A tool for monitoring rockfall protection works and plan the maintenance: the case of the autonomous region of Valle d'Aosta

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A tool for monitoring rockfall protection works and plan the maintenance: the case of the autonomous region of Valle d'Aosta

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Rockfall net fences and drapery meshes constitute two of the most adopted protective structural works against rockfall hazard. During their life, they are subject to ageing, corrosion, and impact loads, with a consequent loss of efficiency or even effectiveness. Due to the variability of the environment and, more in general, to external conditions, a definition of a service life, although not unique but different product by product, is not achievable.
A quick-assessment procedure to evaluate the degree of conservation of these works based on a multi-hierarchical assessment of the damages, already proposed by the Authors, is herein enhanced and applied with a particular focus on net fences. The main components of a net fence, considered as a system, are identified, as well as all the potential damages and a check list to be compiled by experts during the periodic survey is prepared within a codified report form. The report form, specifically created by the Authors, allows to collect data related both to the state of conservation and the original characteristics of the barrier, enabling a precise geolocalisation and census of the protective measures.
The effects of each potential damage on the overall behaviour are considered through the definition of classes of importance. Combining these lasts with the output of the check list for each potential damage, two qualitative indicators, i.e. the diffusion score and the state of functionality, are calculated and, in turn, merged to obtain a qualitative degree of efficiency and a level of maintenance need. A survey campaign realised in the Valle d'Aosta Region (Italy) is presented and the results highlight interesting aspects and suggestions that should be considered in the risk management procedure.
Keywords: *rockfall, net fences, degree of efficiency, management assessment procedure, maintenance.*

1. Introduction

Rockfall represents one of the most hazardous natural phenomena in mountainous areas, or even in mining environment, which can cause severe damages to infrastructures, buildings, and populations (Guzzetti *et al*., 2004; Volkwein *et al*., 2011; Scavia *et al*., 2020). To protect the elements at risk, rockfall net fences are among the most adopted risk mitigation measures, due to their high energy absorption capacity, and their capability to be installed even in hardly accessible places (Chen *et al.,* 2013; Marchelli *et al*., 2021). In particular circumstances, e.g. in case of subvertical weathering rock faces prone to infrastructures, drapery meshes, both simple or reinforced, represent a profitable solution (Giacomini *et al*, 2012; Gabrieli *et al.,* 2017; Marchelli & Giacchetti, 2021).

As civil structures, a service life, i.e. the period of time in which a structure performs its functions without unexpected or extraordinary maintenance or repair, has to be defined also for such structural works. Focusing on net fences, EAD 340059000106 (2018) defines a working life (i.e. service life) for the intended use of 25 years, provided that they are correctly installed, used, and maintained, assuming that no rock impact occurs, and considering an atmospheric condition in terms of corrosivity category equal to C2 (EN ISO 9223). For corrosivity categories C3 and C4 a working life of 10 years can be considered. However, the document states also that in general, in normal use conditions, the real working life may be considerably longer. Similarly, EAD 230008000106 (2016) and EAD 230025000106 (2016) provide similar considerations. In particular the former, related to simple draperies with double twisted steel wire mesh reinforced or not with ropes, defines a working life of 25 years for corrosivity class C1 and C2 and dry conditions, and 10 for C3, on the basis of the current state of the art and the available knowledge. The latter, related mainly to reinforced draperies, assumes a working life for the intended use of 50 years, for corrosivity class C2. Both documents state that these are indications and, thus, cannot be interpreted as a guarantee.

Generally speaking, the environmental conditions in which these works are subjected, together with their execution, use and maintenance, can significantly vary the real working life.

In territories in which both the extension of infrastructures potentially subjected to rockfall and the frequency of rockfall events are relevant and, of course, in which protective measures are extensively employed, the knowledge of the residual efficiency and the maintenance requirements of each work is fundamental to manage the risk and plan maintenance interventions (Govoni *et al*., 2011, Lambert *et al*., 2021, Luciani *et al*., 2018; UNI 11211-5:2019). To achieve such goal, a quick-assessment procedure to evaluate the degree of conservation of drapery meshes (Marchelli *et al*., 2019) and net fences has been developed (Marchelli, 2020) and validated through several inspections performed by the Authors since 2014 (Dimasi *et al*., 2015). Focusing on net fences, the procedure, based on a multi-hierarchical assessment of the damages, is herein enhanced by providing a unique qualitative indicator of the level of maintenance/interventions need. This parameter is additional to the state of functionality of the system and the diffusion score, which are obtained with the already published methods (Marchelli *et al*., 2021). This last indicator responds well to the interventions planning requirement of Authorities. The method has been extensively adopted in the Autonomous Region of Valle d'Aosta.

The paper presents the methodology, in its enhanced version, some examples are proposed, considering a survey campaign performed in Valle d'Aosta (Italy) as representative. The results of its application are reported and discussed.

2. Method

The concept behind the method derives from some important observations performed during inspections over the years. Considerations and methodology are reported focusing specifically on net fences but can be extended to drapery meshes in a similar manner. Different issues can affect the integrity and effectiveness of net fences, considered as a system, that can be grouped as follows:

1. context surrounding the work: reduction in overall efficiency, hence effectiveness, caused by phenomena not directly dependent on the structure or its components, e.g., a planar sliding of the slope on which the barrier is founded;
2. design and installation: reduction in overall efficiency, therefore effectiveness, linked to not proper design and/or executive aspects;
3. incorrect maintenance: arbitrariness of choice of performance recovery intervention by unqualified personnel and/or depending on the requested timing;
4. impacts, even smaller (in size) than expected in the design, with a lack of maintenance;
5. ageing and corrosion, due to absence of maintenance procedures.

Neglecting the design aspect, several damages frequently observed relate with installation errors, and suitable or unsuitable certified technologies (Fig. 1). Focusing directly on degradation and ageing incorrect/absent maintenance procedures, among the problems, the ones related to vegetation, directly interacting with the works or otherwise influencing their performances, are the most common. Corrosion has been frequently observed in several components, even in the anchors, where disrupted. Accumulation of debris, due also to impacts with energy much smaller than the design one, as well as impacts of element differing from rock blocks, i.e. trees after some severe or unexpected

Fig. 1 – Installation errors, and unsuitable or not certified technologies.

Fig. 2 – Accumulation of debris, due also to impacts with energy smaller than the design one (a), and impacts of element differing from rock blocks, i.e. trees after some severe or unexpected climatic events (b).

climatic events, represent recurring situations highlighted during inspections (Fig. 2).

To face all these different situations, the need of an urgent codified method, became almost mandatory. The philosophy behind the proposed method starts from some preliminary observations:

1. the presence of a great variability of technologies also in the same area;
2. local damages can affect the global efficiency in different ways;
3. the damage of a unique element, but fundamental, can compromise the entire system.

Consequently, to define a method of general validity, following observation (i), some main fundamental components have been identified and, following the (ii), all the *n* potential damages related to each component have been defined and assessed. Finally, the idea to assign to each potential damage a level of importance in respect to the entire system derives from the observation (iii). Starting from the hypothesis of initial effectiveness and efficiency of the system, the state of efficiency can decrease until the system becomes not only inefficient but also ineffective, i.e. it completely loses its functionality.

The method is thus based on two fundamental steps: (i) the assessment of the state of damage *d* (from the operator's site survey) for each of the *n* potential damages, (ii) the evaluation of a class of importance *C* (a priori, by the Authors) that details how the different potential damages on the various components modify on the integrity of the system, i.e. how they affect the functionality of the system itself. Three states of damage are considered: *d0*, *d1* and *d2*, for no, moderate, or intense damage, respectively. Similarly, three classes of importance are identified: *C1, C2* and *C3*, i.e. unimportant, moderately important, and very important, respectively. Table 1 shows the *n* potential damages and the associated value of *C*.

From these steps, it is possible to provide an estimation of the

Tab. I – Check list of all the potential damages with the associated value of *C*, subdivided for each component.

Components	***Check of the potential damages***	***Classes of importance C***
Access roads	Presence of vegetation and/or weeds that obstruct access to the work	DOES NOT COMPLY with the total
Slope	Presence of voids at the foot of the barrier	C3
	Presence of elements that limit the deformation capacity of the barrier (e.g. tall vegetation species or bushes close to the barrier, interference between rows)	C3
Primany net	Presence of debris/blocks/notches in the net	C3
	Presence of brush, shrubs and/or creepers in the net	C1
	Tears in the net	C3
	Deformations	C2
	Presence of rusty areas and/or significant damage to the anti-corrosive coating of the net	C1
	Deterioration/damage/corrosion of net panels connections	C2
	Detachment/absence of net panels connections	C3
	Breakage of net-rope junctions	C3

follows tab. I

Components	***Check of the potential damages***	***Classes of importance C***
Secondary net check if not provided ☐	Presence of tears, deformations and/or perforations	C1
	Presence of rusty areas and/or significant damage to the anti-corrosive coating of the net	C1
	Presence of shrubby and/or climbing plant species	C1
Posts	Presence of rusted areas and/or significant damage to the anti-corrosive coating of both the post and its foundation system	C1
	Presence of shrubby and/or climbing plant species	C1
	Damage to the base hinge	C2
	Significant deformation and/or breakage of the post	C3
	Variation in the original geometry of the post anchor (e.g. any nails and/or bars (permanently bent or deformed, fractured or extracted elements and the connection system)	C2
Top support ropes check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C2
	Damage to the rope/post head connection or detachment from the head restraint elements*. *(1 = damage to the connection; 2 = detachment from the restraining elements)	C3
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C2
	Detachment/absence of anchors	C3
	Deterioration/Damage/Corrosion of connecting elements	C2
	Detachment/absence of connecting elements	C3
	Brakes: presence of plant species/debris in the brake sliding area	C2
	Brakes: permanent deformation or sliding	C3
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1
Bottom support ropes check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C2
	Damage to the rope/post foot connection or detachment from the foot restraint elements*. *(1 = damage to the connection; 2 = detachment from the restraining elements)	C3
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C2
	Detachment/absence of anchors	C3
	Deterioration/Damage/Corrosion of connecting elements	C2
	Detachment/absence of connecting elements	C3
	Brakes: presence of plant species/debris in the brake sliding area	C2
	Brakes: permanent deformation or sliding	C3
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1
Lateral ropes check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C2
	Damage to the rope/post head connection or detachment from the head restraint elements*. *(1 = damage to the connection; 2 = detachment from the restraining elements)	C2
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C2
	Detachment/absence of anchors	C3
	Deterioration/Damage/Corrosion of connecting elements	C2
	Detachment/absence of connecting elements	C3
	Brakes: presence of plant species/debris in the brake sliding area	C2
	Brakes: permanent deformation or sliding	C3
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1

follows tab. I

Components	***Check of the potential damages***	***Classes of importance C***
Upslope ropes check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C2
	Damage to the rope/post head connection or detachment from the head restraint elements*. *(1 = damage to the connection; 2 = detachment from the restraining elements)	C2
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C2
	Detachment/absence of anchors	C3
	Deterioration/Damage/Corrosion of connecting elements	C2
	Detachment/absence of connecting elements	C3
	Brakes: presence of plant species/debris in the brake sliding area	C2
	Brakes: permanent deformation or sliding	C3
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1
Downslope ropes check if the ropes are not provided ☐ check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C2
	Damage to the rope/post head connection or detachment from the head restraint elements*. *(1 = damage to the connection; 2 = detachment from the restraining elements)	C2
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C2
	Detachment/absence of anchors	C3
	Deterioration/Damage/Corrosion of connecting elements	C2
	Detachment/absence of connecting elements	C3
	Brakes: presence of plant species/debris in the brake sliding area	C2
	Brakes: permanent deformation or sliding	C3
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1
Other ropes check if the ropes are not provided ☐ check if the anchors are not provided ☐ check if the brakes are not provided ☐	Ruptures, even partial ones, with important lesions of the constituent threads	C3
	Slack or abnormally tight rope (even one)	C1
	Damage to the rope connection * *(1 = damage to the connection; 2 = detachment from the restraining elements)	C1
	Presence of rusty areas/significant damage to the corrosion protection coating of the rope	C1
	Presence of shrubby and/or climbing plant species	C1
	Deterioration/damage/corrosion of the anchors (or anchors head)	C1
	Detachment/absence of anchors	C2
	Deterioration/Damage/Corrosion of connecting elements	C1
	Detachment/absence of connecting elements	C2
	Brakes: presence of plant species/debris in the brake sliding area	C1
	Brakes: permanent deformation or sliding	C2
	Brakes: presence of rusty areas/significant damage to the anti-corrosive coating	C1

degree of efficiency of the system, and a double matrix system provides the calculation of two qualitative indicators:

1. through a 3×3 matrix (illustrated in Table 2), P_i scores are identified, associated with each potential damage according to its importance class and damage level. This allow to obtain an overall percentage score of the system, called diffusion score, as:

$$P_{tot} = \frac{\sum_{i=n}^{n} P_i}{P_{\max}} \quad (1)$$

where Pmax = $5n_{c3} + 3n_{c2} + 2n_{c1}$, being n_{c3}, n_{c2}, n_{c1} the number of

Tab. 2 – Matrix to evaluate P_i scores to be associated to each potential damage according to its importance class and damage level.

C/d	C1	C2	C2
d0	P_i=0	P_i=0	P_i=0
d1	P_i=1	P_i=2	P_i=3
d2	P_i=2	P_i=3	P_i=5

Tab. 3 – Matrix to assign a state of functionality *A* to each potential damage according to its importance class and damage level.

C/d	C1	C2	C3
d0	A0	A0	A0
d1	A0	A0	A1
d2	A0	A1	A2

potential damages having importance class *C3, C2* and *C1*, respectively. This diffusion score allows to define qualitatively the number of damages;

2. through a 3x3 matrix (reported in Table 3), a state of functionality *A* can be reached to be associated to each of the *n* potential damages according to its importance class and damage level. By cross-referencing the corresponding class and the damage level given by the operator, a state of functionality of the system A_{tot} equal to the worst considering each of the *n* potential damages:

$$A_{tot} = \text{worst } (A)_1 \ldots n \qquad (2)$$

It follows that even a single damage, but of importance class *C3* and damage level *d2*, can cause the loss of functionality.

To produce a qualitative subdivision of the efficiency status into 4 levels, as more management-oriented for identifying intervention priorities, the two previous indicators are combined to produce the classification proposed in Table 4, which refers to both the need of maintenance/interventions and a resulting degree of efficiency.

This scheme is implemented by means of survey and evaluation sheets, i.e. reports of inspection. These reports, codified by the Authors, allow localizing, describing, and assessing the state of conservation for each net fence, providing also a powerful tool to conduct a census of the protective works. After the registry of the name of the operator and the date, a code is associated to each net fence and a first descriptive section has to be filled in by the inspector. In this part, the geographical localization is provided together with general and, if possible, detailed information related to the whole net fence and its components in its original configuration. The availability of the design drawings/project and monitoring/maintenance documents is reported. This first part allows localizing and knowing the original state of the works. A second section is composed by the check list of Table 1, in which the *C* parameter is obscured to avoid influencing the filling in. This should be filled in indicating the degree of damage for each potential damage; a column for additional notes, i.e. locating the damage and reporting its extent, is added. A third part with conclusions to sum up what observed and a photographic apparatus complete the sheet. It reveals that the two indicators and the level of maintenance/interventions need are evaluated a posteriori.

3. Example of application

In this section, the results of an example of application are provided. In particular, on July 2022, net fences protecting three sections of the regional roads of Valle d'Aosta Region were inspected, as representative. Neglecting the semi-rigid and the rigid barriers, a sample of 45 net fences has been analysed. Figure 3 displays the obtained results in terms of need of interventions, as reported in Table 4. The great majority of the samples highlights a necessity of maintenance, even though half of the inspected structures is in a medium-high degree of efficiency (i.e. medium level maintenance need). Among

Tab. 4 – Needs of interventions according to P_{tot} and *A* indicators.

Maintenance/intervention need	Degree of efficiency	Conditions	
Low	High	A=A0	$P_{tot} < 0.15P_{max}$
Medium	Medium-High	A=A0	$P_{tot} \geq 0.15P_{max}$
		A=A1	$P_{tot} > 0.30P_{max}$
Medium-High	Medium	A=A1	$P_{tot} \geq 0.30P_{max}$
High	Low	A=A2	

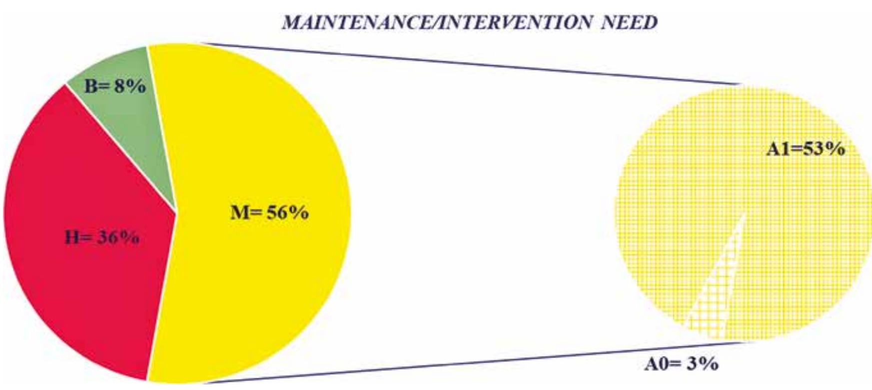

Fig. 3 – Results of the survey in terms of interventions need, as reported in Table 4.

these last, the indicator *A* reveals to affect the ascription of the protective works in the medium level of maintenance need, as for the great majority of the cases, *A* is equal to *A1*, and $P_{tot} < 0.3P_{max}$. No medium-high level of maintenance need is observed, while only 8% has a high degree of efficiency.

Analysing in detail those net fences that display a high need of interventions, the presence of significant void at the foot of the barrier reveals to be the major issue, together with the presence of elements limiting the deformation capacity of the barrier (Figg. 4 and 5). Both these aspects are highlighted in the 62% of the samples (and in many cases they are observed together), while in 31% the presence of debris/blocks/notches in the net is shown. Considering also P_{tot} values, this indicator is lower or equal 15% in all the cases, revealing that in the great majority the indicator *A* mostly affects the results. This implies that, even though high priority levels of maintenance are required, the maintenance procedures to adopt would involve only a single aspect/damage, i.e. closing the net at the bottom, removing blocks or trees interacting with the net are the only actions required.

Fig. 4 – Frequent observed damages: voids at the foot of the barrier (a), debris/blocks/notches in the net (b), and elements limiting the deformation capacity of the barrier (c).

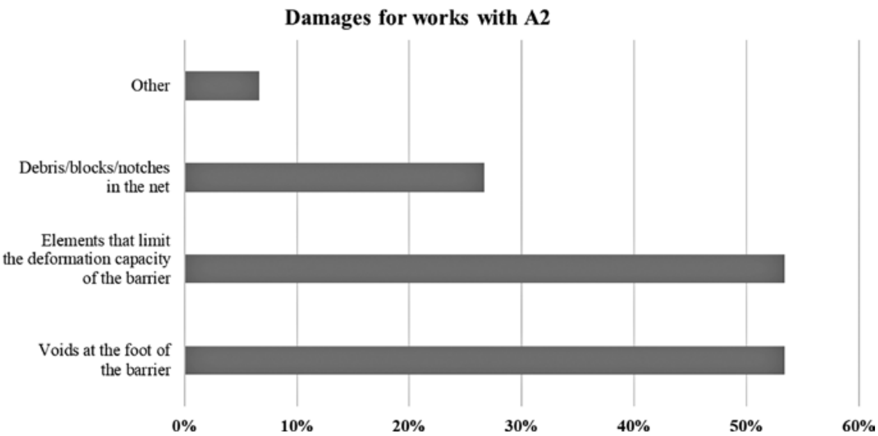

Fig. 5 – Histogram of the observed damages, which lead to a state of functionality equal to A2.

Among the potential damages which can lead to, at least, a medium or medium-high maintenance need, corrosion is the most observed, together with small voids at the bottom and little presence of elements interfering with the net. A very frequently observed potential damage, even secondary, is related to the presence of vegetation, which can make difficult to see and inspect the barrier (Fig. 6). In many cases, thus, an operation of periodic vegetation clearance is strongly suggested. If not periodically removed, the vegetation can promote the occurrence of collateral damages, e.g. corrosion due to the humid environment, and for some species, the trunk could limit the deformation capabilities of the barrier or the sliding capacity of the breaks.

All these results and observations are of great importance for the Authorities, who can define the priorities of interventions together with the economic resources required. In addition, information on the number of damages is provided.

Of course, defining a precise timing for the intervention is difficult to achieve and the periodic inspections could be followed, in case of urgent or medium-high need of maintenance, by integrity inspections to properly evaluate the requested interventions and procedures. Integrity inspections could be also planned for medium need of maintenance or after a predefined number of periodic inspection, e.g. 3 times.

4. Conclusion

The definition of a service life for rockfall protective measures represents an issue difficult to tackle. Environmental and external

Fig. 6 – Presence of dense vegetation.

conditions, even human-driven, can reduce the expected working life significantly. Consequently, a quick-assessment procedure to evaluate the state of conservation and to define the need of maintenance can provide a profitable solution to manage and plan the maintenance, especially for Authorities who have to administer a huge territory.

Focusing on net fences, the Authors present an enhanced profitable tool through which a qualitative degree of efficiency is obtained. Periodic inspections should be performed, during which a pre-determined check list of the all potential damages should be filled in indicating the degree of damage. For each potential damage a class of importance, related to the influence of each damage on the system, was associated by the Authors. Merging these lasts with the output of the check list, two different indicators are calculated to qualitatively define the number of damages and the state of functionality of the system: the diffusion score P_{tot}, and the state of functionality A. Finally, combining the two indicators, a degree of efficiency and, thus, a level of maintenance need is obtained.

A survey campaign was conducted in Valle d'Aosta (Italy) where net fences protecting three sections of the regional roads have been inspected. The great majority require a medium level of maintenance, while the 36% a high level. This last is mainly due to the presence of significant voids at the foot of the barrier, or of elements limiting the deformability of the net. Also the presence of dense vegetation should be taken into account as it can lead to other collateral damages, i.e. corrosion.

These examples provide a powerful tool for Authorities to manage expenses and define a priority of interventions.

Future perspective could link the degree of efficiency of the protective elements, hazardousness of the area, and the vulnerability of the elements at risk, in order to assess the safety and a level of remaining risk.

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