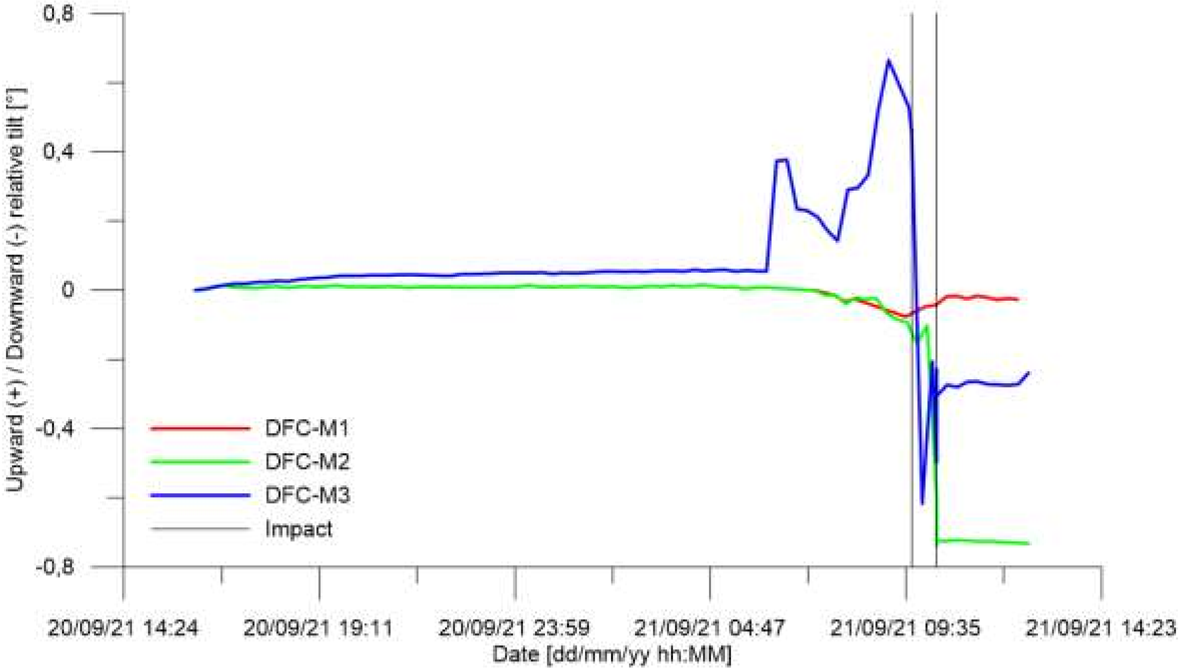

Figure 3. Tilt variation measured along vertical direction by the DFC modules after their installation.

Table 2. Tilt values along vertical direction in different steps of the test.

DFC module	Tilt variation – vertical direction [°]		
	Caused by first impact	Caused by second impact	At the end of the tests
DFC-M1	0.016	0.024	0.058
DFC-M2	-0.059	-0.621	-0.631
DFC-M3	-1.145	-0.068	-0.802

However, as can be observed in Figure 4, the DFC module placed on the external upright recorded a significant converging movement after both impacts, resulting in a tilt of 9.282° measured at the end of the test. DFC-M2 shows a similar behavior, in particular after the impact of the second boulder on the barrier, which produced a peak in tilt variation trend. In both cases, the magnitude of the tilt variation measured in transversal direction was considerably higher compared to the one recorded along the vertical direction. Additionally, it is worth noting that the final tilt recorded after both impacts can be influenced by the elastic movement of the upright that, following the impact, tends to return to its original position.

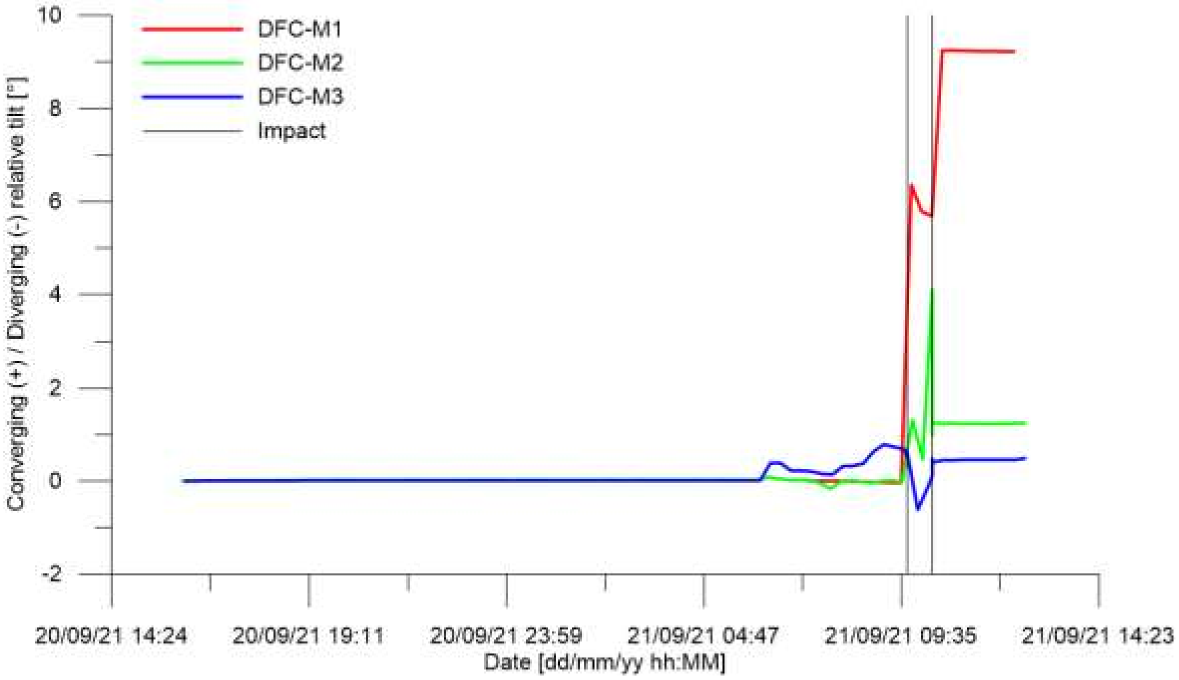

Figure 4. Tilt variation measured along transversal direction by the DFC modules after their installation.

Table 3. Tilt values along vertical direction in different steps of the test.

DFC module	Tilt variation – transversal direction [°]		
	Caused by first impact	Caused by second impact	At the end of the tests
DFC-M1	6.394	3.559	9.282
DFC-M2	1.332	3.626	1.252
DFC-M3	0.684	0.491	0.238

Finally, Figure 5 provides an example of a possible comparison with a predefined threshold after the detection of an impact on the barrier. Thanks to the integration of two different sensors in the same module, it is possible to identify a correlation between the activation of the Shock Sensor and the presence of a significant variation in the upright position due to the impact experienced by the structure. This approach allows to determine if the Shock Sensor triggering is caused by an actual event involving the barrier, or if the sensor activation could be classified as a false alarm since no variations can be observed.

Moreover, it is possible to integrate different kind of threshold in the elaboration process in order to provide a multi-level classification of the recorded event. These can be defined according to information related to the monitored barrier, such as the Service Energy Level (SEL) or Maximum Energy Level (MEL), as well as based on the monitoring outcomes of a time period preceding the impact.

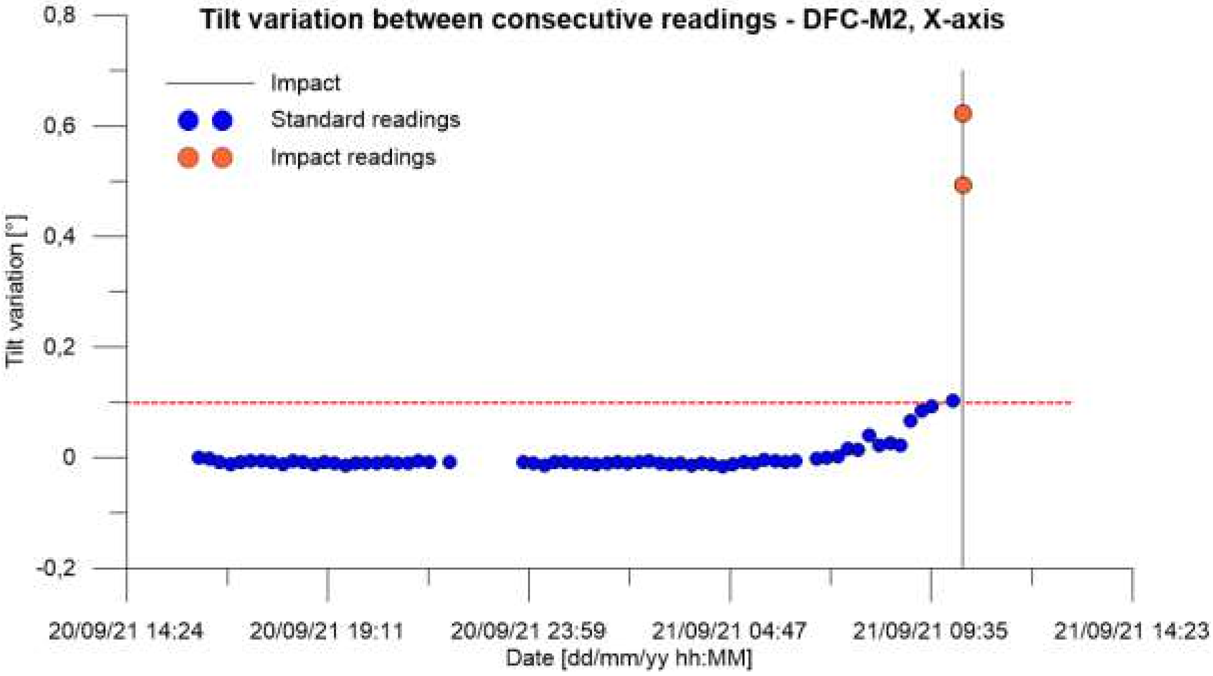

Figure 5. Tilt variation measured between consecutive readings by DFC-M2 compared with a predefined threshold, displaying also the impact detected by the Shock Sensor.

4. Conclusions

Flexible barriers are among the most frequently used structural protection measures to mitigate the risk deriving from rockfall events. Their role is to absorb the energy generated by the impact, preventing the boulder to continue its movement along the slope. The monitoring activity of the structure can be performed to assess the barrier functionality, and also to identify the occurrence of a potentially critical event.

This paper presents the result of a full-scale test performed on a monitoring system, called D-Fence, designed for the control of flexible rockfall barriers. The main component of the system is a wireless apparatus named DFC module, integrating a 3D MEMS sensor and a Shock Sensor. This configuration allows the monitoring of the tilt variation of the upright where the module is installed, as well as the near-real time identification sudden accelerations caused by an impact on the barrier.

The test involved the release of two boulders, with the objective of verifying the system functionality and operativity, identify the impact on the structure, and measure the barrier condition after the event. The outcomes evidenced the D-Fence system ability to provide an accurate description of the ongoing phenomenon, correctly detecting the acceleration induced by the boulder hitting the barrier and displaying the consequent variation of the uprights position. Moreover, the cross-correlation between the sensors makes it possible to use the results for early warning thanks to the integration of alert thresholds in the elaboration software.

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