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Virtual testing of existing semi-rigid rockfall protection barriers

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ABSTRACT

Semi-rigid rockfall protection barriers are steel structures constituted by a principal interception structure made of cables mounted on structural steel posts fully restrained to the ground. Traditionally, they are assigned a low capacity value which ranges from few to less than 300 kJ. Over the last decades, semi-rigid rockfall protection barriers have been installed along areas interested by rockfall events, often in conditions of extreme urgency, without a specific structural design. As a result, they are found in a variety of subtypes, most of them lacking the essential structural information, such as the energy absorption capacity, crucial for a reliable application of procedures for quantitative risk assessment. To fill this gap, and considered the lack of experimental data on semi-rigid barriers, in the present study a numerical investigation of the most common barrier subtypes is developed. In the absence of standards for this kind of barriers, the barriers are virtually tested in conditions inspired by the essential prescriptions included in the European Guideline for flexible barriers (ETAG 27). Results allow to: (i) investigate the performance of the barriers in service condition; (ii) provide an estimate of the barrier capacity and (iii) explore the barrier failure mode.

1. Introduction

The development of rockfall mitigation strategies often concerns areas which have been subjected to former protection actions. These actions commonly involved the installation of structural rockfall protection systems such as barriers, embankments, ditches or galleries [1–3].

In many cases, the structures still rest on the area, identifying its actual protection scenario. Each existent structure offers a specific response to impact that affects the intensity of a rockfall risk on the area [4–7].

A special type of rockfall mitigation structure, hereinafter named semi-rigid rockfall protection barrier, has been extensively employed as a convenient passive countermeasure being cost-effective, versatile, easy to be installed and maintained. Semi-rigid rockfall protection barriers are steel structures made of the repetition of a single functional module. Generally, each module is constituted by a principal interception structure made of cables mounted on structural steel posts fully restrained to the ground. The use of connecting components, such as further cables or clamps, produces a variety of barrier subtypes. Semi-rigid rockfall protection barriers are usually less than four meters high and can be several meters long.

The capacity of a falling rock protection barrier is identified with a kinetic energy value, associated to the maximum energy possessed by a block that the barrier is expected to arrest, and may range from few up to 8000 kJ. Semi-rigid rockfall protection barriers are also described as low-energy barriers. Although there are no experimental evidences, they are traditionally assigned capacity values ranging from few to less than 300 kJ [8].

Semi-rigid barriers are typically found just above road stretches and railways, installed directly to the ground or on gravity retaining walls to arrest the blocks at the very end of their fall.

Recently, the Autonomous Province of Bolzano (Italy) has counted on its territory about a thousand working falling rock protection barriers. About a half was recognized to belong to the semi-rigid type, installed in a variety of subtypes during the last two decades [9].

The barriers are typically installed without specific design instructions and often used as a fast response in condition of emergency. As a result, the essential structural information are missing. Further, this type of barrier received only little attention up to now [10–13].

In response to the lack of data, a numerical study offers a suitable alternative to carry out a complete description of the response to impact of semi-rigid rockfall protection barriers.

The base of the study is provided by a FE strategy, devised by the authors, which provides all the elements for the development of simple structural models of falling rock protection barriers

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[14]. The strategy was assessed using results of full scale tests carried out on various prototypes of flexible falling rock protection barriers [15]. Rather than a single model, the proposed procedure enables the definition of key numerical choices of general validity that enable the development of reliable numerical models of any type of falling rock protection barriers. Two-dimensional [16,17] and three-dimensional non linear, dynamic models made of one-dimensional FE elements of all the tested prototypes were devised according to that strategy, with special emphasis on the modeling of the components, such as the net panel and energy dissipating devices [18].

The strategy was shown to be effective independent of the barrier type and impact energy, encouraging its use as a predictive tool [19]. In the last two decades, other studies have confirmed that numerical models based on finite elements, or discrete elements, certainly are a powerful tool to investigate the dynamic behavior of highly flexible barriers [20–25], establishing a consolidated numerical research environment.

Within this context, the main objective of the research is to investigate the response of semi-rigid rockfall protection barriers, widely used but narrowly studied. In response to the lack of experimental evidences, the study presents the results of a virtual testing program conducted on four semi-rigid rockfall protection barrier types developed according to the above mentioned strategy. In particular, the most commonly installed barriers along the Alps are considered. Models are kept as simple as possible, with truss and beam elements to represent the components of the barriers, focusing on the connection between the elements.

In absence of specific instructions for semi-rigid rockfall protection barriers of energy lower than 100 kJ, the essential instructions included within the European Guideline, ETAG 27 [26] for comparatively higher capacity barriers were used as a guide in developing the virtual testing program. Thus, barrier models are made of three functional modules and are subjected to the central impact of a concrete block of known mass and velocity. Vertical-drop testing conditions were considered. In order to investigate the structural behavior of the barriers in service condition, the models are subjected to two subsequent launches at the same energy level, verifying that the barrier was able to arrest the block. Based on the service energy threshold, limit state was associated to a value of kinetic energy of the impacting block equal three times the service energy, ensuring that the barrier was still able to stop the block. Then, the barriers are taken to failure increasing in constant steps the kinetic energy of the block, detecting the failure energy and failure mode of each barrier type.

The paper is organized as follows. In Section 2, the main features of the four types of barriers under study are presented. In Section 3, the numerical procedure and the virtual testing program are shown. Results of the study are discussed in Section 4.

2. Semi-rigid rockfall protections barriers

Semi-rigid rockfall protection barriers are steel structures made of the repetition of a single functional module. Each module consists in an interception structure, a supporting structure and various connecting components. In many cases, the interception structure is made of evenly spaced longitudinal cables of various diameters and a secondary steel hexagonal meshwork. Steel posts such as I-beams or flange beams are the supporting structure. Connecting components are all the further cables (uphill cables, lateral cables, etc.), studs or clamps resulting in a variety barrier subtypes. A typical semi-rigid rockfall protection barrier, located within the territory of the Autonomous Province of Bolzano (Italy), is depicted in Fig. 1.

Semi-rigid and flexible barriers, though quite alike in the essential features, present crucial differences which influence the deformation mode and the energy absorption capacity.

Fig. 1. A typical semi-rigid rockfall protection barrier installed in the Autonomous Province of Bolzano (Italy).

The posts of semi-rigid rockfall protection barriers are fully restrained to the ground, so that both the supporting and interception structure bear the impact loads. Semi-rigid rockfall protection barriers are generally not provided with energy dissipating devices and are used where rockfall events are expected to be of low intensity, while flexible barriers are used when boulders would fall with energy comparatively higher (from few hundreds to more than 5000 kJ).

In a flexible barrier, this function is primarily fulfilled by the interception structure made of highly deformable net panels and connecting components such as energy dissipating devices and the posts are provided with hinges at the base.

Flexible barriers have been studied thoroughly within the last ten years and their design is supported and regulated by international and national standards and guidelines. On the contrary, the structural behavior of semi-rigid rockfall protection barriers, is still not adequately characterized.

This study attempts to fill this gap considering four types of semi-rigid rockfall protection barriers, selected among those most frequently encountered along the Alps. These barriers, identified hereinafter with the labels SF1, SF2, SF3 and SF4, are illustrated from Figs. 2–5, respectively.

In particular, barrier SF1 is illustrated in Fig. 2. The nominal height h_N of the barrier is 3.2 m and the post spacing is equal to 5 m. The principal interception structure is made of longitudinal steel cables of 12 mm diameter. Internal posts, I-beams of European type IPE 200, are provided with special eyelets to let the longitudinal cables of the interception structure pass through. External posts are steel beam IPE 300, provided with a further beam as a trestle support and suitably modified to accommodate the ending loops of each longitudinal cable. The barrier is provided with side cables of 18 mm diameter.

Semi-rigid barrier SF2, Fig. 3, has the same dimensions of barrier SF1, but it is provided with a secondary hexagonal meshwork, made of twisted steel wires of 2.7 mm diameter, attached with clamps or steel threads to the uppermost and lowermost longitudinal ropes. This barrier configuration is the most frequently installed.

Barrier SF3 features a set of steel clasps mounted on the principal interception structure. Each clasp of 12 mm diameter retains two successive longitudinal cables defining the regular pattern represented in Fig. 4.

Barrier SF4, shown in Fig. 5, features three couples of cross cables mounted on the interception structure and four uphill cables. The diameter of the cross and uphill cables is 12 mm. The principal dimensions of barriers SF3 and SF4 are those of barrier SF1.