THE ROLE OF FALLING ROCK PROTECTION BARRIERS IN THE CONTEXT OF LANDSLIDE RISK ANALYSIS AND MITIGATION

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ABSTRACT

In this paper, the authors investigate the behaviour of the falling rock protection barrier at present installed within the territory of the Autonomous Province of Bolzano (PAB). Information relevant to the description of these structures are found in the complete inventory of all rockfall protection works, recently developed by PAB (VISO). Based on these data, suitably integrated with the available technical documentation and in situ surveys, a set of FE models was developed to predict the response of such structures to the impact of blocks of known kinetic energy. The models were designed so that the results could be interpreted to evaluate the effectiveness of existing barriers toward any possible rockfall event, in terms of structure deformation and forces developed at the foundations and anchoring points. This study forms part of the research activities of the European project PARAmount: imProved Accessibility, Reliability and safety of Alpine transport infrastructure related to MOUNtainous hazard in a changing climate.

Keywords: Natural hazards, risk mitigation, falling rock protection barriers, rockfall, FE modelling.

INTRODUCTION

Falling rock protection barriers are metallic structures used as passive measures against rockfall, with the aim of intercepting and stopping the blocks moving along an unstable slope.
As illustrated in Figure 1a, these structures are made of a series of identical functional modules installed in sequence up to the desired length. Each functional module generally features an interception structure, kept in position by support structures. Connecting components join the barrier elements and transfer the loads to the foundations. Falling rock protection barriers are able to intercept the blocks moving along a slope and stop them by developing elasto-plastic deformations of the system and its components: the higher the structure compliance, the greater the barrier energy absorption capacity from few to more than 4500 kJ (Descouedres et al., 1999), as it is schematically illustrated in Figure 1b. Available in a variety of models, these structures are widely used since they are light, versatile, easy to be maintained and particularly effective towards rockfall risk mitigation.
The Autonomous Province of Bolzano has recently catalogued about one thousand falling rock protection barriers installed on its territory: approximately more than a half are of low capacity (lower than 100 kJ). In order to evaluate the effectiveness of these structures against rockfalls, the position and the behaviour under dynamic conditions should be known and compared with the data relevant to the description of predicted rockfall events (Giani, 1992; Corominas et al., 2005; Oggeri and Tosco, 2005, Peila and Guardini, 2008). The dynamic behaviour of a falling rock protection barrier is traditionally evaluated by means of full-scale tests, in which the ability of the system to stop blocks having energies up to the nominal value is assessed on prototypes. However, experimental evidences are not available for all the existing falling rock protection barriers and a relevant procedure becomes necessary.

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Within such context the paper presents a numerical procedure for the investigation of the behaviour of falling rock protection barriers in dynamic conditions. The procedure has been developed and assessed on the basis of high quality experimental results of flexible falling rock protection barriers (Gottardi and Govoni, 2010) and has shown to be of general validity (Gentilini et al. 2011), as it is able of producing a very accurate description of the response of various types of flexible systems to a wide range of impact kinetic energies. The procedure is herein extended to predict the behaviour of barriers for which experimental data are not available. Numerical analyses enable to predict the parameters relevant to the evaluation of the effectiveness of existing barriers against rockfall events.

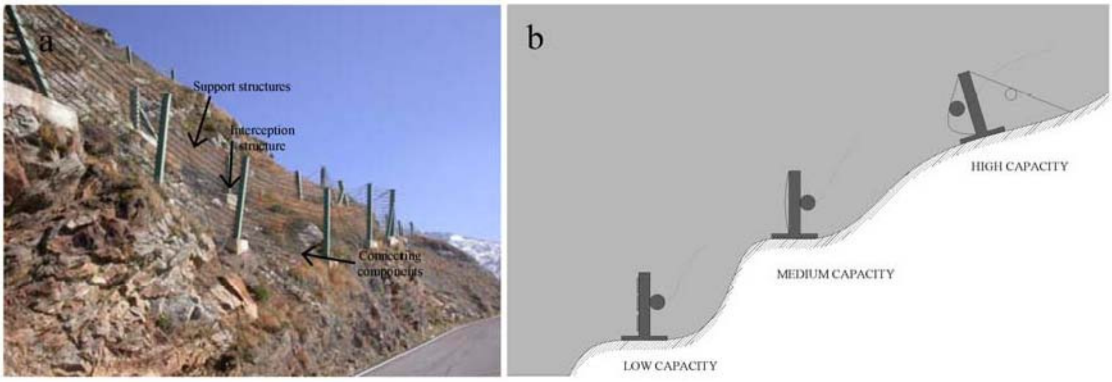

Fig. 1 Falling rock protection barrier: a) functional modules and structural components, b) compliance and capacity

THE FALLING ROCK PROTECTION BARRIERS WITHIN THE AUTONOMOUS PROVINCE OF BOLZANO

A complete database of the falling rock protection barriers at present installed within the Autonomous Province of Bolzano has been recently developed. The starting point was found in VISO, a thorough inventory of the protection works now installed within the Province area. With reference to the specific hazard events and threatened items, passive systems such as ditches, wire nets, earth dams, sheds and falling rock protection barriers have been registered within the inventory. Information included in VISO have been mostly acquired by direct inspections carried out over the last few years and essentially concerns the position, typology and principal dimensions of each protection work, along with relevant photographs and remarks on the state of maintenance.

With reference to the sole falling rock protection barriers, including those of low (Figure 2a and 2b) and high (Figure 2c) energy absorption capacity, further data were collected in order to provide each item with a complete structural description. These data, generally collected from the available technical documentation along with suitably carried out in-situ surveys, enable both geometry and mechanical properties of the barrier functional module to be accurately depicted.

Fig. 2 Falling rock protection barriers within the Autonomous Province of Bolzano: a) and b) low capacity systems, c) high capacity systems

Since the goal of the database is to provide the information necessary to investigate the response of such structures, technical reports on relevant full-scale tests were included in the catalogue.

Experimental results were available for only about one tenth of the inventoried works (all high capacity barriers) and no behavioural data were found for the rest of the structures.
Barriers were then grouped according to their functional module, providing the identification of a set of falling rock protection barriers types. Each type features a specific interception structure, support structure and connecting components and has been, in general, distributed by a single manufacturer.
Although barriers belonging to a given type might feature minor differences among each other (e.g. dimensions, special components), they are expected to exhibit a similar response to block impacts.
Therefore, behavioural studies were carried out for each barrier type and results were considered as reference data for all the barriers belonging to the group.
In Figure 3, pictures of the ANAS barrier type are shown. The functional module of this barrier type features: equally spaced longitudinal ropes, steel I-beam posts, side cables and special eyelets which let the longitudinal ropes slide horizontally through the posts while no vertical movement are enabled.
Several barrier types are currently under investigation. However, for brevity the study is presented and discussed in the following section with reference to the ANAS barrier type only.

Fig. 3 The ANAS barrier type: a) general view, b) details of the connecting components

MODELLING OF FALLING ROCK PROTECTION BARRIERS

The dynamic behaviour of a falling rock protection barrier is traditionally evaluated by means of full-scale tests on prototypes and experiments are generally carried out at test sites (Figure 4) suitably instrumented for the measurement of the quantities relevant to the description of the structure response to block impacts, such as displacements and forces mobilised at the anchorages. In a test site as such, a barrier prototype, made of three functional modules, is subjected to the impact of blocks of known kinetic energies into the middle functional module. Results of the tests provide the complete time histories of the force-displacement response of the barrier and enable the assessment of its energy absorption capacity (the nominal capacity). According to the recently published Guideline for the European Technical Approval of falling rock protection kits, ETAG 27 (EOTA, 2008), full-scale testing is now mandatory for high capacity falling rock protection barriers. The Guideline, which has recently come into effect, provides all the requirements which a barrier should meet for being classified and distributed with a CE marking, as a proper construction product kit.
Over the last few years, significant improvements in testing set-ups and procedures have been made to meet the instructions included in the ETAG 27 and accurate and reliable experimental data on the behaviour of these structures in dynamic conditions have now become available (Gottardi and Govoni, 2010). Based on these data, a comprehensive strategy for the numerical modelling of falling rock protection barriers have been recently developed. The numerical procedure was designed on a set of numerical solutions for the modelling of the barrier structural components and impact conditions, which enable simple and effective models to be implemented (Govoni et al., 2011; Gentilini et al., 2011). Finite element, non linear, dynamic models of different high capacity barrier types were developed according to such procedure and analyses were run under various levels of impact kinetic energy using commercially available FEM codes. All the models have shown to be able to accurately

reproduce the experimentally observed behaviour, thus assessing the general validity of the numerical procedure. Such accuracy can be qualitatively appreciated in Figure 5, where the response of a model of a high capacity barrier type to a central impact is compared to the response of the corresponding prototype. Further details and results of the procedure are found in Gentilini et al. (2011). The findings would encourage the use of such numerical procedures to predict the response of any barrier type to any impact condition.

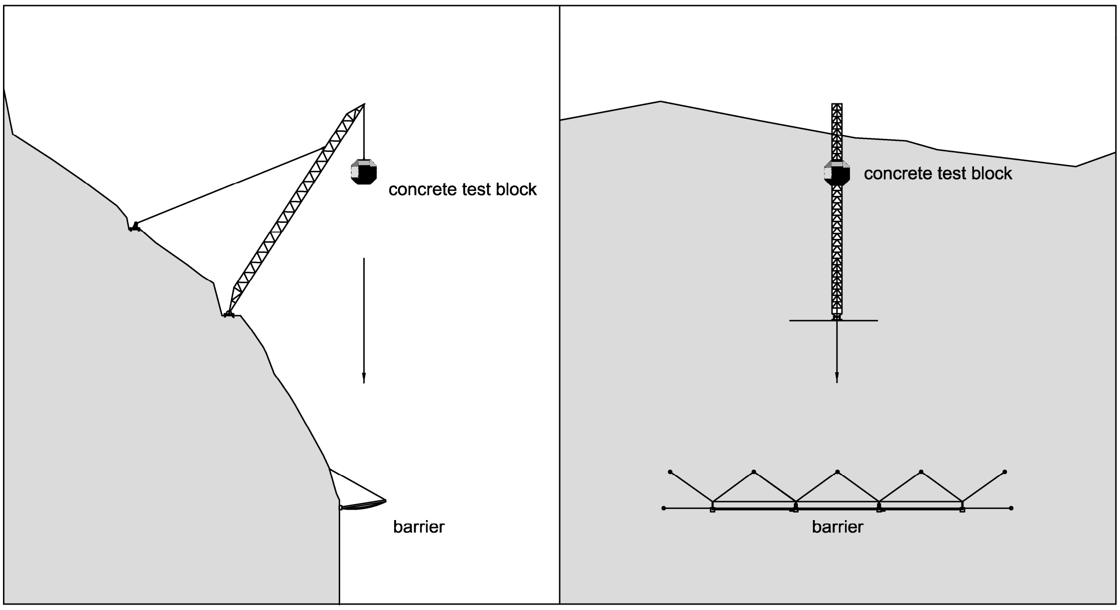

Fig. 4 Full-scale testing procedures on a three functional modules prototype at a vertical-drop test site

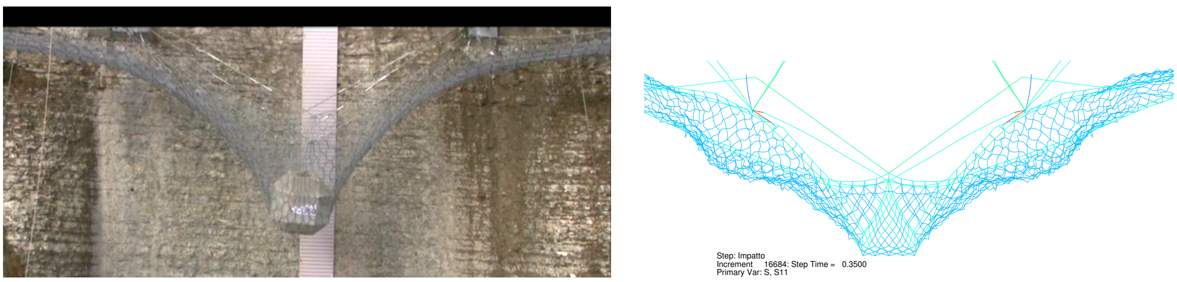

Fig. 5 Physical and numerical modelling of a falling rock protection barrier prototype in a vertical-drop test site

NUMERICAL MODELLING OF THE ANAS BARRIER TYPE

According to the data collected in the above described database of the falling rock protection barriers of the Autonomous Province of Bolzano, there is no experimental evidence of the response to block impacts of the ANAS barrier type.

In order to evaluate the effectiveness of this structure against possible rockfall events, a numerical study has been carried out, which can yield information on the behaviour that this structure would exhibit in full-scale testing conditions. Results of such analyses enable a thorough investigation of the structure force-displacement response along with an estimate of its nominal energy absorption capacity.

To this end, a prototype of ANAS barrier was devised, as schematically illustrated in Figure 7, according to typical full-scale testing conditions, i.e. a prototype made up of three functional modules and each module featuring an interception structure, a support structure and special connecting components. The interception structure is made of 12 mm longitudinal ropes, equally spaced; the support structures are made of two internal and two external I-beams; the connecting components are two side cables, each 18 mm in diameter. Eyelets let the ropes move through the posts while vertical movements are prevented. The dimensions of the module are described by the barrier height, defined as the distance between the top and the bottom longitudinal ropes (h_N = 3.2 m) and the post spacing (I = 5 m). Posts are fully restrained at their base.

A FE model of the prototype has been then developed according to the model proposed by Gentilini et al. (2011): the interception structure was modelled with one-dimensional truss elements and no flexural rigidity. For the side cables, truss elements were used as well. For the posts, one-dimensional beam elements were adopted with flexural rigidity. The one-dimensional constitutive behaviour assigned to these elements is schematically shown in Figure 8, in terms of stress-strain and moment-curvature. In particular, an elastic perfectly plastic behaviour was introduced for the I-beams (Figure 8a). All the ropes were assumed to have a simple bi-linear, elastic hardening-plastic behaviour with no ability to sustain compressive stresses (Figure 8b), as it is observed on cables in conventional tensile tests (Fontanari et al., 2009; Castro Fresno et al., 2008).

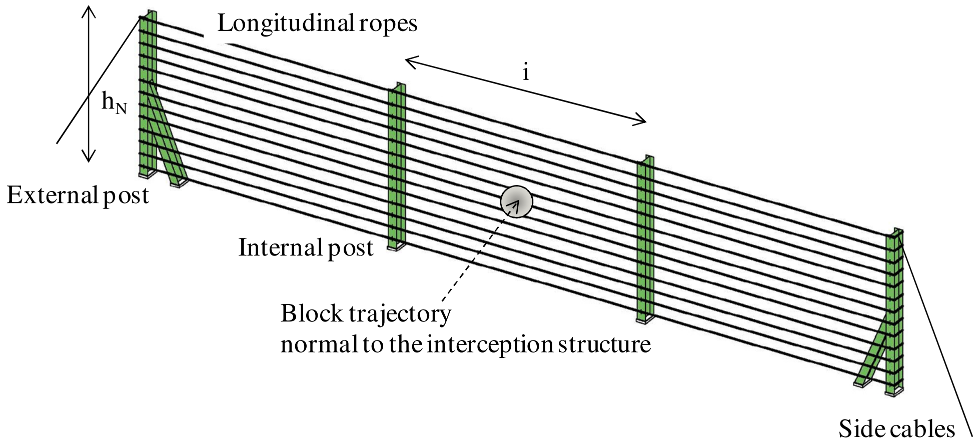

Fig. 7 FE Model of the ANAS type of semi-flexible falling rock protection barrier: geometry and impact conditions

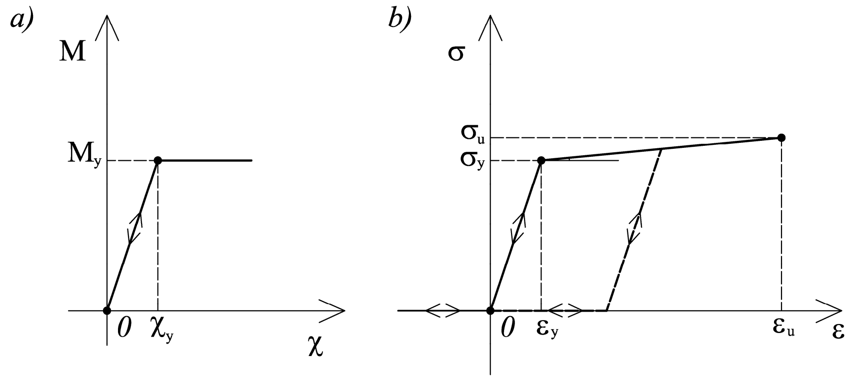

Fig. 8 FE Model of the ANAS type of semi-flexible falling rock protection barrier: material properties a) posts, b) interception structure

RESULTS OF THE NUMERICAL ANALYSES ON THE ANAS BARRIER MODEL

Analyses were run following the procedures of vertical-drop test site: the impact of the test block, normal to the centre of the middle functional module, was simulated by a set of lumped masses (311 kg) distributed on the impact area. A velocity was assigned to the masses in the direction normal to

the interception structure plane. Such procedure has been proved effective onto other barrier types (Gentilini et al., 2011).
Results of the analyses enable the behaviour of a given falling rock protection barrier type to be described. In particular, the simulations allow for the identification of a collapse mechanism for the investigated prototype, obtained by observing the development of plastic hinges within the structural components.
As it is illustrated in Figure 9, with reference to the ANAS barrier type, in response to a central impact, plastic zones start to develop at the external posts and then move to the base of the internal posts. Such mechanism was previously observed and used in simplified analytical procedures for the investigation of the behaviour of this structure type (Paronuzzi and Coccolo, 1998). A set of analyses was performed by varying the intensity of the velocity vectors in order to identify a threshold level after which the model no longer converges. Such velocity level, combined with the applied mass value, provides the maximum kinetic energy that the model is able to absorb prior to fail. Such value was taken as the barrier type nominal capacity, in the case of the analysed ANAS barrier type 50 kJ.

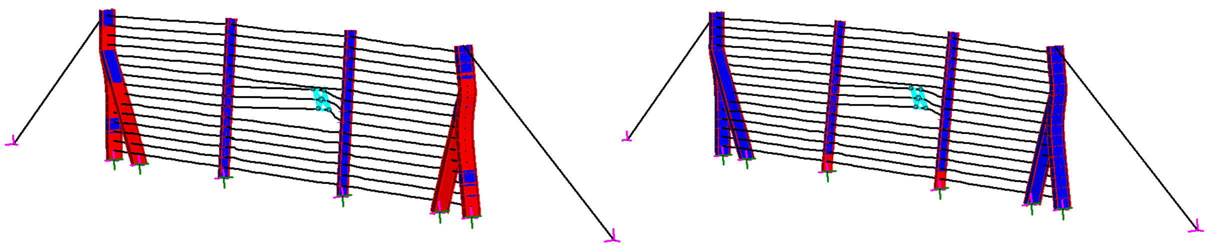

Fig. 9 Results of FE analyses of the ANAS type of falling rock protection barrier: failure mechanism

Results provide also information on the system maximum displacements. The time-history of the barrier elongation, given by the movement of the impact points in the direction normal to the interception structure, is given in Figure 10a. The peak value on the curve (1 m for the ANAS barrier type), when compared with the in-situ minimum distance between the barrier and the protected items, gives a further crucial information on the barrier effectiveness against rockfall.
Other relevant results are those concerning the reaction forces developed at the foundations. Again, the peak value on the curve can be suitably used to verify the adequacy of such foundation design. For the ANAS prototype, the tensile force developed at the side anchorages is given in Figure 10b, while the time histories of the force and moment resultants mobilised at the internal post foundations are shown in Figure 10c and 10d.
These results provide the reference data for all the barriers installed within the Autonomous Province of Bolzano and catalogued in the ANAS barrier type group. Since these barriers can be found on the Bolzano territory in several geometrical (post spacing, nominal height) and mechanical (posts and rope sections) configurations, parametric analyses were run to investigate their influence. Noting that parameter values in italic are those of the reference model, results of the simulations are summarised in Table 1, with relation to the capacity values and maximum forces and moments acting on the foundations. Results were obtained by varying one parameter at time on the reference barrier model. A preliminary parametric study was also carried out to investigate the effects of the impact location and results are also reported in Table 1. In particular, the structure response was studied for impacts onto the top longitudinal rope (top) and side span (lateral). More details can be found in Gorlato (2011). As it can be observed, the barrier capacity increases with its dimensions, both in terms of post spacing and height. Higher posts sections produce higher capacities, whereas larger rope diameters produce lower capacities. The capacity of this barrier type, as predicted by numerical analyses, is found between 30 and 90 kJ. It is also worth noticing that non standard and symmetric impact conditions can significantly reduce the barrier capacity.

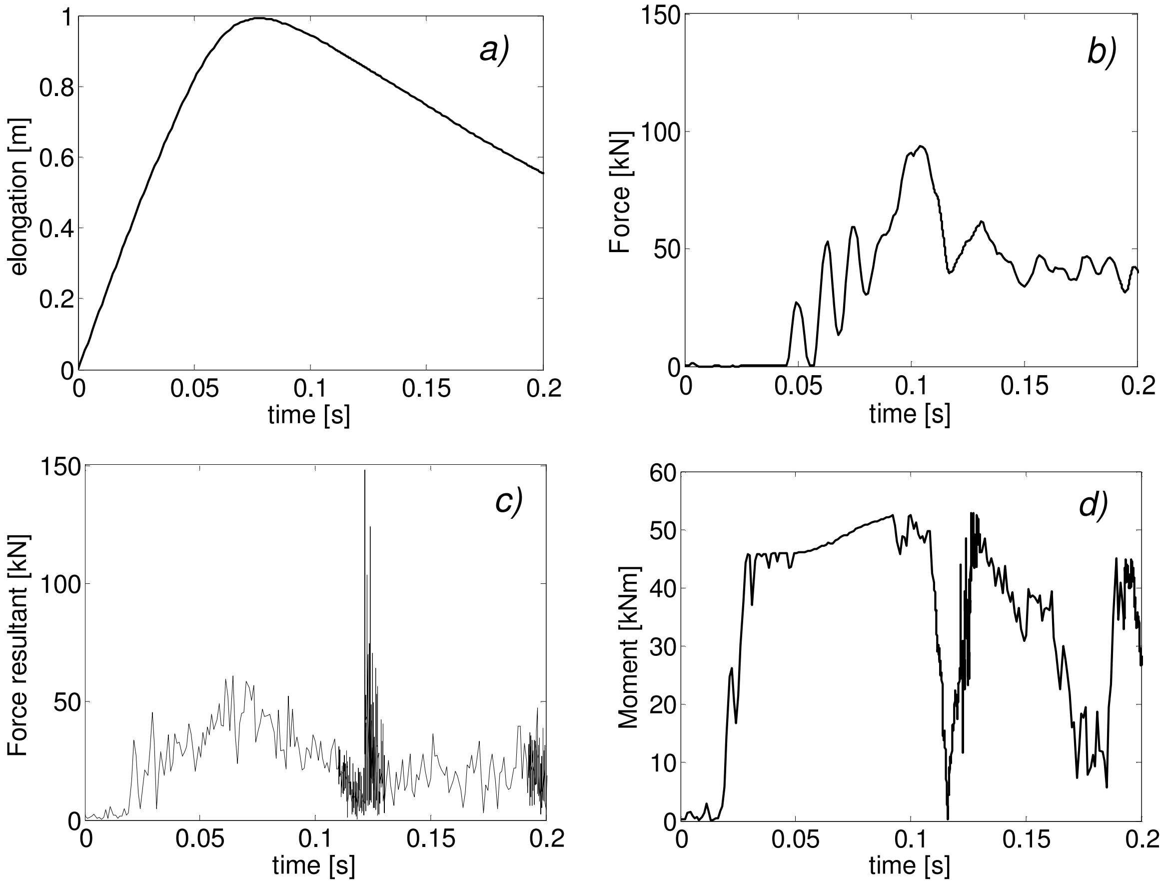

Fig. 10 Results of FE analyses of the ANAS type of falling rock protection barrier: time histories of a) the barrier elongation, b) the tensile force at one side anchorage, c) the force resultant at one internal post foundation and d) the resultant moment at one internal post foundation

Tab. 1 Parametric analyses on the ANAS type of semi-flexible falling rock protection barrier

Parameters		Capacity [kJ]	Max reaction force [kN]	Max reaction Moment [kNm]
Post spacing i	3.5 m	40	600	50
	5 m	*50*	*600*	*50*
	6.5 m	70	500	55
Nominal height h_N	2 m	40	500	55
	3.2 m	*50*	*600*	*50*
	4 m	70	400	50
Internal posts diameter	*IPE 200*	*50*	*600*	*50*
	IPE 220	70	600	60
	IPE 240	90	700	80
External posts diameter	IPE 270	40	550	50
	IPE 300	*50*	*600*	*50*
Longitudinal rope diameter	*12 mm*	*50*	*600*	*50*
	16 mm	30	600	50
	18 mm	30	700	50
Impact conditions	*central*	*50*	*600*	*50*
	top	30	350	50
	lateral	30	600	45

CONCLUDING REMARKS

The paper has presented a procedure to investigate the behaviour of the falling rock protection barriers at present installed within the territory of the Autonomous Province of Bolzano. The procedure has been developed from the information collected in a database of all the barriers catalogued within the inventory of all the protection works of the Province territory. The aim of the study is to provide the data relevant to the description of the effectiveness of these special structures toward possible rockfall events. The data enabling the description of the behaviour of these structures in dynamic conditions are generally available only for high-capacity falling rock protection barriers, as they are typically subjected to suitably developed full-scale tests, while no experimental evidences on the response to block impacts of lower capacity falling rock protection barriers are currently available. A FE procedure, recently developed and assessed, has been then applied to investigate numerically the response of such low capacity barriers in conditions similar to those encountered in a test site. The procedure has been applied to various barriers and presented in the paper with reference to the widely used ANAS type. Results of the simulations provide parameters relevant to the evaluation of the effectiveness of this structure type against rockfall, such as the barrier absorption capacity, deformation and force mobilised at the foundations. Results of specific parametric analyses were also briefly presented.

This study forms part of the research activities of the European project PARAmount: imProved Accessibility, Reliability and safety of Alpine transport infrastructure related to MOUNtainous hazard in a changing climate.

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