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An energy allocation based design approach for flexible rockfall protection barriers

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ABSTRACT

This paper proposes an effective design approach for quickly determining the specification, size and amount of components of a flexible rockfall protection barrier structure. The approach is based on a reliable numerical modelling validated by several experimental tests that include both component tests and full-scale impact tests. The interception structure made up of a steel wire-ring net is accurately investigated through a series of in-plane and out-of-plane quasi-static tests carried out on net specimens, to define the ring constitutive model and failure criterion. The accuracy of the numerical strategy for an overall barrier structure with nominal energy level of 1500 kJ is validated by a full-scale in-situ test including service energy level (SEL) and maximum energy level (MEL) impacts, according to the European guidelines. From the numerical models, it is inferred that the total energy of the impact is simultaneously dissipated in different ways, where the internal energy of the structure plays a significant role. The distribution of the absorbed energy among the different barrier components is explored and defined by means of the developed finite element model. Besides, the design values of the internal force in the ropes are derived with an adequate safety margin. The proposed design procedure, applied to a barrier structure with nominal energy level of 3500 kJ, is assessed by a full-scale impact test, proving that the design approach is reliable and efficient.

1. Introduction

Protection barrier systems have been evolving since the middle of the last century, starting from an embryonic form of metallic ring nets connecting to float bowls in the water, to intercept submarines and torpedoes in military field during the Second World War. The first application of a barrier to slope disaster prevention dates back to 1951, when the original protection system consisted of wooden columns and steel wire nets for avalanche interception, which subsequently caught many fallen stones by coincidence, so that the rockfall protection barriers were raised and developed [1,2].

So far, many different protection measures against geological collapse and rockfall impact can be selected, like rigid fences characterized by an ease installation and ground embankments effective in case of repeated collapse events [3]. Flexible rockfall barriers have become one of the most common measures which cover a wide range of energy absorption capacities ranging from 50 kJ up to more than 8000 kJ [4], as shown in Fig. 1 [5]. Flexible barriers are characterized by a high deformability of the interception structure that is typically a steel wire-ring net to which a secondary hexagonal meshwork is fastened on the upslope side, Fig. 2. It is the principal net that bears the block impact, while the secondary meshwork is intended to arrest debris. Wire meshes or a cable nets are also employed as interception structures. Other components of such barriers are the support structure (posts), connecting components (ropes), energy dissipating devices and foundations.

Compared with other engineering structures, there is no specific design standard for flexible rockfall protection barriers. Therefore, in the past several decades, the progress in design theory and the update of the products in this field relied, to a great extent, on the experience of engineers, as well as on the trial-and-error method by means of many experiments [6–13]. However, these tests, carried out by manufacturers and researchers, were developed using different methods and procedures so that the results were not easily comparable. For unifying the qualification and improving the performance of the products, the European Organization for Technical Approvals (EOTA) has promulgated a European Technical Approval Guideline (ETAG 027) since 2008, in which a standard full-scale testing procedure was defined [14]. Nowadays, in many countries to ensure a satisfying performance of a rockfall barrier structure, the full-scale impact test based on the

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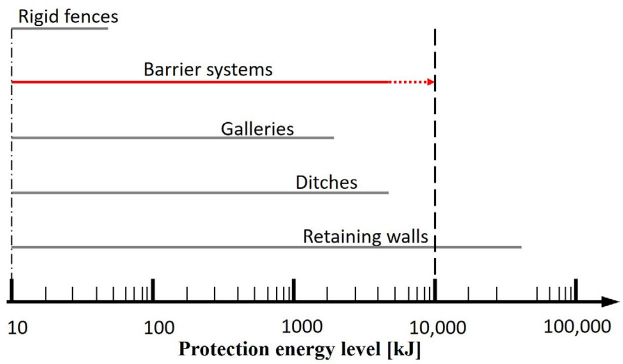

Fig. 1. Protection capacity of common engineering measures against rockfall (modified from [5]).

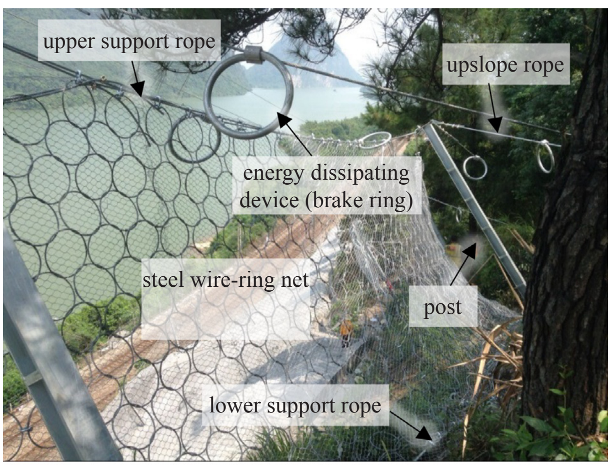

Fig. 2. Typical flexible barrier structure and its main components.

standard procedure is compulsory [15,16] or strongly recommended [17]. However, due to the high cost of full-scale tests as for any other complex engineering projects, numerical approaches were used and developed for system analysis and design [18,19].

For the study of rockfall barriers, finite element (FE) [20–27] and discrete element (DE) [28–31] models were both employed, and the validity of these approaches was verified based on available experimental data. In [32], a flexible barrier with nominal energy level of 3000 kJ was optimized in cost and performance by removing all the energy dissipating devices from the longitudinal ropes and adding just two of them at the outermost portion of the longitudinal upper ropes. In [33], two extreme load cases on a barrier (one was a rock impact with a velocity greater than 25 m/s and the other was an impact by a tree trunk with a much smaller puncturing area) were considered for design. A theoretical model in the elasto-plasticity framework for the constitutive behavior of steel wire-ring nets was developed in [34]. In [35], a scaling relationship, validated by means of data generated with a finite element model, was introduced to quantify the capacity of rockfall barriers to withstand impact from blocks, and, in particular, it allowed to investigate the bullet effect. Further, a program capable of analyzing flexible barriers was developed in [36], in which the high nonlinear features of the structure were considered, and an efficient incremental-iterative procedure was adopted for tracing force equilibrium within the barrier system. Besides, maintenance problem of net fences was also dealt using numerical approaches. In particular, the influence of installation issues and deterioration of the system, as well as the damage induced by ageing of the material, were taken into account in [37,38]. Additionally, it should be noted that in the planning phases of rockfall protection devices, a key aspect is the correct definition of the design block and its return period. A probabilistic approach that allows to define this relationship is described in [39] based on statistical analyses of historical data sets (see, among the others, [40]).

Although numerical simulations could significantly enhance the efficiency of design effort, owing to the complexity of the systems, some aspects still need further improvements, such as an accurate definition of the contact among the components and failure criteria. Besides, the wide application of numerical simulations in practical design may also be restricted by the unfeasibility of a too sophisticated modelling.

Most of the available studies involving design methods for barrier structures mainly focused on the initial conditions or input parameters such as the trajectory of the falling rock, the incidence angle and initial velocity, [41–44], rather than on the mechanical properties and dynamic response of the structure. On the contrary, few researches have considered effective and rapid design methods that dealt with the barrier as a whole, which can, to some extent, replace the full-scale dynamic tests and the numerical simulations.

Within this context, a simplified and quick design approach based on energy allocation for flexible barrier structures is herein proposed. To this aim, a reliable numerical model is developed as an analysis tool. A series of tests under quasi-static loadings was conducted to calibrate the dominant parameters of key barrier components such as the wire-ring net and the energy dissipating devices. In particular, energy dissipating devices were tested following the recommendations of the ETAG027 [15], where it is suggested the execution of quasi-static tests. However, for an accurate analysis of the brake behavior more close to real loading conditions, the performance of dynamic tests is advisable as highlighted in [7].

Additionally, a full-scale dynamic impact test on a barrier structure of capacity 1500 kJ was carried out according to the European guideline [15], to verify the accuracy of the numerical model. Accordingly, the relationship among the nominal energy, the total energy of the impact and the design energy was discussed, and the distribution of the dissipated energy of the different barrier parts was studied. Internal forces of each steel wire rope were evaluated, and magnified with safety factors for the design. Based on that, a rapid procedure for determining each component specification is presented and applied to a new barrier structure with nominal energy level of 3500 kJ. Finally, an additional full-scale test on such barrier validated the proposed method, and the comparison between design values and experimental results showed that the approach is reliable.

The paper is organized as follows: the details of the experiments conducted on barrier components and on a full-scale barrier are given in Section 2; the numerical models of the components and of the whole barrier are described in Section 3; the composition of the total energy consumed by the barrier, and its distribution among each part, as well as the prediction of the peak forces in the different ropes, are discussed in Section 4. Finally, the design approach is applied to another full-scale barrier and assessed experimentally in Section 5.

2. Experimental program

In this section, the experimental tests conducted on barrier components (wire-ring net specimens and energy dissipating devices) and on a full-scale barrier prototype are presented and described. In particular, both in-plane and out-of-plane tests were conducted on ring specimens and net panels to accurately explore their mechanical behavior which enables the calibration of a FE numerical model.

2.1. Component tests: wire-ring net and energy dissipating devices

A series of component tests was carried out under quasi-static loading conditions in laboratory, including tests on wire-ring net specimens and on energy dissipating devices.

Four types of wire-ring specimens were considered: one-ring, three-ring and five-ring specimens as well as net panels. For the first two types, six groups of specimens, depending on the number of windings of