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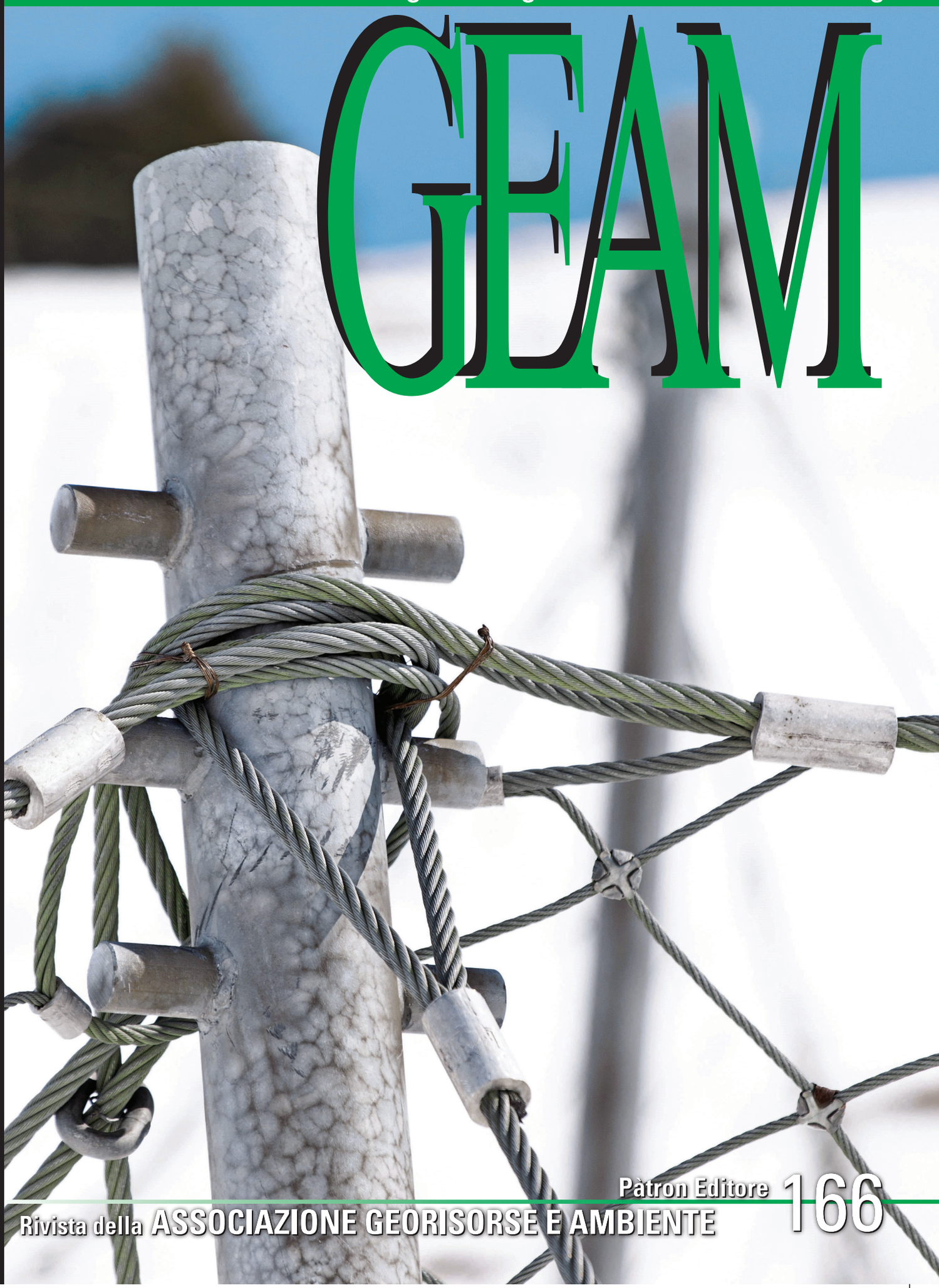

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Editoriale
25 anni di Geoalp - Winter Cup

L'evento Geoalp Winter Cup è stato avviato 25 anni fa dal dr. Ludwig Noessing allora direttore dell'Ufficio Geologia e Prove Materiali e un giovane gruppo di geologi locali per aprire un forum di informazione professionale tra geologi e ingegneri geotecnici e professioni affini. L'obiettivo era quello di organizzare periodicamente queste informazioni per garantire una formazione continua dei professionisti e raggiungere gli amministratori e la popolazione. Lo sguardo è sempre andato anche oltralpe invitando i colleghi austriaci alla partecipazione. Geologia, Geotecnica e Geologia Ambientale sono stati il focus delle interessanti giornate congressuali per ben 25 anni.

In occasione del Giubileo è stato organizzato un convegno diviso in due sessioni, una prima dedicata alle novità nell' ambito della mitigazione del rischio caduta massi è stata concepita in collaborazione con il Politecnico di Torino, e una seconda dedicata ai principali progetti infrastrutturali degli ultimi anni sul territorio.

Questo numero di Geam è dedicato alla prima sessione, la mitigazione del rischio caduta massi. A questo seguirà un numero dedicato alla seconda sessione.

Dott.ssa Claudia Strada

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Quantitative rockfall physical risk on settlements: an example

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A quantitative assessment of the risk of rockfall on a local scale is a complex and challenging task since both the randomness of the natural event and the unpredictability of the behaviour of the elements at risk must be considered. From a technical standpoint, the impact of a block against a building is a phenomenon with a lot of variability, because the location of the impact point on the building (e.g. pillar, infill, roof) affects the level of damage and the possibility that the damage will spread throughout the entire structure. Similarly, impact energy can enhance the level of damage. Logic trees (or event trees) can be used to solve such problems in engineering systems. Event trees, in particular, allow a collection of probability outcomes for a given event to be calculated. As a result, if a block collides with a building, one can estimate the likelihood of hitting either a column (essential component of a concrete structure) or an infill wall (nonstructural component). Different scenarios may occur depending on the hit element, all of which can be represented using the event tree. In this technical note, an example of application of the approach is proposed to compute the physical risk on a settlement in a rockfall hazardous area.

Keywords: *Event tree analysis, rockfall, building.*

1. Introduction

The risk is the product of hazards, vulnerability and values of elements at risk (Scavia *et al*., 2020). The quantification of rockfall risk on buildings is a complex task since several variables are involved (De Biagi *et al*., 2015). On one side there is the natural phenomenon that must be correctly modelled. The quantification of the main kinematic parameters, i.e., velocity and height of the trajectory, needs specific and detailed modelling and a distribution of results rather than a single value is usually obtained as output of the propagation analyses. On the other, the physical phenomena involved when a rock boulder impacts against a structural element are non-trivial (Delhomme *et al*., 2007; Bertand *et al*., 2015; Ventura *et al*., 2017).

The behavior of the construction following the impact of a falling block is the vulnerability term of the risk equation. So far, several approaches have been proposed to compute the vulnerability of buildings. Li *et al*. (2010) proposed vulnerability curves that depend on building characteristics (construction type, material, etc.) and velocity of the landslide, with the possibility of accounting for slow and fast moving phenomena. Agliardi *et al*. (2009) analyzed the damages due to a real rockfall events on an urbanized area in North-Italy and computed a function that links block kinetic energy to the "degree of loss". Delhomme *et al*. (2007), first, and Bertand *et al*. (2015), later, focused on the behavior of single structural components subjected to rockfall impact. Mavrouli and Corominas (2010) introduced a method to account the effects on building structure of the impact of a block against a structural member. Mavrouli *et al*. (2014) suggested the application of fragility curves to evaluate the degree of loss of buildings impacted by rockfalls. Vallero *et al*. (2020) proposed a set of calculations to evaluate the vulnerability of buildings with load bearing walls based on the possible collapse mechanisms of structural masonry.

De Biagi *et al*. (2015) proposed an event tree risk analysis focusing on the possible failure of structural and nonstructural components of building impacted face. Differently from the previous cases, this approach considered the possibility that the impact against nonstructural components can create a harm to the occupants of the building. Although the approach allows to draw all the possible scenarios that can verify when the impact occurs, its application is still non-trivial.

The present technical note presents an example of an event-tree analysis on structural and nonstructural components of a settlement subjected by rockfalls. The physical risk, i.e., the reparation cost, is the evaluated parameter, while social and societal risks are not considered herein. The paper is organized as follows. Section 2 details the bases of event tree analysis and risk calculation, Section 3 directly jumps into the worked example.

2. Quantiative rockfall risk assessment on buildings

The adopted methodology follows the approach proposed by De Biagi *et al*. (2015). A multi-step decision

analysis based on event-tree framework is thus considered. Event-tree is a modeling technique for scenarios derived from success and failure outcomes. The event tree starts from a single initiating event following which several possible consequence are possible. To each outcome a probability is attributed (Marchelli *et al*., 2021). The approach accounts for the fact that a falling block can impact against a structural or a nonstructural component of the building. In the former case, the collision can engender a local damage that might propagate into a progressive collapse and causes the failure of the structure. In the latter, the damage remains local and does not propagate. The definition of the possible scenarios results from the occurrence of a sequence of events related to the local effects of the impact (local damage) and the propagation of the damage itself to the remaining part of the structure. A probability is assigned to each sub-event and the probability of each final scenario is the product of the probabilities of the events that describe it (De Biagi *et al*., 2015).

As the vulnerability of the building depends on the magnitude of the impact, the velocity of the falling block is considered as a relevant parameter. As described in the following, a unique block mass was considered in the analysis. The total risk is thus evaluated by integrating the possible velocities with respect to their expectation, the vulnerability and the damage.

3. Case study: a settlement in a rockfall hazardous area

3.1. Description of the settlement

To illustrate the procedure previously described, a case study is herein proposed. The elements at risk are represented by two constructions located at the foot toe of a slope along which rockfall events occur. The two buildings are part of a small trade company. Figure 1 sketches a plan view of the settlement. In the upper part, a 50 m^2 rectangular plan building houses the offices of the company, while a 320 m^2 warehouse is depicted in the bottom part.

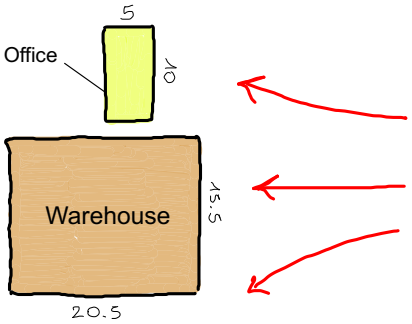

Fig. 1 – Plan of the settlement. Light grey depicts the office building, dark grey represents the warehouse. The arriving direction of the falling rocks is represented by the arrows. The sizes are in meters.

The office building is a one-floor reinforced concrete structure made of six columns (35 cm × 35 cm) disposed along a 4.8 m × 4.8 m grid, as depicted in Figure 2, and one top slab. Masonry infills are present, with a 12+12 cm thick wall. No partition walls are present in the office building. The total height of the office building is 4 m.

The warehouse is a one-floor precasted and assembled reinforced concrete structure made of six columns (50 cm × 50 cm) supporting three precasted prestressed concrete triangular beams. Roof transverse beams are hinged at the columns and the columns are hinged in the foundations. The horizontal capacity of the structure is provided by cross bracings in the cladding made of a double layer of insulating slabs with an aluminum finish. The roof is made of a lightweight steel beam grillage that supports a steel corrugated sheet. The total height of the warehouse building is 8 m at roof

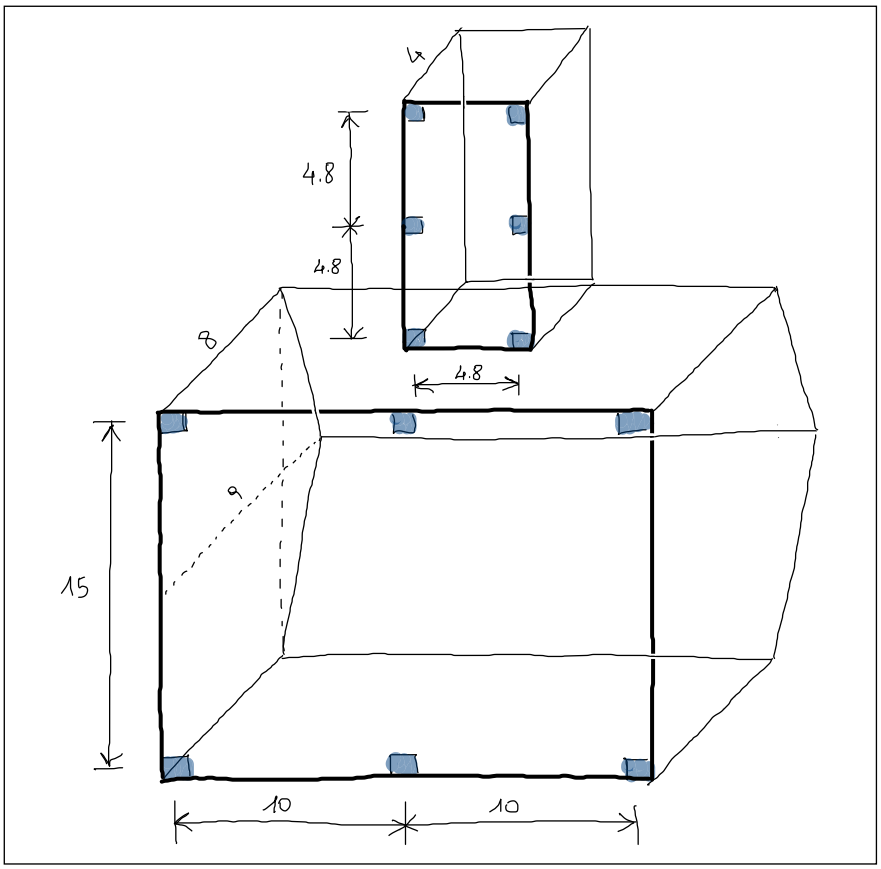

Fig. 2 – Three-dimensional view of the structures of the settlement.

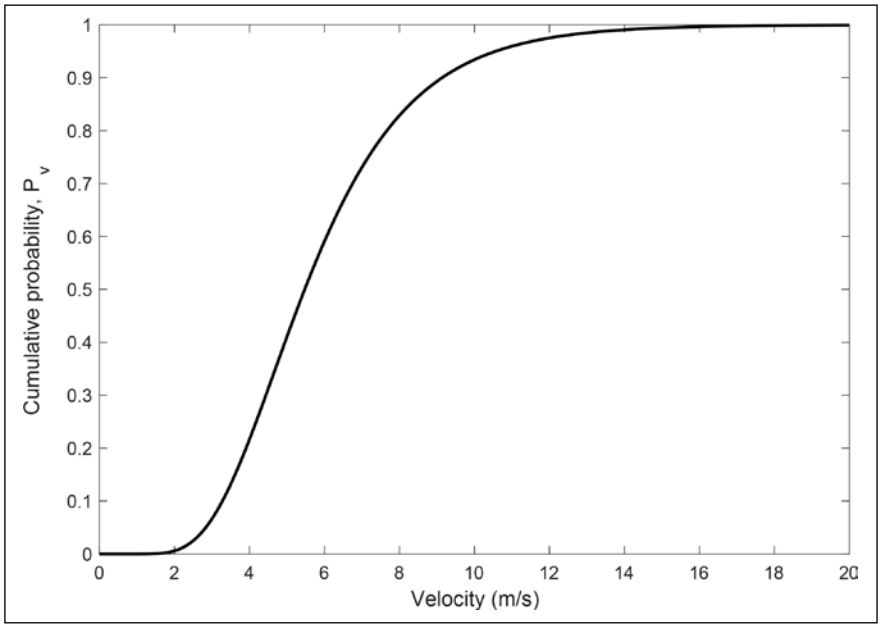

Fig. 3 – Velocity of the blocks at the settlement.

eaves and 9 m at the top of the roof.

Referring to the rockfall phenomenon, for the particular configuration of the source area, well-shaped blocks of around 0.25 m^3, i.e., 500 kg, reach the inhabited area. The average frequency of the events is about 0.1 events per year. Rockfall propagation analyses provide that the cumulative distribution P_V of the velocities of the blocks at the settlement is the one represented in Figure 3.

3.2. Event tree for rockfall risk assessment

This section is devoted to the description of the event tree that describes the effects of the impact of a falling block against the two buildings. The event tree has its root on the source event, i.e., the falling block trajectory reaches the settlement. Usually, tridimensional propagation analyses provide a reaching probability or the number of simulated rockfalls that reach a particular area. Once the block arrives in the inhabited area, two possible outcomes are possible: the impact can occur on the office building or on the warehouse. The probability that the block impacts against the office is smaller than the one that the impact occurs on the deposit since the frontal area (10 m wide) of the former is smaller than the size of the exposed face of the warehouse (15.5 m wide). Briefly, provided that the block arrives in the area, the probability of impact against the office building is 10/(10+15.5) = 0.4, hence the probability of impact against the warehouse is 0.6.

Once the block reaches the exposed wall of the office building, it can impact against a concrete column or against an infill wall. The probability of impact against one of the two components depends on the extent of each of these along the front. The 35 cm x 35 cm concrete columns occupy roughly 10% of the face, while 90% is masonry. If the impact occurs against the masonry, depending on the kinetic energy of the moving rock, a failure of the wall is possible and the block enters and causes damages to the activity. It can be stated that when the block enters, it damages an area as wide as 4 times its diameter. On the contrary, if the falling block strikes a concrete column, which is a structural load bearing component, depending on its kinetic energy, a failure is expected, with the possible activation of progressive collapse mechanisms. In the office building, structural system is not robust and when a column fails, half of the building collapses.

If the block reaches the exposed wall of the warehouse, it can impact against a concrete column or against the cladding. As in the previous case, the probability of impact against one of the two components depends on the extent of each of these along the front. The 50 cm x 50 cm columns occupy the 7% of the face, while 93% is cladding. If the impact occurs against the cladding, depending on the kinetic energy of the moving rock, a failure of the face is possible and the block enters and causes damages in the deposit with an extent (in width) of 4 times block diameter. If the impact occurs against a structural component, since the system is statically determined, the failure of the whole building occurs.

3.3. Damage on concrete and masonry building components

The failure probabilities of the impacted columns are computed with respect to the results proposed by Bertrand *et al*. (2015). To express the probability of failure for a given external action *x*, namely, the energy of the impacting block or its velocity, fragility curves can be adopted. They consist in a continuous function between 0 and 1 expressed as

$$p_f = \Phi\left[\frac{\ln(x/\mu)}{\beta}\right] \qquad (1)$$

where $\Phi[°]$ is the standard normal distribution, μ is the median of failure and β is the dispersion. Based on the fragility curves obtained

Tab. 1 – Parameters of the fragility curves.

Component	Building	μ (m/s)	β
Column 4 m	Office	4.0	0.17
Column 8 m	Warehouse	6.0	0.17
Infill wall (40 cm)	Office	7.5	0.12
Cladding (25 cm)	Warehouse	4.1	0.10

by Bertrand *et al*. (2015) on impacting blocks of 500 kg mass, it is possible to determine the parameters of the fragility curve for columns of different length (4 m and 8 m). Referring to masonry infills, considering the punching failure described in Vallero *et al*. (2020), the fragility curve was determined for a 40 cm thick wall (f_c = 1MPa). For the cladding a 25 cm thick wall was considered. The details of parameters are reported in Table 1.

3.4. Risk analysis

To estimate the physical risk of the two constructions when impacted by a rockfall, the event tree analysis was performed at various levels of velocity. Following the event tree, four damage scenarios are present:

- the block impacts against the office building, hits a concrete column causing its failure and half of the construction collapses (D1): to this scenario a physical damage of about 50 k€ is attributed
- the block impacts against the office building, hits an infill wall causing an opening (D2): to this scenario a physical damage of about 5k€ is attributed;
- the block impacts against the warehouse building, hits a concrete column causing its failure and one quarter of the construction collapses (D3): to this scenario a physical damage of about 150 k€ is attributed;
- the block impacts against the warehouse building, hits the cladding causing an opening (D4): to this scenario a physical damage of about 20k€ is attributed.

For example the damage D1 is computed as

$$D1 = 0.4 \times 0.1 \times p_f \times 50\ k€ \quad (2)$$

where p_f is computed through Eq.(1) using the parameters related to "Column 4 m" component. Similarly, damages D2, D3 and D4 are evaluated. For a given velocity, the total damage is the sum of the single damages, i.e.

$$D(v) = D1 + D2 + D3 + D4 \quad (3)$$

Figure 4 depicts the values of the damage D(v) at various impact velocities. Considering that a given value of the velocity is defined from the cumulative distribution determined from the propagation analysis, as

$$p_v = \frac{d}{dv} P_V \quad (4)$$

it results that the total risk following the occurrence an event is

$$R = \int_0^\infty D(v) p_v dv \quad (5)$$

In the given example, the resulting total risk is R = 13.02 k€. Remembering that the annual frequency of occurrence of an event is 0.1, the annual risk is equal to 1.302 k€/year.

4. Conclusions

A quantitative assessment of the risk of rockfall on a local scale is a complex and challenging task since both the randomness of the natural event and the unpredictability of the behavior of the elements at risk must be considered. Event-tree is a logical tool that is adopted in engineered systems to understand the potential failure scenarios. Such tool, anticipated by the Authors in the quantification of rockfall risk on buildings (De Biagi *et al*., 2015) or infrastructures (Marchelli *et al*., 2021), has been applied to a case study. A settlement constituted of an office

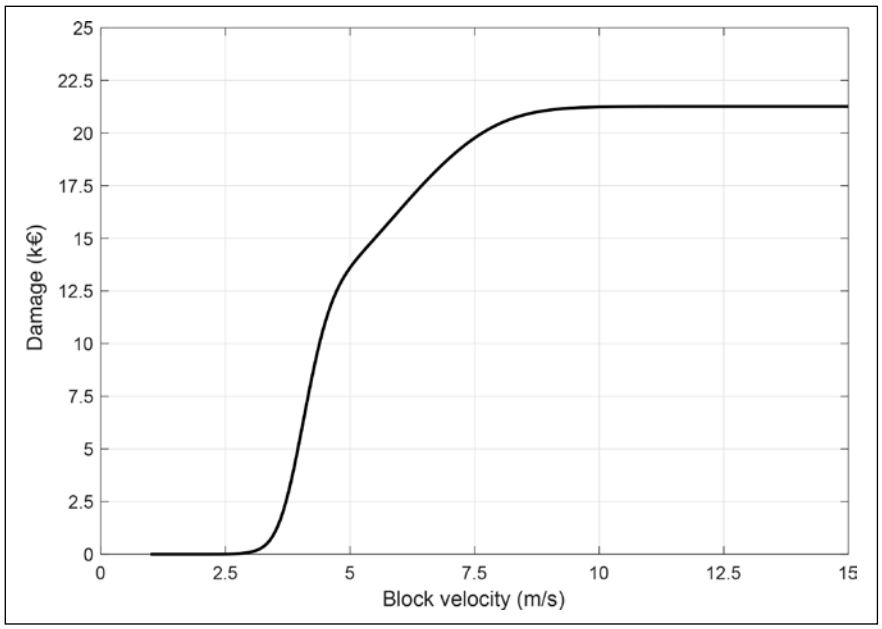

Fig. 4 – Physical damage for various impact velocities.

building and a warehouse located in a rockfall hazardous area served as an example to show the major steps for the quantification of the risk. The proposed analysis, although simplified, shows the potentialities of the method, in particular when the structure is not simple, and structural and nonstructural components are present.

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RaStEM: an ISPRA application for the analysis of the mitigation effects of hydrogeological risk mitigation measures

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The National Repository of hydrogeological risk mitigation measures (ReNDiS) is the platform for monitoring measures funded by MiTE from 1999 onwards which aims to managing the evaluation of funding requests coming from Regions. The platform currently contains 6,402 measures for € 6.962 billion and 9,249 project proposals corresponding to € 29.141 billion.
In the consistent case history of measures for hydrogeological risk mitigation, it has been highlighted that designs do not always adequately take into account the typological and spatial characteristics of the instability and the relations that exist between these and elements at risk.
Starting from this consideration, ISPRA developed a web application, RaStEM (Standardized Representation of Mitigation Effects), with the aim of providing technicians with a public and freely accessible tool that allows them to represent, in a simplified way standardized on national scale, the significant elements of hydrogeological risk mitigation designs.
The expected result is to contribute to spreading a correct design approach in which the elements that contribute to defining the risk scenario are always clearly documented, even in their geographical component; this approach also allows the drafting of projects according to the criteria defined by the DPCM (Prime Ministerial Decree) of 09/27/2021 to be included in national funding programs.
Keywords: *ReNDiS, RaStEM, hydrogeological risk, mitigation measures, designs, programming, planning.*

1. Hydrogeological risk mitigation measures: design, funding and implementation

The implementation of a hydrogeological risk mitigation measure with resources allocated by the Ministry of Ecological Transition (MiTE) is only the final part of a process that begins with the identification of the local needs of the territory for which a condition of risk is assessed by the competent local Authority such as, for example, the *Autorità di Bacino Distrettuale* (ABD), the *Consorzio di Bonifica*, the Municipalities. Designs are generally developed by local authorities (on their own or through external assignments) and then presented to Regions or Autonomous Provinces who evaluate whether to proceed with the request for funding to MiTE.

The submission of requests takes place through well-defined selective procedures regulated by the DPCM (Prime Ministerial Decree) of 27 September 2021. These procedures are activated through the compilation of a Form, specially implemented in the information system dedicated to the National Repository of hydrogeological risk mitigation measures (ReNDiS, www.rendis.isprambiente.it) and the contextual upload of the design by the proposing Region/Autonomous Province.

The requests are then examined as part of an investigation phase by ADB and MiTE (which can be supported by ISPRA) which establishes the possible eligibility for funding of the proposed measure and which also clearly identifys the actual purpose and effectiveness of the measure. Therefore, on the basis of the score attributed to each request for funding pursuant to DPCM of 27/07/2021, the "Regional Ranking of Funding Requests" is defined. Finally, the intervention is carried out in relation to a specific funding program defined by MiTE.

2. Criteria for measures financing with MiTE resources

A correct approach to the design of a hydrogeological risk mitigation measure financed by MiTE must meet certain technical and regulatory requirements.

With regards to the first aspect, in order for a design to be considered technically correct, its minimum contents must allow the definition of the risk scenario, clearly explaining the conditions of hazard, exposure and vulnerability of the design area, referring both at the conditions ante operam and at those expected to be achieved with the implementation of the measure (post operam). These significant elements of the design must be represented in a standardized, clear and homogeneous way, also in terms of spatial and geographical information, so that

they can then be easily verified in the preliminary phase relating to the request for public funding.

As regards the second aspect, in order to access public funding made available by the various bodies and, in the specific case, for the inclusion of a measure in national funding programs defined by MiTE, the design must meet the requirements of the DPCM of 27/09/2021 which establishes the priority criteria for assigning MiTE resources to a hydrogeological risk mitigation measure. On the basis of these criteria, the Preliminary Investigation Form for funding requests was created on ReNDiS. The Form is divided into different Sections containing administrative and economic/financial information (e.g., amount requested, progress, duration of the measure) and technical data (e.g., location, area classification and hazard, type of elements exposed, estimate of people at direct and indirect risk and house-loss) which must be clearly deducible from the designed presented.

3. ISPRA role

Since the Legislative Decree 180/98 and subsequent amendments, the so-called "Sarno Decree", ISPRA provides support to MiTE in planning, design and monitoring of hydrogeological risk mitigation interventions financed by the Ministry.

In this context, ISPRA provides support to designers by making available a series of information layers and basic data that can constitute a useful tool for drafting the project (Fig. 1).

Furthermore, starting from 2005, as part of the monitoring of the aforementioned measures, ISPRA has developed the ReNDiS platform aimed at creating an information system that incorporates information relating to hydrogeological risk mitigation measures carried out by administrations operating on the national territory.

Specifically, ReNDiS allows the management of both the preliminary phase relating to new requests for funding with resources provided by MiTE, through the loading of the Preliminary Investigation Form by Regions/Autonomous Provinces and the related project documents, and the monitoring of the measures already financed. For the latter, the information collected concerns the amount funded, their distribution throughout the national territory, the classification of the risk in the areas where the measures are located, the technical studies accompanying the projects, time for carrying out the works from the funding until the drafting of the certificate of regular execution as required by DM (Ministerial Decree) 37/2008 (Fig. 1). These activities were described in the ISPRA Report ("*ReNDiS 2020 – Hydrogeological risk mitigation in twenty years of ISPRA monitoring*"), to which reference should be made for further information.

Knowledge acquired through this experience highlights that specialized studies supporting measures design are sometimes lacking in many essential parts from a technical point of view, with serious impact to the effectiveness of the works and, therefore, to the effective assessment of the risk mitigation. On the basis of these premises, in 2017 the "Guidelines for the planning of landslide risk mitigation measures" were drawn up, in collaboration between ISPRA and AGI (Italian Geotechnical Association), which detail the methodological approach to be carried out in the specific case of landslides and provide the procedural guidelines for their correct design.

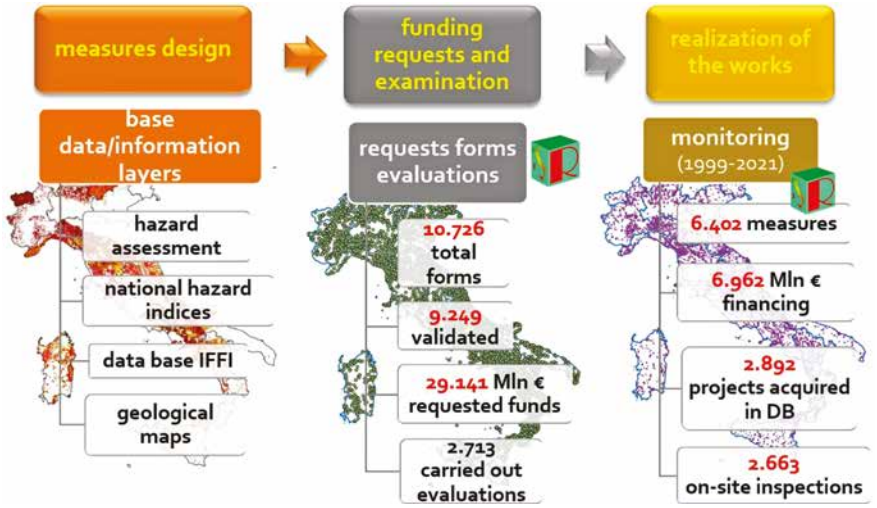


Fig. 1 – Activities carried out by ISPRA as part of the planning, design and monitoring of hydrogeological risk mitigation mesures funded by MiTE.The data shown in the figure are updated as of 31/12/2021.

4. RaStEM: the ISPRA application for representing designs

In relation to what emerged from the monitoring activities, part of an Agreement stipulated with the General Directorate for Climate and Energy of MiTE, ISPRA has carried out a series of activities aimed at developing a methodology for the analysis of the effects of mitigation resulting from the implementation of hydrogeological

risk mitigation measures, based on the definition of standardized criteria for the representation of the significant elements of a design, in order to define a set of indices useful to describe on which aspects and to what extent the measure expresses its effectiveness over time. In this regard, it should be noted that the methodology developed is applicable to all the different types of hydrogeological instability, namely landslides, hydraulic, avalanches and coastal ones.

The objective of the methodology is to ensure that the aims of a measure are well documented in the designt (in terms of risk mitigation), in order to allow a "transparent" evaluation of the mitigation effects induced and based on objectively identified elements. Therefore, the following significant elements, grouped in five categories, must be clearly represented:

- hazard area in ante opeam layout;
- exposed elements (people and physical assets) in ante opeam layout;
- design works;
- hazard area in post opeam layout;
- exposed elements (people and physical assets) in post opeam layout.

This methodology is the basis of the web application developed by ISPRA and called "RaStEM – Standardized Representation of Mitigation Effects", a freely accessible public tool that allows the significant elements of a project for hydrogeological mitigation measures to be represented on a national scale. In relation to the criteria according to which RaStEM was built, the application allows the drafting of designs compliant with the provisions of the DPCM of 09/27/2021 for the purpose of their inclusion in the national funding programs activated by MiTE.

In particular, the significant elements of the design are represented through geo-referenced polygons with specific attributes associated to each polygon category (Fig. 2) using a digitization format conforming to the shapefile standard, themed in five information layers, corresponding to the five polygon categories defined above.

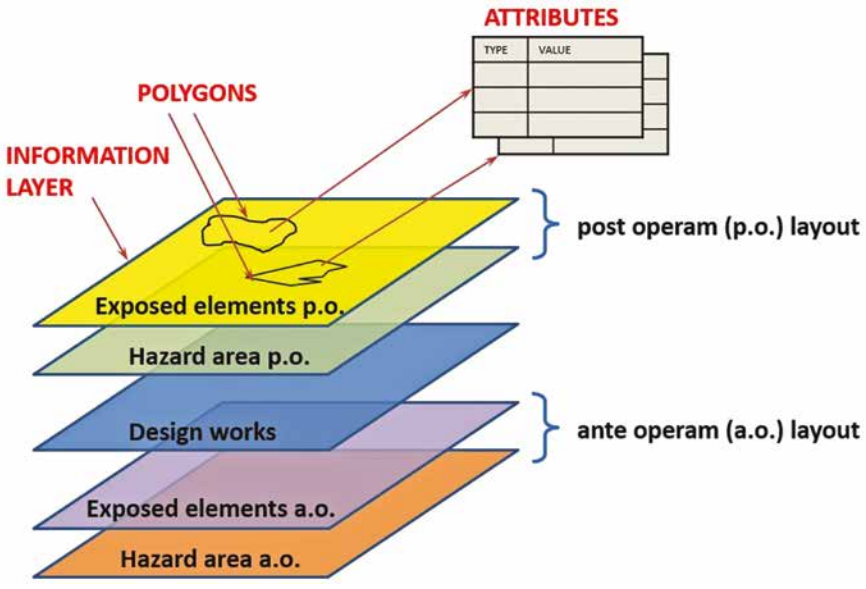


Fig. 2 – The significant elements of the project are represented with RaStEM through geo-referenced polygons defined on distinct information layers and equipped with specific attributes in relation to the different category of the significant element considered.

4.1 Hazard area ante *and* post operam

This information layer contains the polygons of the areas directly affected by the hazard in reference to the time horizon considered significant for the useful life of the works in the design. In particular, the areas of instability to be represented in *ante operam* layout refer to the exposed elements for which the design expects to mitigate the existing risk and to the works connected to it; in post-operam layout, areas that are expected to be still affected by the instability are identified after the implementation of the project measure (Fig. 3).

Each instability can be represented with a corresponding polygon or, depending on the scale of representation or the level of detail, a single polygon can be used to represent the envelope of multiple areas, even with different types of instability.

The characteristics of each instability contained in the polygon, ante and post operam, are described in an attribute table that specifies the classification of the phenomenon, the hazard class assigned to the area and a specific parameter, different for each type of instability, according to what defined in DPCM of 09/27/2021.

4.2. Exposed elements ante and post operam

In this information layer, the polygons relating to the elements exposed to risk considered significant in relation to one or more hazard areas are represented (Fig. 4).

Likewise previous case, depending on the scale and level of detail, the polygons can be related to a single element or represent the envelope of several elements belonging to different types. The characteristics of the different elements displayed contained in each polygon are described in a table of attribu-

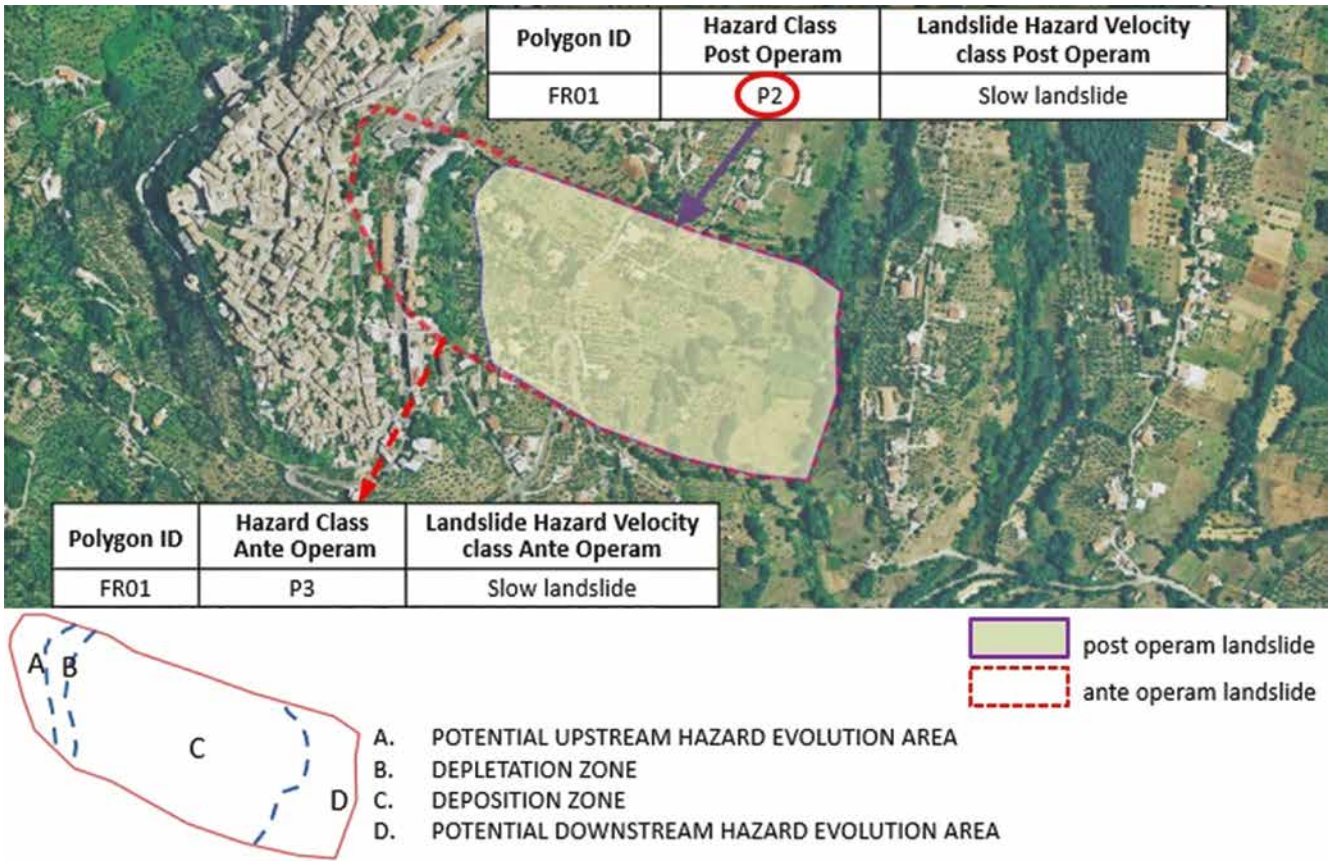


Fig. 3 – Definition of hazard area, ante and post-operam, and the associated attributes in the case of a landslide.

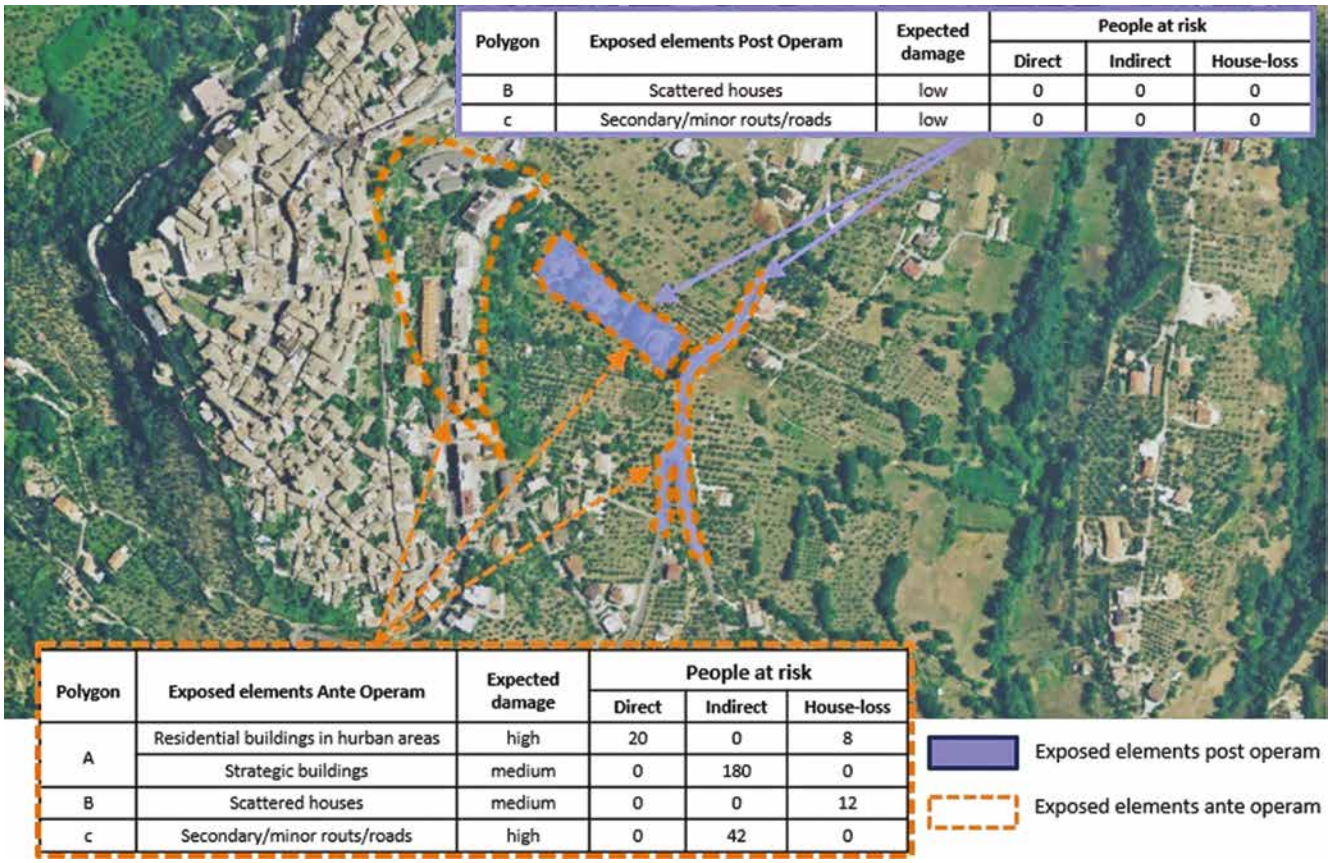


Fig. 4 – Definition of the polygons of exposed elements, ante and post operam, and of the attributes associated with them.

tes where the corresponding types must be indicated, in accordance with the classification used in ReNDiS and as indicated in DPCM of 27/09/2021. Exposed elements are essentially diveded in two main categories: physical assets, associated to their vulnerability, and the number of people at risk, distinguishing those at direct risk, at indirect risk or at risk of house loss. The criteria used to define the above parameters must be fully described in the design documents.

This category of polygons must be identified in both ante and post operam layout according to the above defined criteria.

4.3. Design works

In this information layer, polygons relating to the areas directly affected by the works or by their envelope are represented (Fig. 5).

Each polygon can incorporate one or more works whose typology must be indicated in an attributes table according to the classification used in ReNDiS.

5. Analysis of measures mitigation effects

With reference to the characteristic attributes for each category of polygon represented, a method was developed for the analysis of the mitigation effects related to the implementation of the measures through the definition of standardized parameters, each of which divided into dimensional parametric classes, to allow the comparison between the ante operam and post operam layout. Therefore, eight parameters have been identified (Tab. 1), through which it is possible to represent, in a concise and homogeneous way, the most significant aspects for this analysis.

Tab. I – List of parameters defined for mitigation effects analysis.

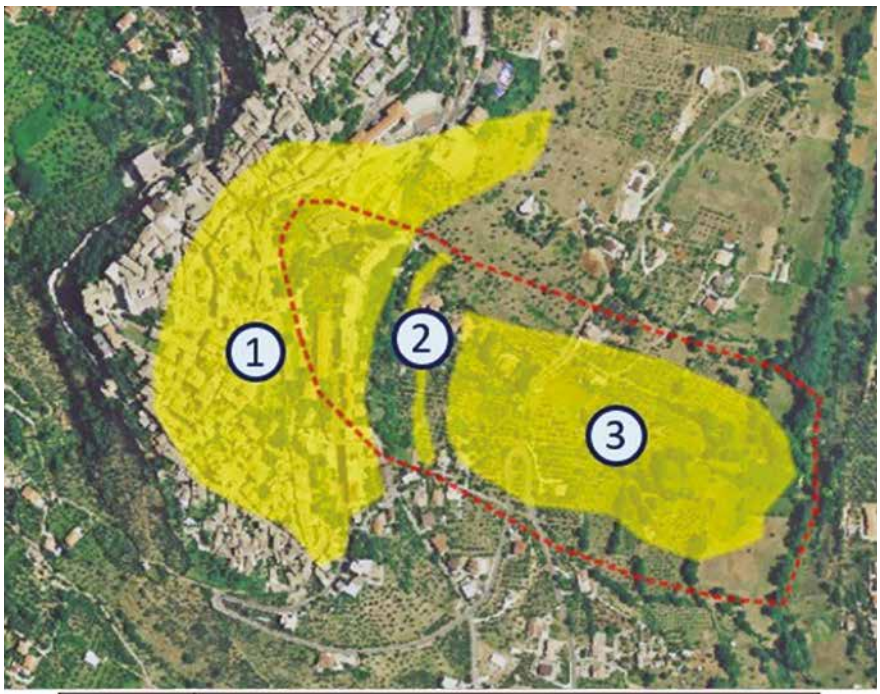
Parameter	Code
Total hazard area	Ad
Max characteristic value	Vm
Max hazard	Pm
Exposed elements (high damage)	Dg
Exposed elements area	Ae
People at direct risk	Pr
People at indirect risk	Pi
People with risk of house loss	Pa

Most of the parameters (Exposed elements, Max characteristic value, People at direct and indirect risk, People with risk of house loss) were obtained by referring to those identified first by DPCM of 28/05/2015, subsequently updated in relation to the new DPCM of 09/27/2021 (Tab. 2), while the others (Total hazard area, Exposed elements area, Max hazard) were derived through the statistical processing of data held by ISPRA and in accordance with the classifications used by ABD.

Using the parameters listed in Table 1, the developed methodology states that each measure is characterized by the values and corresponding classes (*ante* and *post operam*) of each parameter which define the degree of relevance of the risk scenario represented and, with reference to their variation, the degree of Relative Effectiveness of the intervention.

In particular, three Parametric Indices are obtained for each parameter:

- *Ante operam Relevance Index (IRa)* – this Index derives from



Polygon	Type of design
1	complementary works – Pipelines adaption
2	supporting structures – piling
3	drainage works – trench drain
	water regulating measures – rock or wood spillway

Fig. 5 – Definition of the polygons of the works in the project and their associated attributes.

Tab. 2 – Parameters with relative attribution of Value and Weighted Value used in DPCM 27/09/2021 to classify measures on a regional basis to define the "Regional Ranking of Funding Requests". The fields of the table in light gray are those that contain the parameters also used in RaStEM (Tab. 1) for the purpose of evaluating the mitigation effects.

Criterium		Weight	Class	Value	Weighted value
Regional priority		30	AA	4	30
			A	3	22,5
			M	1	7,5
			B	0	0
Approved design		10	Preliminary study pursuant to 3 c.4 DPCM 16/07/2016	0	0
			Technical and economic feasibility study	1	3,3
			Definitive design	2	6,6
			Executive design	3	10
Suppletive works		10	SI	1	10
			NO	0	0
People at direct risk		30	N>1000	4	30
			200≤N<1000	3	22,5
			50≤N<200	2	15
			0<N<50	1	7,5
			0 (no estimation)	0	0
Exposed elements		30	Strategic buildings (hospitals, schools, etc.)	4	30
			Residential buildings in hurban areas	4	30
			Strategic communication lines	4	30
			Large hydraulic infrastructers	4	30
			Industries at major risk	4	30
			Lifelines	3	22,5
			Others	3	22,5
			Scattered houses	3	22,5
			Accommodation and leisure facilities	3	22,5
			Productive/commercial settlements	3	22,5
			Cultural heritage	3	22,5
			Natural and protected areas	1	7,5
			Other structures of public interest	1	7,5
			No assets or No estimate	0	0
Hazard specific characteristic parameter	Flood return period	30	0<P≤50	4	30
			50<P<100	3	22,5
			100<P≤200	2	15
			P>200	1	7,5
	Avalanche hazard		High hazard	2	30
			Low hazard	1	15
	Residual beach width (coastal erosion, m)		W≤10	4	30
			10<W≤20	3	22,5
			20<W≤40	2	15
			W>40	1	7,5
	Floosd return period (coastal erosion)		0<P≤20	4	30
			20<P≤100	3	22,5
			100<P≤200	2	15
			P>200	1	7,5
	landslides		rapid	2	30
			slow	1	15

follows tab. 2

Criterium	Weight	Class	Value	Weighted value
Expected damage	10	Y	1	10
		N	0	0
Percentage reduction of people at risk (ratio between estimated ante operam and post operam values)	30	80≤%≤100	5	30
		60≤%<80	4	24
		40≤%<60	3	18
		20≤%<40	2	12
		0≤%<20	1	6
		0 (no estimate)	0	0
Compensation and mitigation measures	5	Y	1	5
		N	0	0
Implementation of plan measure (PAI, PGRA or similar)	30	Full implementation	2	30
		Medium implementation	1	15
		No implementation	0	0

the ratio between the value of the class associated with the ante operam parameter and the maximum value that the same class can assume;

- *Post operam Relevance Index (IRp)* – this Index derives from the ratio between the value of the class associated with the post operam parameter and the maximum value that the same class can assume;
- *Relative Effectiveness Index (IER)* – this Index derives from the ratio between the variation of the class associated with the parameter (difference between the post-operam and ante-operam values) and the maximum value that the same class can assume. For non-numerical parameters (speed, hazard, exposed elements) the Index is calculated with reference to the variation of the class and not of the value.

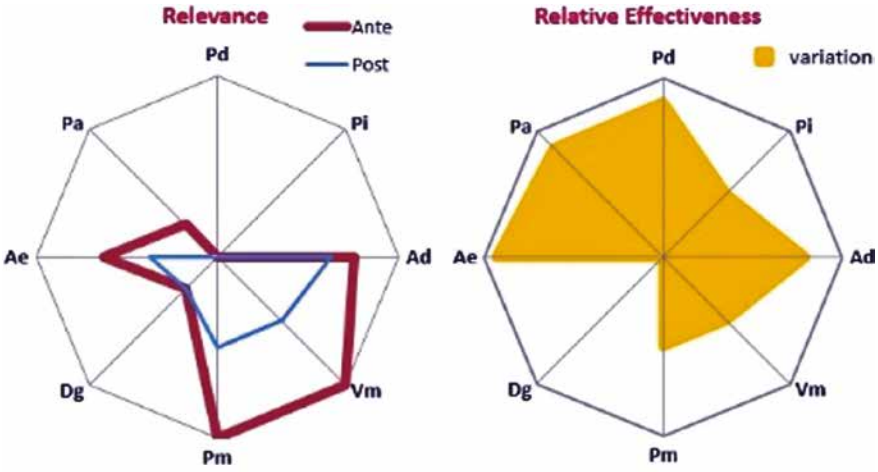
The arithmetic mean of the Indices referring to each parameter provides three Synthetic Indices which are referred to the overall characterization of the measure:

- *ISRa – Synthetic Relevance Index ante operam*
- *ISRp – Synthetic Relevance Index post operam*
- *ISER – Synthetic Index of Relative Effectiveness*

All the Indices obtained are summarized by the application in a summary table (Tab. 3) in which the fields in light gray are those relating to the input data that the designer must enter, the other fields are those relating to the output data that are calculated from the application. It should also be noted that the dark gray cells contain the parameters for which the relative effectiveness is calculated based on the variation of the class and not on the numerical values of the indices.

Tab. 3 – Summary table produced by the RaStEM application with the definition of the Parametric Indices and Synthetic Indices obtained for a project.

Parameter	Code	Value			Class			delta	Parametric Indices		
		ante	post	ND	ante	post	(max)		Relevance ante	Relevance post	Relative effectiveness
Total hazard area (m^2)	Ad	265.795	55.555	–	6	5	8	210.240	0,75	0,63	0,79
Max velocity or Frequency	Vm	V2	V1	-	2	1	2	1	1,00	0,50	0,50
Max hazard	Pm	AA	P2	– P	0	*2*	4	*-2*	0,00	*0,50*	*0,00*
Exposed elements (high damage)	Dg	E2o	E2o		1	1	4	0	0,25	0,25	0,00
Exposed elements area (m^2)	Ae	90.486			5	0	8	90.486	0,63	0,00	1,00
People at direct risk	Pa	89	12		1	0	4	77	0,25	0,00	0,87
People at indirect risk	Pd	15	2	A –	*0*	0	4	13	*0,00*	0,00	*0,87*
People with risk of house loss	Pi	6	3		0	0	4	3	0,00	0,00	0,50
								Synthetic Indices	ISRa	ISRp	ISER
									0,36	0,23	0,57



Parameter	Code	Parameter	Code
Total hazard area	Ad	Exposed elements area	Ae
Max characteristic value	Vm	People at direct risk	Pr
Max hazard	Pm	People at indirect risk	Pi
Exposed elements (high damage)	Dg	People with risk of house loss	Pa

Fig. 6 – Kiviat diagrams for the representation, for each parameter, of the Relevance Indices in ante and post operam layout and of the Relative Effectiveness Indices.

The set of all Indices can also be represented graphically through Kiviat diagrams that allow user to represent the results of the analysis of the mitigation effects connected to the implementation of a measure, highlighting with "visual" immediacy which are the characteristics of the measure and on which elements of the risk scenario the measure has an impact (Fig. 6) causing a variation in the parameters that contribute to the definition of the scenario itself.

The values of the Relevance Indices (ante and post operam) can vary between zero and one for each parameter, depending on the assessments and evaluation of the risk scenarios associated with the area of influence of the measure considered, where highest values are indicative of worse conditions for the area interested by the measure. Similarly, the Relative Effectiveness Indices also vary between zero and one but in this case higher values correspond to a higher estimated effectiveness of the planned measure referring to the initial conditions of the specific parameters considered.

Conclusions

The projects of hydrogeological risk mitigation measures presented to MiTE by Regions and Autonomous Provinces for the funding request often highlight technical gaps in the information that, instead, are needed for a correct and clear definition of the risk scenario. In many cases, actually, the significant elements of a design, such as hazard, exposed elements and design works, are not adequately represented, both in typological and spatial terms, elements which are essential to define the scenario in ante operam layout and the results expected in relation to the realization of the design works.

On this matter, ISPRA has acquired twenty years of experience gained implementing the activities of monitoring the measures financed by MiTE and improved through the ReNDiS platform. In this context, ISPRA has also collaborated with AGI (Italian Geotechnical Association) for the drafting of new guidelines for the design of landslide risk mitigation measure by preparing an operating methodology useful to correctly represent the significant aspects of the designs.

The methodology developed by ISPRA and improved for all types of instability, allows to represent in a rapid and simplified way, but standardized on a national scale, the significant elements of a hydrogeological risk mitigation measure. On the basis of this methodology, ISPRA took care of the implementation of a web application, called RaStEM (Standardized Representation of Mitigation Effects), which constitutes a useful tool for designers in preparing, even on a geographical basis, the essential information data set necessary for the correct definition of the risk scenario, making it possible to share the information set between all the administrations involved in the preliminary assessment phase of the eligibility for public funding of a measure through the communication of the univocal code associated with the measure.

RaStEM, moreover, has the aim of supporting designers in requests for access to national funding programs defined by MiTE, allowing an immediate and clear reading of the significant elements of the design as part of the preliminary investigation for financing purposes.

RaStEM application is available on ReNDiS web (http://www.rendis.isprambiente.it/rendisweb/) (Fig. 7.a and b), where it is possible to download the policy document which describes the criteria used to implement the application (http://www.rendis.isprambiente.it/rendisweb/doc/indications_e_metodologia_caratterizzazione_progetti.pdf) and the guidelines (http://www.rendis.isprambiente.it/rendisweb/doc/rastem/manuale_RASTEM_rev_beta01.pdf).

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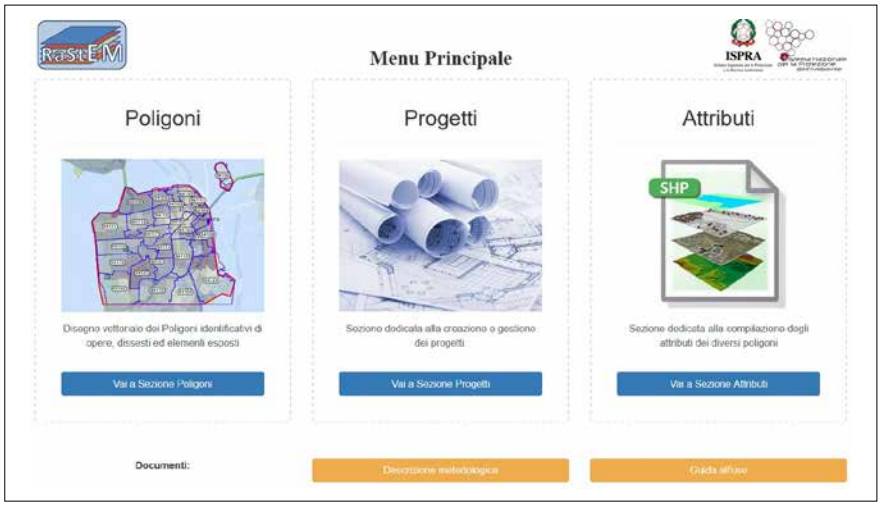

Fig. 7 – (a) Home page of the RaStEM application with authentication via login credentials and (b) Main Menu for accessing the application functions.

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A design method for double line of rockfall net fences in the framework of prabilistic trajectory analyses

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Rockfall net fence are a widely adopted rockfall risk mitigation measures, suitable for the great majority of the cases. Nevertheless, in particular complex morphologies, the trajectories of the possible detached blocks can be anomalous, with very high values of both the kinematic parameters of passing height and kinetic energy. In this case, a double line of net fence can be a convenient solution. In this case, the upper line is conceived as a fuse element that intercepts a percentage of blocks at least lowering them, while the lower line stops the remaining part. In the framework of partial safety factors design approach, a design method conceived by the Author is herein explained and tailored for a practical application in the common design practice, i.e. with the common trajectory softwares. An example of application on a real site is provided, showing the importance of performing a set of trajectory analyses to optimize the design of the whole system.
Keywords: *double line rockfall barreier, net fence, probabilistic trajectory analysis, mitigation measures.*

1. Introduction

Net fences, or flexible barrier, are among the widely adopted protective mitigation measures against rockfall (Hearn *et al*., 1995, Peila & Ronco, 2009; Lambert *et al*., 2021). Their high energy absorption capacity as well as their easiness of installation, even in very steep slope faces, represent the most recognized advantages (Marchelli, 2020; De Biagi *et al*, 2020). Nevertheless, rockfall prone areas on slopes with a particular complex morphology, directly insisting on infrastructures or buildings, might involve very high trajectories, often associated very high kinetic energies (Giacomini *et al.,* 2009, Matasci *et al*, 2018). In these cases, a single line of net fences could not be sufficient to intercept and arrest all the potential detached blocks. Thus, two lines of net fences, both below the rockfall source area and one parallel to the other can represent an effective and efficient solution for mitigating the risk.

The present paper focuses on the design of the double line of net fences, considered as a system capable, as a whole, to satisfy the safety requirements. The design methodology developed by the Author (Marchelli, *under review*) is herein presented in its exact expression. In the common practice, following the Eurocodes (EN 1990:2002, EN 1997-1:2004), the design of a structural work starts from the evaluation of the effects of the actions, choosing reference, say characteristic, values inside their frequency distributions. The design values are obtained by applying appropriate safety factors to the characteristic values. In case of net fences, the actions are represented through the height and the velocity, and thus the kinetic energy, of the possible impacting blocks. These quantities can be computed through probabilistic trajectory analyses (Li & Lan, 2015; Macciotta *et al*., 2015), allowing to obtain frequency distributions of both height and velocity. According to the existing National Standards (UNI 11211-4:2018; ONR 24810:2021), the characteristic values are chosen as the 95th or 99th percentiles of these distributions. This approach has thus been tailored by the Author to a double line considered as a system, i.e. the generally adopted characteristic values for the actions are considered as acting on the entire set of barriers. Consequently, the reference value to design the lower line only reveals to be lower than the 95th (or 99th) percentile.

In this work, the proposed method is fitted to the common practice, i.e. the adoption of semi-probabilistic trajectory models capable to insert a physical barrier inside themselves (Dorren *et al*., 2011; Leie *et al*., 2013; Grimod & Giacchetti, 2014). These barriers serve to evaluate the interception capacity of both the upper and the lower line, computing the percentage of blocks lowered by the upper line. An example of application with a lumped-mass 2D model, through RocFall code (RocSciene Inc., 2022) is presented and discussed. Finally, conclusion and further perspectives are outlined.

2. Method

This section illustrates a methodology to design a double line system of net fences, i.e. a system of two lines, intercepting blocks

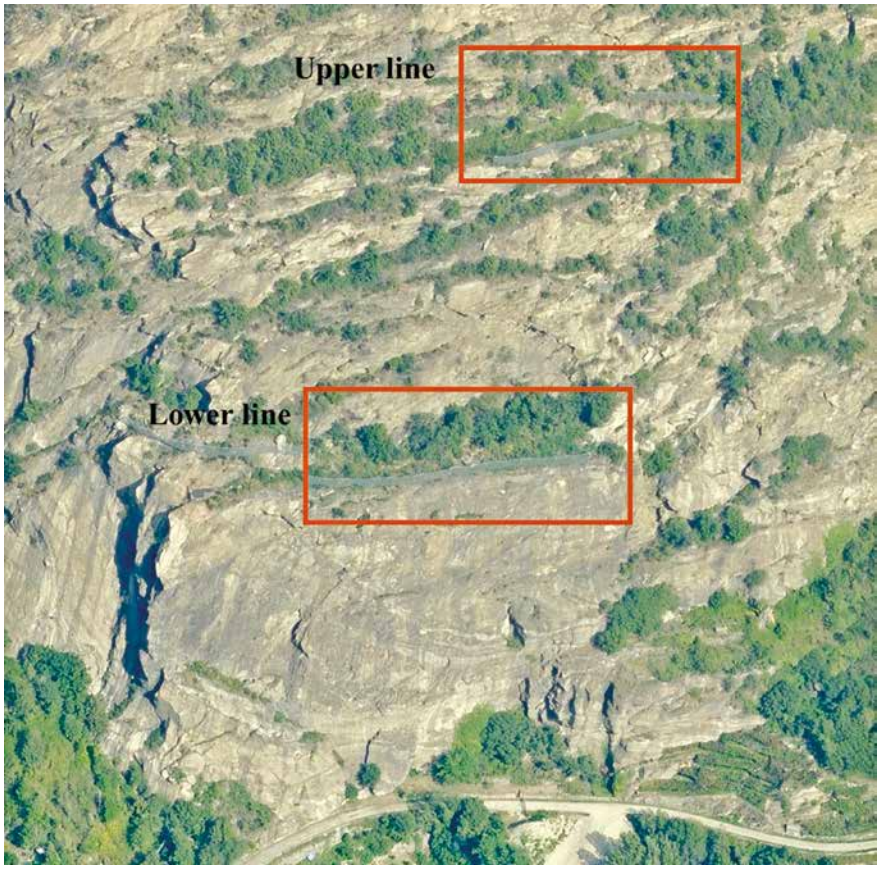

Fig. 1 – Double line system (Valle d'Aosta, Italy).

from the same source area, located above the upper line (Fig. 1). Consequently, the situation in which another rockfall source area is identified in between the two lines is not considered here. In this last case, each line has to be designed separately according the standard procedures. A double line is thus here intended as a system in which: (i) the upper line is conceived to intercept the great majority of blocks, stopping them or at least lowering their velocity, (ii) while the lower line should stop the remaining fraction of blocks. The upper line is thus like a fuse element of the system, while the lower line should not fail in either of the two failure modes, i.e. it should both intercept and arrest blocks.

In the framework of partial safety factors design approach promoted in the Eurocodes Standards for civil structures (EN 1990:2002), the proposed methodology and its application are based on performing probabilistic propagation (or trajectory) analyses, i.e. where the input parameters representing the interaction between block and slope, as well as the initial detachment conditions, are not deterministic values but vary inside a predefined range. Consequently, a trajectory analysis consists in a series of launches, i.e. simulations, from the individuated source area, in which each of the inputs are randomly selected inside their range. The number of simulations has to be statistically significant and, generally, not less than 1000. The results, in terms of velocity, or energy, and passing height are provided as distributions, from which reference, i.e. characteristic, values can be selected and used for the design.

In a standard design procedure for a single line, the characteristic value of each output is chosen as the 95^{th} or 99^{th} percentile of the distribution. In particular, for the passing height both the Italian (UNI 11211-4, 2018) and Austrian Standards (ONR 24810, 2021) suggest to take the 95^{th} percentile, while for velocity, or kinetic energy, UNI 11211-4 recommends the 95^{th} percentile, while ONR 24810 the 99^{th}. These values, once applied the appropriate partial safety factors, are adopted to evaluate the effects of the actions and to properly choose the performances of the barrier to satisfy the safety requirements. Leaving aside the partial safety factors, and taking the values suggested by UNI 11211-4 (2018) as representative, the minimum required performances are those for which the 95% of the simulations are intercepted and stopped. The design concept of a double net system is that the resistances, i.e. the performances, of whole system, i.e. upper line plus lower line, should be at least equal or greater than the effects of the actions. Practically the upper and the lower lines should intercept and stop at least the 95% of the simulations. Providing that the 95^{th} of the total should be intercepted, it reveals that, as a percentage of the simulations are stopped by the upper line, the actions for which the lower line should be designed pertain to a percentile lower than the 95^{th}, say the q^{th} percentile.

In the following the proposed methodology is explained in the more general situation. N simulations are considered. From here on, the terms "blocks" stands for "simulations". Table 1 reports the list of the adopted nomenclature.

Starting from a source zone insisting on both the upper and the lower lines, a number $n_{s,u}$ of simulations stops before reaching the upper line. The remaining N_1 blocks arrive at the upper line location.

In this line, a percentage α_1 of the N_1 blocks can be intercepted

Tab. I – List of symbols.

Symbol	Meaning
General	
h_b	Height of the barrier as sold by the producer: subscripts *u* and *l* stand for upper and lower, i.e. $h_{b,u}$ and $h_{b,l}$
E_b	Energy of the barrier as sold by the producer: subscripts *u* and *l* stand for upper and lower, i.e. $E_{b,u}$ and $E_{b,l}$. Generally $E_b = E_{MEL}$
$\gamma_{E,b}$	Partial safety factor relating to the energy of the barrier. Generally $\gamma_{E,b} = \gamma_{MEL}$
$v_{k,max}$	Maximum blocks velocity retained by the barrier, assumed m_k as the characteristic value of the impacting blocks mass: subscripts *u* and *l* stand for upper and lower, i.e. $v_{b,u,max}$ and $v_{b,l,max}$
h_k	Characteristic value of the trajectories height, as used for the design of a single line, whatever the source area (TA1, TA2, or the combining). Applying UNI 11211-4:2018, *k*= 95. Subscripts *u* and *l* stand for quantities recorded in the upper and lower line location, respectively, i.e. $h_{k,u}$ and $h_{k,l}$
v_k	Characteristic value of the trajectories velocity, as used for the design of a single line, whatever the source area (TA1, TA2, or the combining). Applying UNI 11211-4:2018, *k* = 95. Subscripts *u* and *l* stand for quantities recorded in the upper and lower line location, respectively, i.e. $v_{k,u}$ and $v_{k,l}$
$h_{k,i}$	Characteristic value of the trajectories height of the intercepted block, only, whatever the source area (TA1, TA2, or the combining). Applying UNI 11211-4 *k* = 95. Subscripts *u* and *l* stand for quantities recorded in the upper and lower line barrier, respectively, i.e. $h_{k,i,u}$ and $h_{k,i,l}$
$v_{k,i}$	Characteristic value of the trajectories velocity of the intercepted block, only, whatever the source area (TA1, TA2, or the combining). Applying UNI 11211-4:2018, *k*= 95. Subscripts *u* and *l* stand for quantities recorded in the upper and lower line barrier, respectively, i.e. $v_{k,i,u}$ and $v_{k,il}$
m_k	Characteristic value of the blocks mass
γ_h	Partial safety factor relating to the trajectories height
γ_v	Partial safety factor relating to the trajectories velocity
γ_m	Partial safety factor relating to the blocks mass
Trajectory Analysis TA1	
N	Number of simulations in the initial analysis TA1
N_1	Number of simulations arriving in the upper line location
n_i	Number of simulations intercepted: subscripts *u* and *l* stand for upper and lower, i.e. $n_{i,u}$ and $n_{i,l}$
$\overline{n_i}$	Number of simulations not intercepted: subscripts *u* and *l* stand for upper and lower, i.e. $n_{i,u}$ and $n_{i,l}$
n_a	Number of simulations arrested: subscripts *u* and *l* stand for upper and lower, i.e. $n_{a,u}$ and $n_{a,l}$
$\overline{n_a}$	Number of simulations not arrested: subscripts *u* and *l* stand for upper and lower, i.e. $n_{a,u}$ and $n_{a,l}$
n_a	Number of simulations stopped before reaching the barrier line location: subscripts *u* and *l* stand for upper and lower, i.e. $n_{s,u}$ and $n_{s,l}$
α_1	% of blocks, among those arrived, intercepted but not arrested by the upper barrier $\alpha_1 = \frac{\overline{n_{a,u}}}{N_1}$
α_2	% of blocks, among those arrived, not intercepted by the upper barrier $\alpha_2 = \frac{\overline{n_{i,u}}}{N_1}$
β	% of blocks, among those intercepted but not arrested by the upper line, arrived in the lower location $\beta = \frac{\overline{n_{a,u}} - n_{s,l}}{\overline{n_{a,u}}} = \frac{n_{i,l} + \overline{n_{i,l}}}{\overline{n_{a,u}}}$. This value, following Sec. 3, can be estimated thanks to TA2, i.e. $\hat{\beta}$.
$\tilde{\beta}$	% of blocks, among those not intercepted by the upper line, arrived in the lower location $\tilde{\beta} = \frac{\overline{n_{i,u}} - n_{s,l}}{\overline{n_{i,u}}} = \frac{n_{i,l} + \overline{n_{i,l}}}{\overline{n_{i,u}}}$

follows tab. I

Symbol	Meaning
Trajectory Analysis TA2	
N^*	Number of simulations
v_i	Initial velocity of the simulations $v_i = \gamma_v \sqrt{v_{k,u}^2 - \frac{2E_{b,l}}{m_k \gamma_{E,b} \gamma_m \gamma_v^2}}$
$n_{i,l}^*, \overline{n_{i,l}^*}, n_{a,l}^*, \overline{n_{a,l}^*}, n_{s,l}^*$	Number of simulation intercepted, not intercepted, arrested, not arrested, stopping before the lower line, respectively, pertaining to TA2
$\hat{\beta}$	% of blocks arrived in the lower location pertaining to TA2, $\hat{\beta} = \frac{n_{i,l}^* + \overline{n_{i,l}^*}}{N^*} = \beta$
Trajectory Analysis TA1 + TA2	
$n_{i,l}^+, \overline{n_{i,l}^+}$	Number of simulation intercepted and not intercepted by the lower line, respectively, pertaining to TA2 but scaled to consider that $N^* \neq \overline{n_a}$. $n_{i,l}^+ + \overline{n_{i,l}^+} = \hat{\beta}\alpha_1(1-\alpha_2)N_1$
δ	% of blocks, among those arrived, not intercepted by the lower barrier $\delta = \frac{\overline{n_{i,l}}}{n_{i,l} + \overline{n_{i,l}}}$
q	Percentile to consider to compute the characteristic value of the velocity in the lower line
$v_{q,l}$	Characteristic value of the trajectories velocity, for the design of the lower line, in a double net system.

but not arrested, while a percentage α_2 of the N_1 blocks can be higher than the height of the upper barrier. The presence of the upper line reduces thus the velocity of the α_1 blocks, and $(\alpha_1 + \alpha_2)$ N_1 blocks continue their motion along the slope. While some of the blocks ($n_{s,l}$) can stop in between the two lines, a reduced number of blocks, i.e. $(\alpha_1 + \alpha_2)N_1 - n_{s,l}$, arrive at the lower line location. Considering separately $\alpha_1 N_1$ and $\alpha_2 N_1$, i.e. not arrested and not intercepted by the upper line, respectively, a percentage of each of them arrive on the lower line location, namely β and $\tilde{\beta}$, respectively.

At the lower line location, the blocks can be intercepted, or not. Bearing in mind that, to accomplish the safety requirement, the sum of the blocks not intercepted and not stopped by the double line system should be lower or equal the 5% of N_1, the height of the lower net fence $h_{b,l}$ is selected among the products and the ratio δ between the number of blocks not intercepted and those arrived is defined. To achieve the target of the double line system, the capacity of the lower line must be selected in such a way that the ratio q between $n_{a,l}$ and $n_{i,l}$ satisfies:

$$q = \frac{\tilde{\beta}\alpha_2 + \beta\alpha_1(1-\alpha_2) - 0.05}{\left[\tilde{\beta}\alpha_2 + \beta\alpha_1(1-\alpha_2)\right](1-\delta)} \quad (1)$$

Thus, the characteristic value of the trajectories velocity, for the design of the lower line, is obtained taking the q^{th} percentile $v_{q,l}$ of the distribution of the velocities among those intercepted by the barrier. If all blocks are intercepted, but not all stopped, by the upper line, i.e. $\alpha_2 = 0$, Eq. (1) reduces to:

$$q = \frac{\beta\alpha_1 - 0.05}{\beta\alpha_1(1-\delta)} \quad (2)$$

On the contrary, if all blocks are intercepted by the lower line, i.e. $\delta = 0$, Eq. (1) turns into:

$$q = \frac{\tilde{\beta}\alpha_2 + \beta\alpha_1(1-\alpha_2) - 0.05}{\left[\tilde{\beta}\alpha_2 + \beta\alpha_1(1-\alpha_2)\right]} \quad (3)$$

Finally, for simulations with trajectories lower of both the upper and the lower barriers, i.e. $\alpha_2 = 0$ and $\delta = 0$, Eq. (1) becomes:

$$q = \frac{\beta\alpha_1 - 0.05}{\beta\alpha_1} \quad (4)$$

2.1. Applying the method in the common practice

The above presented methodology was merged with the practice, i.e. with the existing software tools to perform trajectory analyses. Generally speaking, among the existing codes (Steven, 1998; Dorren, 2015), a net fence with its performance can be inserted in the simulation. However, if a block impacts on the barrier with an energy higher than its capacity, it is assumed that the block can continue its motion without being affected by the impact neither in its velocity nor in its direction. This implies that, in modelling double line systems, the energy reduction effect of the upper line barrier is not considered in the software, with the blocks arriving at the lower line with a velocity greater than what is expected in reality.

To tackle this problem, a profitable solution could be performing a trajectory analysis (TA1) inserting in the software, in correspondence of the upper line, a barrier with a height equal to $\frac{h_{b,u}}{\gamma_h} - t$, being the tolerance (e.g. the block radius), and an infinite capacity. Blocks not impacting against the barrier ($\alpha_2 N_1$), i.e. not intercepted by the upper line, continue their motion along the slope.

Knowing the real nominal capacity of the product chosen as upper barrier, i.e. $E_{b,u}$, the maximum block velocity that can be arrested is:

$$v_{b,u,max} = \sqrt{\frac{2E_{b,u}}{m_k \gamma_{E,b} \gamma_m \gamma_v^2}} \quad (5)$$

From the blocks velocity distribution in the upper line location, the number of not retained blocks, $n_{a,u}$, among the total intercepted can be computed. If thus $\alpha_1 \neq 0$, another additional trajectory analysis (TA2) should be performed, with a source area located in the upper line location, with an initial velocity equal to:

$$v_i = \gamma_v \sqrt{v_{k,i,u}^2 - v_{b,u,max}^2} \quad (6)$$

being $v_{k,i,u}$ the 95th percentile of the velocities distribution of blocks impacting against the upper line. This velocity should be oriented parallel to the slope, as it has been observed during impact tests that blocks are generally accompanied by the net in the slope direction. Relating to the initial height of simulations, precautionary, it is suggested to consider:

$$h_i = \gamma_h \, h_{k,i,u} \quad (7)$$

being $h_{k,i,u}$ the 95th percentile of the heights distribution of blocks impacting on the upper line. It should be noted that the number of simulations N^* in TA2 should be statistically representative, i.e. minimum 1000.

To properly design the lower line, the results from TA1 and TA2 should be merged. Since the number of simulations of TA2 differs from $\alpha_1 N_1$, consequently, the number of blocks arrived in the lower line location should be appropriately scaled when merged to those arrived in TA1. The scaling must not vary the trend of the distributions of blocks heights and velocities (see Sec. 3).

Similarly to the upper line, a product with a height $h_{b,l}$ should be selected for the lower line. The maximum intercepted height is thus $h_{b,l}/\gamma_h$. Among blocks arrived in the lower line location, the percentage δ, i.e. blocks not intercepted by the lower line, can be obtained. Thanks to Eqn (1), (2), (3), and (4), the q^{th} percentile of the distribution of the velocities, related to the trajectories intercepted by the barrier, only, is computed and then adopted to define the absorption capacity required by the lower line.

3. Example of application

The proposed methodology and the possible suggestions in its application are herein proposed in a 2D case, with a lumped-mass trajectory model. A real slope profile in the North-western Italian Alps is used as representative of the scenario in which a double line of net fences could be a suitable solution for risk mitigation, i.e. a very steep rock face insisting on a transportation infrastructure (Figg. 1-2). The source area is located at an altitude in between 507 m a.s.l. and 520 m a.s.l., with a possible release volume equal to 2 m^3. It should be noticed that even though the definition of the design block volume is beyond the scope of the example, its choice should be accurately performed through, whenever possible, surveys on the discontinuities sets on the rock face and the distribution of blocks volumes in the possible location of the mitigation measures. RocFall v8.017 (RocScience Inc, 2022) is the software selected for the lumped-mass trajectory analysis. In the adopted model, the input parameters representing the block-slope interaction properties are the normal and tangential restitution coefficients, R_N and R_T, respectively, and the friction angle φ. Similarly to the design block volume, also these parameters should be carefully evaluted, through both *in-situ* surveys and back-analyses of past events. Table 2 reports the selected values. The number of performed simulations is 1000, verified as statistically representative of the results. The method illustrated in Sec. 2 is herein applied, adopting both the characteristic values and the partial safety factors suggested by the Italian Standards UNI 11211-4 (2018). In the analysis, the selected design block volume, topography of the slope, and the other input parameter are assumed as the "most accurate possible", thus the lowest coefficients are required. The input details are reported in Table 3, together with the results.

First, a simulation without net fences is performed to examine the potential trajectories. Figure 2.a depicts the results in absence of mitigation measures. This analysis

Tab. 2 – Soil input parameters for lumped mass analysis with RocFall.

Soil type	R_N	R_T	Color in Fig. 2
Rocky outcrops	0.4 ± 0.04	0.8 ± 0.04	Grey
Vegetated rock	0.3 ± 0.04	0.7 ± 0.04	Violet
Debris with vegetation	0.3 ± 0.04	0.6 ± 0.04	Yellow
Asphalt	0.4 ± 0.04	0.8 ± 0.04	Grey

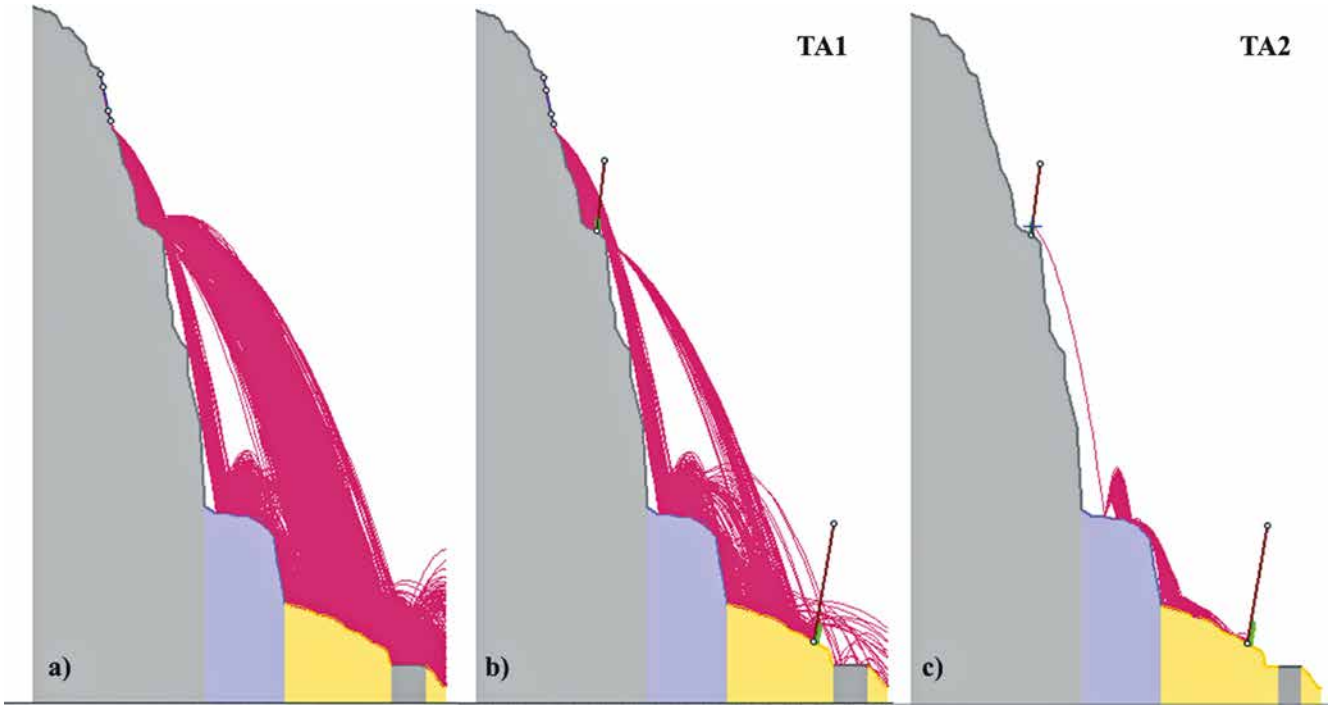

Fig. 2 – Trajectory analyses in the considered path (RocFall v8.017). See Table 2 for details on input parameters: a) without barriers, b) TA1 with a physical barrier with infinite capacity in the upper line locations, and a physical barrier in the lower line, c) TA2. Red lines state as collectors, while green for physical barriers. The source zone location is indicated in blue.

serves to evaluate whether a single line is sufficient or a double line is a suitable solution. In the present case, due to the very high trajectories, a single line in the upper or in the lower portion of the slope is not able to intercept and stop at least the 95% of the trajectories. Thus, an alternative solution must be considered. Assuming the double line as the most convenient solution, a proper location for the upper barrier is selected, together with its performances, according to the constraints imposed by the construction difficulties. In the present case a barrier with $h_{b,u}$ equal 5 m and absorption capacity of 1000 kJ is selected. Meanwhile, a preliminary location for the lower line should be identified. In this case, the upper line is located at 474 m a.s.l., while the lower line at 346 m a.s.l.

Following this step, the specific trajectories simulations are performed. As suggested in Sec. 2.1, a physical barrier with a height $h_{b,u}/\gamma_h$ and infinite capacity is inserted in the model and the simulation TA1 is performed (Fig. 2.b). Table 3 displays the obtained results. It reveals that the 35,5% of the blocks are not intercepted by the upper line (α_2), while, among those intercepted, the 96.6% are stopped ($1-\alpha_1$). In the same trajectory analysis, the blocks not intercepted by the upper barrier arrive in the lower line location with $v_{k,l}$ equal to 16.86 m/s and $h_{k,lu}$ equal to 9.68 m. As third step, further trajectory analysis, TA2, is realised, standing for those blocks that are intercepted but not arrested by the upper barrier. As reported in Sec. 2.1, the number of simulations of TA2, N^*, should be chosen as to be statistically significant, thus, the obtained results should be scaled proportionally to α_1. Figure 2.c reports the obtained trajectories.

The fourth step is to merge the results from TA1 and TA2. This process consists in scaling the number of trajectories arrived in the lower line in TA2, i.e. subdividing the cumulative frequency distribution of the height obtained in TA2 in $n^+_{i,l} + \overline{n^+_{i,l}}$ intervals equally spaced, and extracting thus $n^+_{i,l} + \overline{n^+_{i,l}}$ values of height inside the intervals. These values should be added to those obtained by the all trajectories arrived in the lower line location in TA1 and, thus, a cumulative distribution of the height pertaining to TA1+TA2 is obtained. In the present case, as α_1 is equal to the only 3.4%, only one value of TA2 should be added to TA1. Among the products, a barrier 6 m height is selected to intercept the great majority of the blocks. Considering thus an effective intercepting height equal to $h_{b,l}/\gamma_h$, i.e. 5.77 m, among those arrived, the percentage of block not intercepted by the lower barrier is equal to 15%. Practically speaking, inserting in the model a physical barrier, with a height $h_{b,l}/\gamma_h$ at the lower line location, allows determining, among those arrived, the percentage of block not intercepted by the lower barrier, i.e. δ. As the goal of the design method is that the double line, as a system, intercepts and arrests at least the 95% of the blocks, applying Eq. (1), and considering the velocity distri-

Tab. 3 – Input and output values in the performed example.

Symbol	Value
General	
m_k	5400 kg
γ_m	1.02 (-)
γ_v	1.04 (-)
γ_h	1.04 (-)
$\gamma_{E,b}$	1.2 (-)
$h_{b,u}$	5 m
$E_{b.u}$ (= E_{MEL})	1000 kJ
$v_{b,u,max}$	16.73 m/s
$h_{b,l}$	6 m
$E_{b,l}$ (= E_{MEL})	2000 kJ
Trajectory Analysis TA1	
N	1000
$n_{s,u}$	0
N_1	1000
$v_{k,u}$	25.40 m/s
$h_{k,u}$	8.21 m
$n_{i,u}$	645
$\overline{n_{i,u}}$	355
$n_{a,u}$	611
$\overline{n_{a,u}}$	34
α_1	3.4 %
α_2	35.5 %
$n_{s,l}$	250
$n_{i,u}+\overline{n_{i,u}}$	105
$v_{k,l}$	16.86 m/s
$h_{k,l}$	9.68 m
$v_{k,i,l}$	16.72 m/s
$h_{k,i,l}$	4.95 m
$n_{i,l}$	86
$\overline{n_{i,l}}$	19
$\tilde{\beta}$	29.6 %
δ	18%
$n_{a,l}$	86
$\overline{n_{a,l}}$	0

Symbol	Value
Trajectory Analysis TA2	
N^*	1000
$v_{k,i,u}$	23.23 m/s
v_i (Eq. 6)	10 m/s
$h_{k,i,u}$	3.33 m
h_i (Eq. 7)	3.46 m
$n^*_{i,l}+\overline{n^*_{i,l}}$	20
$\hat{\beta}$	2%
$v_{k,l}$	11.01 m/s
$h_{k,l}$	1.41 m
$v_{k,i,l}$	11.02 m/s
$h_{k,i,l}$	1,29 m
$n_{i,l}$	20
$\overline{n_{i,l}}$	0
Trajectory Analysis TA1 + TA2	
$n^+_{i,l}+\overline{n^+_{i,l}}$	1
$v_{k,l}$	16.21 m/s
$h_{k,u}$	9.47 m
$n_{i,l}$	89
$\overline{n_{i,l}}$	17
$v_{k,i,l}$	15.03 m/s
$h_{k,i,l}$	4.95 m
δ	16%
q	0.54
$v_{q,l}$	12.84 m/s
$n_{a,l}$	89
$\overline{n_{a,l}}$	0

bution of the blocks intercepted only, the q^{th} percentile to compute $v_{q,l}$, i.e. the value to which partial safety factors should be applied for the design value, is obtained (Fig. 3). The design energy $E_{d,l}$ that the lower line should stop, is thus computed as $E_{d,l}=\frac{1}{2}m_k\gamma_m v^2_{q,l}\gamma^2_v$, in this case equal to 530 kJ. Thus among the products available with $h_{b,l}$ equal to 6 m, a 2000 kJ barrier is chosen.

Although this represents only an example, it can be noticed that a single line cannot be adopted at a first solution, due to the high trajectories. A double line system composed of a 5 m-1000 kJ barrier for the upslope line, and a 6m-2000 kJ for the downslope line can be installed to adequately intercept and stop the 95% of the falling blocks.

Conclusion

Rockfall barriers are among the most adopted solution for mitigating rockfall risk. Nevertheless, in some morphological situations a single line is not sufficient to intercept and stop the blocks or a suitable product could present difficulties in its installation. The present study focuses on net fences disposed along double lines, i.e. on approximately parallel isohypses, stopping blocks from the same source area. The upper line serves to intercept and at least decelerate the great majority of the blocks, while the lower line to stop the remaining ones.

With the idea that the entire set of net fences constitutes a system, a methodology to design a double line system of net fences, developed by the Author, is herein reported. To merge the proposed method with the common practice, i.e. probabilistic trajectory analyses allowing obtaining the output quantities as distributions, inside which a characteristic value is selected for the design, tailored formulas are conceived and reported. Following the proposed approach, the design values should thus be considered pertaining to the whole system, and, consequently, the required products have global performances generally lower than those required by a single line positioned on the slope toe.

According to the procedure, separated trajectory analyses should be realised in order to obtain the reference values for the lower line design.

Further developments could consider the tailoring the proposed method accounting also for the presence of multiple source zones.

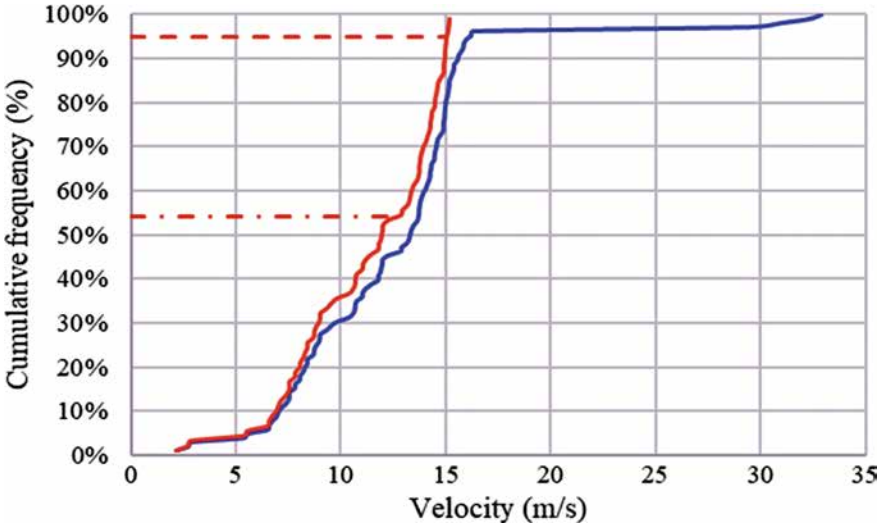

Fig. 3 – Cumulative frequency distribution of the velocity. The blue line represents the distribution of all blocks passing in the lower line position, while the orange considers the only blocks intercepted by the loer barrier. The dotted line refers to the 95th percentile, while the dash-dotted line to the q^{th} percentile.

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Proposal for expeditious inspection sheets that can also be carried out with a drone for rockfall protection works

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A proposal for the management of rockfall protection works on complex infrastructure networks such as that of the Autonomous Province of Bolzano through planned inspections. A conscious management requires an adequate planning of inspections and the determination of economically sustainable 'thresholds' of intervention. Since it is not possible to predict the frequency of detachments that could cause deterioration of structural elements, it is necessary to plan different types of inspections: a more frequent visual inspection and a more detailed inspection leading to the planning of maintenance or monitoring projects.
Keywords: *rockfall, protective works, inspections, maintenance, management.*

1. The Manager's functions on the heritage of rockfall mitigation works

The heritage of rockfall protection works along a complex infrastructure network is not fully known due to changes in management and the lack of habit of keeping records of the works, especially when emergency works are being carried out. The inspection of works involves an expenditure of funds that is often unsupportable by a public or private manager. Their maintenance is not provided for by national or European legislation, but there is a technical report UNI/TR UNI 11211-5 that defines the methods and the role of the manager.

The Autonomous Province of Bozen/Bolzano, following Legislative Decree No 112 of 31 March 1998, manages the state and provincial roads in its territory with more than 6,000 rockfall protection works. According to Article 14 of the Highway Code: 'The road-owning authorities, in order to ensure the safety and smooth flow of traffic, shall: a) maintain, manage and clean the roads, their appurtenances and furnishings, as well as equipment, installations and services…'

Rockfall protection works are to all intents and purposes to be considered as pertaining to the road itself.

The works are surveyed within the VISO database, which serves as a digital archive. Each work has been assigned a 'speaking name', the work code, indicating the road and the surveyor's code (e.g. SS042_SC_ 01) and an internal VISO database identification number. In some cases, such as rockfall barriers, the work code is applied to the work by means of an aluminium plaque.

VISO acts as a digital archive and for recently constructed works contains all information about the work (location, geometry, project documentation of the work, inspections and maintenance)

Operator's archive (VISO): for new works it is necessary to provide the operator with the works file and all the documents required by the regulations in force (NTC 2018, L.D. 9 April 2008 n 81) including information for the safety plan during maintenance operations.

For each work, the geometry, type, length, height and parameters defining its functionality are:

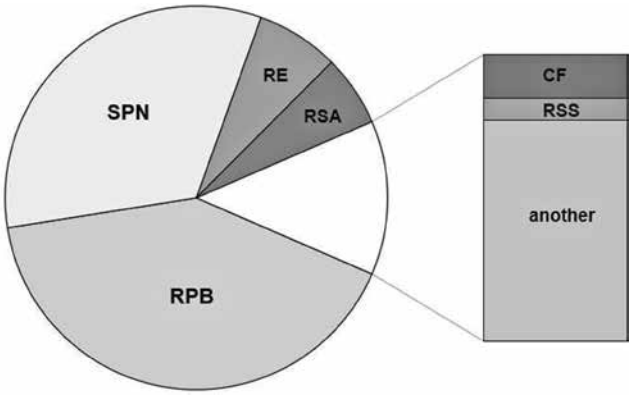

Fig. 1 – Percentage distribution of the main categories of works. RPB = rockfall protection barrier; SPN = slopes protection nets; RE= rockfall embankments (reinforced with geogrid or without); RSA = rock anchors or soil nailing anchors; CF = concrete foot (with or without anchors); RSS = rockfall sheltering structures.

a) recorded:Protection System Location (P.S.L.)
b) Protection System Design (PSD)
c) Preservation Protection System (P.P.S.)

These parameters also made it possible to classify all the works dated or inherited from Anas management, making it possible, by comparing them with the dangerousness of the slope and the expected damage, to give a parametric assessment (risk index) of the safety of the road section with regard to the rockfall hazard. On the basis of the risk index of the road sections, a list of intervention priorities is drawn up every 6 months Council Resolution 842 08/07/2014. The list is continuously updated with new designs, works realised, periodic inspections and events.

From this initial survey through the analysis of the state of the works, it was possible to define the works in need of maintenance and add them to the priority list.

The analysis of anomalies performed by the DICAM of University of Bologna made it possible to recognise the most frequent anomalies found on the works of the most important highways.

In order to manage the existing works in the best possible way with the human and financial resources available to the operator, the Province of Bolzano is developing a Management Plan, as a single coordination tool that harmonises the activities of the operator.

1.1. Viability Information Operating System

The main activities of the Manager on the existing assets, besides managing the data archive of the works (VISO) are inspection, maintenance and monitoring activities.

2. Inspections

There are 2 types of inspections, the first simpler and more frequent type A inspections based on visual observations determine a score. If the maximum score exceeds the threshold of 10 points, a second, more thorough inspection of type B is required.

2.1. Type A inspections

Type A inspections involve a series of checks by a Roads Service technician or operator that can be carried out by a simple inspection in the countryside without the need for monitoring or specific tests. They are carried out with on-site inspections from the ground, also with the aid of binoculars, and with the aid of drones for works that are not visible from the road and not easy to access. For inspections with drones, the winter months when the vegetation is free of fo-

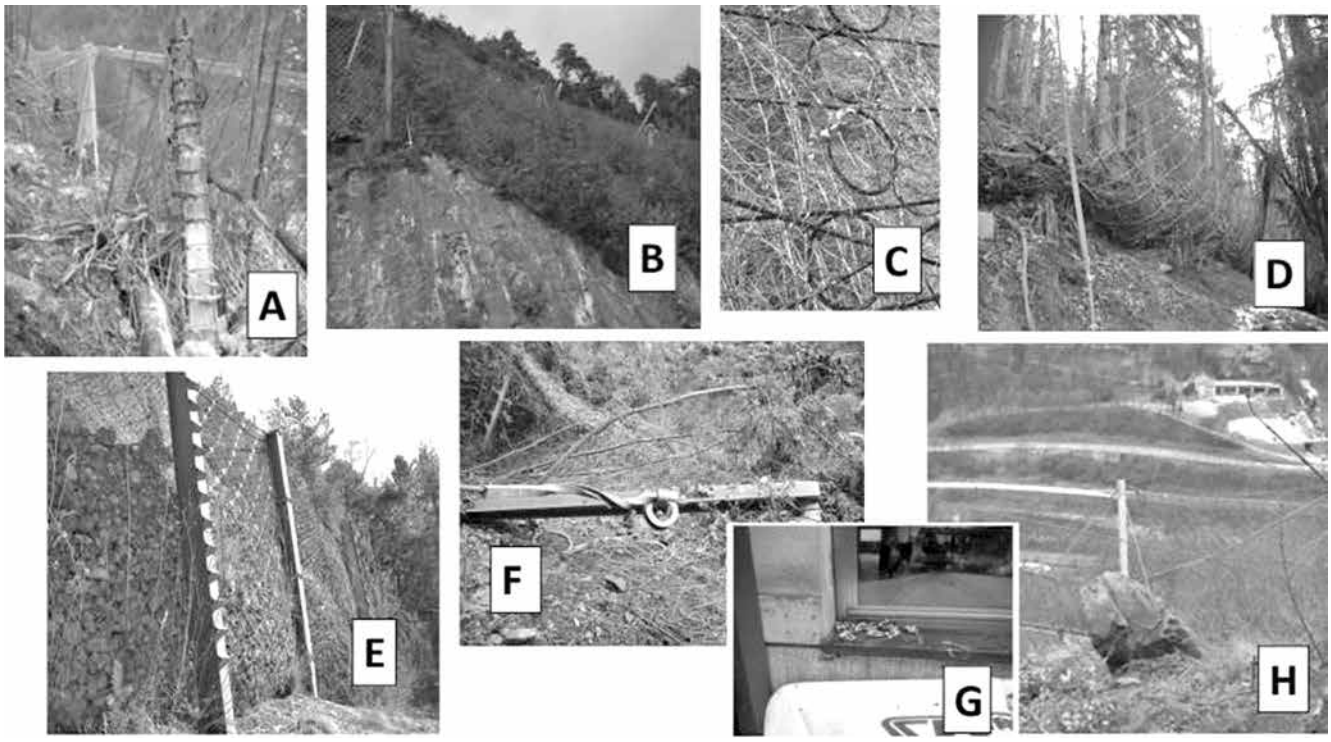

Fig. 2 – Examples of frequent anomalies found on rockfall barriers A) damage to the receiving structure, B) interference with vegetation, C) corrosion D) filling of plant material E) filling of stone material F) loosening or damage to brakes G) loosening of shackles and clamps H) damage to posts.

liage are preferred. The sheets include scores that are assigned to the various situations detected.

In addition to information on the anomalies, the sheets include the code of the work, the date of the inspection, the name and surname of the surveyor, photos and any considerations of the surveyor.

The sum of the anomalies detected determines the threshold for assignment in efficiency classes (P.P.S.) based on an index of conservation of the work (I.P.P.S.).

Tab. 1 – Split out into P.P.S. classes based on the I.P.P.S.

IPPS > 9	9 > IPPS > 3	3 > IPPS > 1	IPPS = 0
damage impairing the efficiency of the system; urgent maintenance or cleaning required insufficient P.P.S.; problematic	maintenance or clearance work is required but the efficiency of the system is not affected. P.P.S. sufficient	limited material clearing or cleaning/ cleaning work required discrete P.P.S.	requires no maintenance P.P.S. good

Type A ispectionsshets are provided for the following works: rockfall protection barrier; slopes protection nets; rockfall embankments (reinforced with geogrid or without); rock anchors or soil nailing anchors; concrete foot (with or without anchors); rockfall sheltering structures.

2.1.1. Rockfall protection barrier

Tab. 2 – Observations on rockfall protection barrier and scoring.

General state of the structure	Score
Abnormalities in the geometry and shape of the structure as a whole (gaps under the net, detensioning of ropes, obvious rotation of posts, displacement of foundation plinths and/or anchorages, etc.)	☐ [10]
General collapse of the structure or filling with material exceeding 30% of the initial height	☐ [10]
Impact damage to the rockfall barrier components (nets, ropes, posts, sliding energy dissipators, loose clamps)	☐ [10]
Presence of material and boulders in the interception structure for a height of less than 30% initial height	☐ [5]
Crash of trees on ropes / netting	☐ [5]
Presence of weed vegetation	☐ [1]
Abnormalities in the state of accesses to the work and/or complementary works to it	☐ [1]

2.1.2. Slopes protection nets

Tab. 3 – Slopes protection nets and scoring.

General state of the structure	Score
General structure collapse due to slope instability	☐ [10]
Abnormalities in the geometry and shape of the structure as a whole (gaps and/or deformations in the net, rope detensioning, displacement/deformation of anchorages, etc.)	☐ [10]
Presence of accumulations in the net (thickness over 20 cm)	☐ [5]
Presence of accumulations in the net (thickness up to 20 cm)	☐ [1]
Presence of weed vegetation	☐ [1]
Abnormalities in the state of accesses to the work and/or complementary works to it and/or surface water drainage works	☐ [1]

2.1.3. Rockfall embankments (reinforced with geogrid or without)

Tab. 4 – Observations on rockfall embankments (reinforced with geogrid or without)and scoring.

General state of the structure	Score
Anomalies in the geometry and shape of the structure as a whole (subsidence of the embankment foundation, lowering of the embankment crest, erosion of the structure that compromises its functionality)	☐ [10]
Stability of the slope-embankment system	☐ [10]
Penetration of the boulder into the embankment for more than half its width at the point of impact	☐ [10]
Check whether fires in the vicinity of the work have damaged reinforcing structures (geogrids, wire mesh, boulders)	☐ [10]
Presence of material and boulders upstream of the embankment (thickness more than 50 cm)	☐ [5]
Presence of material and boulders upstream of the embankment (thickness up to 50 cm)	☐ [1]
Crashing trees and presence of weeds	☐ [1]
Abnormal condition of accesses to the works and/or complementary works to the works (e.g. foundation kerbs, micropiles) and/or surface water drainage works	☐ [1]

2.1.4. Rock anchors or soil nailing anchors

Tab. 5 – Observations on rock anchors or soil nailing anchors and scoring.

General state of the structure	Score
General collapse of structure due to slope instability	☐ [10]
Deformation, displacement, slipping of anchors and/or anchor head (distribution plate, nut, etc.)	☐ [10]
Degradation (rust, etc.) anchor head (distribution plate, nut, etc.)	☐ [5]
Presence of weed vegetation	☐ [1]
Abnormal state of access to the work and/or complementary works to it and/or surface water drainage works	☐ [1]

2.1.5. Concrete foot (with or without anchors)

Tab. 6 – Observations on concrete foot (with or without anchors) and scoring.

General state of the structure	Score
General structure collapse due to slope instability	☐ [10]
Deformation, displacement, rotation of concrete structure	☐ [10]
Deformation, displacement, slipping of anchors and/or anchor head (distribution plate, nut, etc.)	☐ [10]
Degradation (rust, etc.) anchor head (distribution plate, nut, etc.)	☐ [5]
Presence of weeds	☐ [1]
Abnormal state of access to the work and/or complementary works to it and/or surface water drainage works	☐ [1]

2.1.6. Rockfall sheltering structures

Tab. 7 – Observations on rockfall sheltering structures and scoring.

General state of the structure	Score
General structure collapse due to slope instability	☐ [10]
Penetration of the boulder into the topsoil for more than half its thickness at the point of impact	☐ [10]
Presence of material and boulders on the ground cover (thickness more than 50 cm)	☐ [5]
Presence of material and boulders on topsoil (up to 50 cm thick)	☐ [3]
Presence of weeds on the ground covering the tunnel	☐ [1]
Defects in the condition of accesses to the works and/or complementary works to the works and/or surface water drainage works	☐ [1]

2.1.7. Type B inspections

Type B inspections involve a whole series of checks and monitoring to quantify the type of maintenance work required. They can only be carried out by experienced technicians.

The result of these inspections is a detailed picture of the anomalies and deteriorations with a graphic diagram of the work examined, advice on any ordinary or extraordinary maintenance operations or monitoring requirements, and an actual maintenance project in which the categories and quantities are indicated.

For the time being, the following works are envisaged: rockfall protection barrier; slopes protection nets; rockfall embankments (reinforced with geogrid or without); rock anchors or soil nailing anchors; concrete foot (with or without anchors); rockfall sheltering structures

3. Inspection times

The inspection times depend on the characteristics of the road section (TGM, strategic nature of the section, climatic conditions) and on the characteristics of the slope that underlies it (rockfall danger, vegetation) as well as on the technical characteristics of the existing rockfall mitigation works. The inspection times are defined by the area manager according to the indications in the following chapter, the peculiarities of the area and the availability of staff and funds to be allocated for maintenance.

Periodic intervention times indicate the time intervals in which type A inspections are repeated. For "exceptional" intervention times, the time intervals are indicated when the inspection and extraordinary maintenance activities are foreseen to extend the useful life of the work and depend on the requirements for that type of work (e.g. rockfall barriers certified by Etag 25 years)

The criteria identified to define the periodic intervention times derive from studies conducted on existing works, from the analysis of existing literature and from the experience and practical considerations of the Road Service of the Province of Bolzano. They are:

a) presence of Etag 2007 rockfall protection barriers for which inspections are scheduled after 1 year and every 5 years.
b) TGM: average daily traffic recorded by the Autonomous Province of Bolzano with fixed survey stations or mobile stations.
c) importance of the road section examined: if it is the only access to a valley or to important tourist areas, presence of detours, type of road.

Tab. 8 – Weights to be assigned to the various road sections according to these criteria for evaluating intervention times. (dark grey = very short times, grey = short times, light grey = intermediate times, white = possibility of intervention in longer times).

Presence of rockfall barriers Etag 2007	TGM	Strategic section	Area subject for long stretches to snow and ice	Frequency of rockfall events	Vegetation
Yes	< 15.000	Yes	Yes	very frequent	shrubland
No	< 5.000	No	No	frequent	coppice forest
	< 5.000				coniferous forest

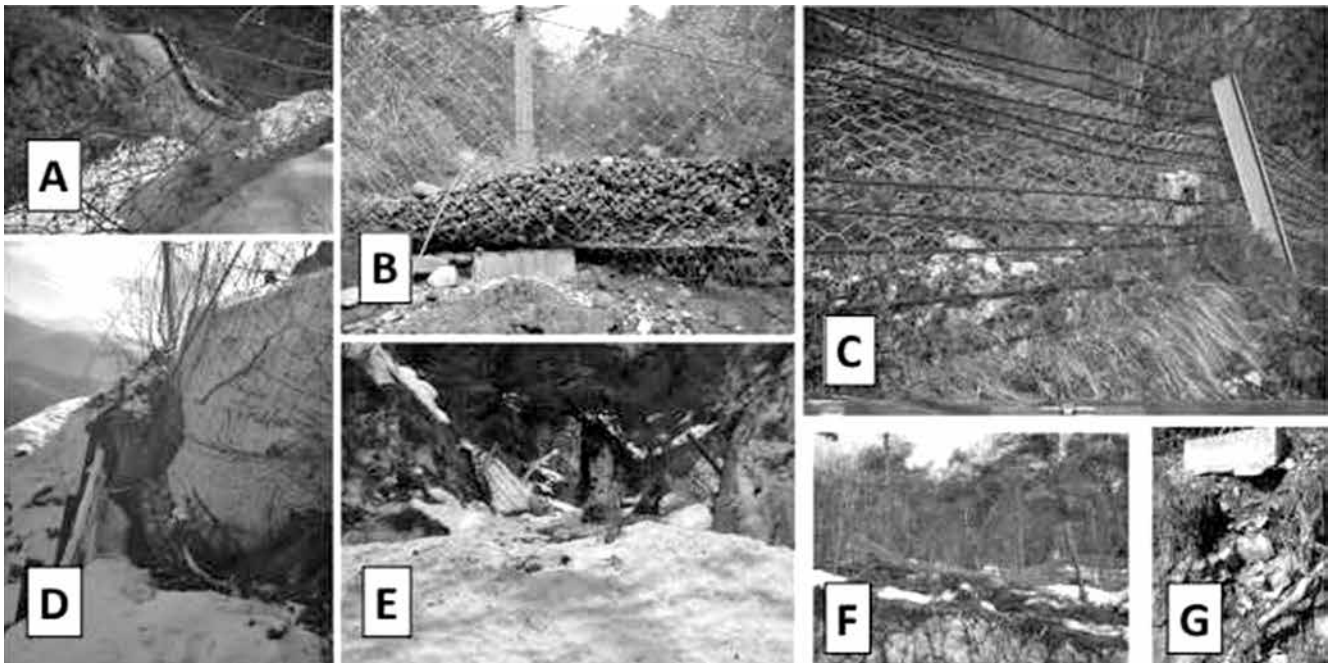

Fig. 3 – Damage after a very snowy winter season: A bending of uprights B filling with stone materials; C loosening of ropes; D breaking of netting E felling of uprights F filling with plant material; G under-excavation of foundations.

d) area subject for long stretches to snow and ice: generally, these are high altitude areas, alpine passes where it has been observed that the action of snow and ice produces frequent damage to structures;
e) the frequency of collapse events affects the possibility of damage to structures
f) type of vegetation: depending on the type of vegetation it has been noted that the access routes to the works and the works are greeted with different times.

Intervention times are defined according to the maximum weight given to the road or section examined.

Intervention times of less than one year are to be considered in exceptional circumstances (extreme weather events, earthquakes, fires, large-scale rockfall events resulting in damage to structures, etc.).

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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:

$$A_{tot} = \text{worst } (A)_1 \dots n \quad (2)$$

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	

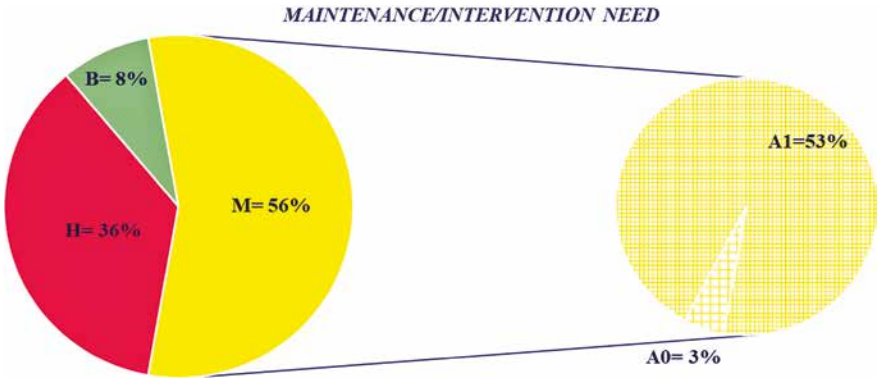

Fig. 3 – Results of the survey in terms of interventions need, as reported in Table 4.

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).

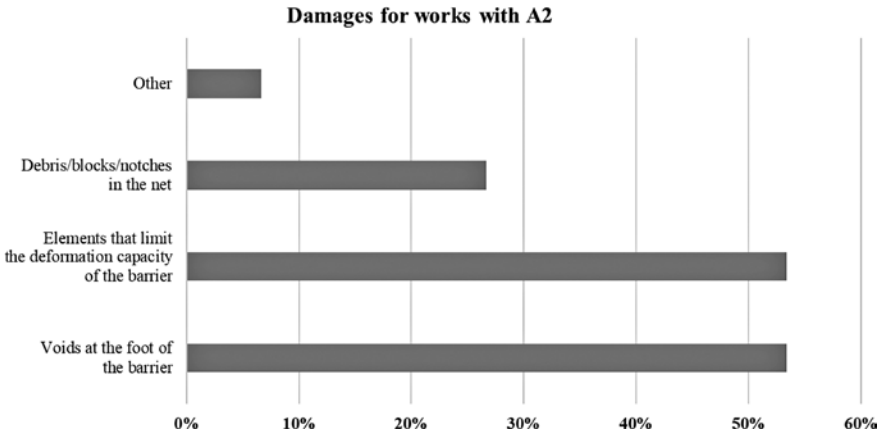

Fig. 5 – Histogram of the observed damages, which lead to a state of functionality equal to A2.

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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Geological conservation of natural and cultural heritage: the Italian experience in the 'Siq' of Petra

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The Petra Archaeological Park, a UNESCO World Heritage site since 1985, is characterized by a spectacular landscape but also by a great fragility fragile being prone to a diversity of natural risks (e.g. landslides, flash-floods, earthquakes) which can cause a potential danger to cultural heritage and visitors. The 'Siq', a natural canyon which constitutes the main entrance to the archaeological site, is among the most fragile areas of Petra due to its geological, geomorphological and geostructural characteristics. After the occurrence of rock falls occurred in the last decades, the UNESCO Amman Office in partnership with the Department of Antiquities of Jordan and the Petra Archaeological Park has therefore engaged in the 'Siq Stability Programme, a multi-year project, funded by AICS – Italian Agency for Development Cooperation. The project, presently in the 4th Phase of the Programme is mainly aimed at the analysis, monitoring and landslide mitigation works in the Siq of Petra. The paper resumes main characteristics of the project design and slope consolidation works of large blocks recently implemented with the fundamental support of Italian alpine climbers. A special attention has been provided non only to the works technical component but overall to the complex aspects of the logistics, site safety and use of the 'Siq' by tourists during the implementation of the works. Finally, the consolidation works in the 'Siq' of Petra represent a unique and challenging experience undertaken in a UNESCO World Heritage site in terms of technicality, continuous and positive cooperation and involvement of the local authorities and community engagement in the light of sustainable management of the cultural and natural heritage of Petra.

Keywords: *Rock slope consolidation, Risk Management, Petra Archaeological Park, UNESCO World Heritage site.*

1. Introduction

Reinforcement of natural or artificial slopes generally involve well-established methods, technologies, materials which are specifically designed and utilized according to site conditions and use. Nevertheless, usual civil engineering techniques and approaches adopted for consolidation of unstable slopes in UNESCO World Heritage sites have to provide, as much as possible, minimization of visual impacts and ensure at the same time a long-term effectiveness of the works. Following this fundamental prerequisite, the present paper reports the methods and the main results of slope consolidation works recently implemented in the 'Siq' of Petra (Jordan).

The World Heritage Site of Petra is located at ca. 200 km south of Amman, close to the town of Wadi Musa (Fig. 1). Petra was the capital city of the Nabataeans and became during Hellenistic and Roman times a major caravan centre and a crossroads for commerce in the Middle East. Petra is also worldwide known for the spectacular rock monuments carved in a multi-coloured sandstone landscape and the ingenious water management system which supplied the city, placed essentially in an arid environment. Nowadays, is one of the most visited archaeological site in the World and represent a fundamental cultural and also economical asset for Jordan. Petra, on the other hand, is also a very fragile site facing different climate-driven (e.g. flash-floods, wind erosion, weathering) and geological hazards (e.g. landslides, earthquakes) that constitute a permanent threaten for tourists and the long-term conservation of the monuments. In this regard, the 'Siq' of Petra, a 1.2 km naturally formed canyon that constitutes the main entrance to the archaeological site, present evidence of slope instability that has recently resulted in rock fall phenomena.

In line with the UNESCO Strategy for Risk Reduction at World Heritage properties (UNESCO, 2006), since 2009, the UNESCO Office in Amman has supported the Petra Archaeological Park and the Department of Antiquities, through the long-term 'Siq Stability Programme', funded by AICS (Italian Agency for Development Cooperation). The programme is addressed at assessing, managing and mitigating natural hazards in the 'Siq' with the final objective to develop a strategy towards prevention and mitigation of instability phenomena at the 'Siq' and, thus, further contribute to the management and conservation of the site. The 'Siq Stability Programme' incorporates different phases

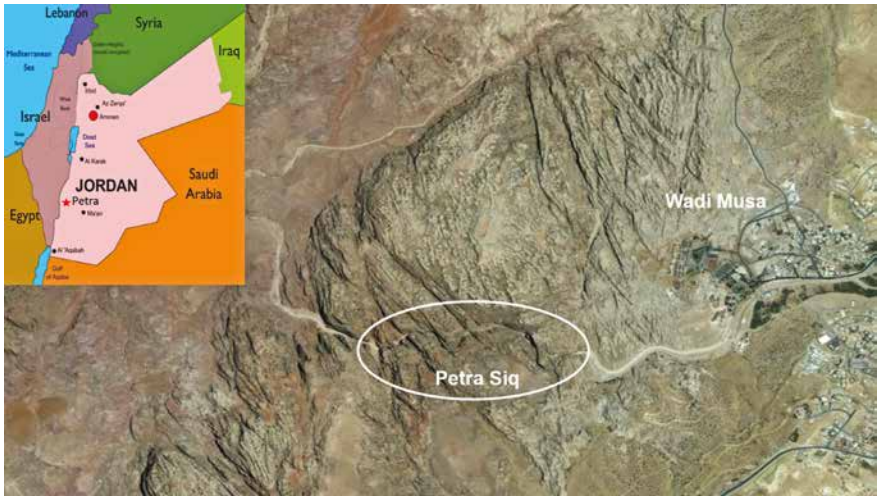

Fig. 1 – Location of the Petra archeological site and the 'Siq'.

Fig. 2 – UNESCO's 'Siq' Stability Programme methodological approach.

and projects. In 2009 a technical expertise in engineering geology was provided to the national authorities to support the consolidation of a large unstable block in the 'Siq'. The projects 'Rapid Risk Assessment' (2011) and 'Siq Stability' Phase I (2012-2015), were mainly focused on engineering geological analyses, the installation of an integrated monitoring system and a preliminary assessment of mitigation measures against rock instability (Delmonaco *et al.*, 2013; 2014; 2015; Cesaro and Delmonaco, 2017; Cesaro *et al.*, 2017). The subsequent Phase II (2015-2016) was aimed at the removal of potentially unstable small volume blocks and debris in the upper 'Siq' plateau and on the slope; this activity was undertaken by Jordanians workers and climbers in coordination with international experts (Delmonaco, 2016). The further step for the consolidation of larger potentially unstable blocks was planned after a detailed joint site survey carried out in cooperation with professional climbers. Specific guidelines and preliminary design for landslide risk reduction of the most critical areas in the 'Siq' were provided to UNESCO (Delmonaco *et al.*, 2017a). In the Phase III and IV (2017-2021), slope consolidation works of large blocks were implemented by an Italian company under the supervision of UNESCO as the final stage, although not yet completed, of the methodological process illustrated in Figure 2. An outline and main results of such works are reported in the following paragraphs.

2. Geology and slope instability in the 'Siq'

The 'Siq' of Petra is a 1,2 km long and from 3 m to 15.70 m wide natural canyon characterized by very steep slopes with variable height from few meters at the entrance to several tens of meters in some areas of the path. The 'Siq' being one of the main channels of the Wadi Musa catchment, collects a series of lateral steep channels that convey superficial water during short and intense rainfall events causing quite frequent flash-floods (Fig. 3).

Geologically, the 'Siq' is prevalently formed by the Disi and Umm Ishrin Sandstone Formation (Cambrian-Ordovician) with a typical rupestrian and massive forms (Bender, 1974). The sandstone rock is mostly composed of medium-coarse grained, well-sorted quartz combined with highly variable proportions of cements consisting (Amireh, 1991) of authigenic kaolinite, hematite,

Fig. 3 – Flash-flood in the 'Siq'.

Fig. 4 – View of Al-Khazneh ('the Treasury').

Fig. 5 – Rock fall occurred in the 'Siq' in May 2015.

goethite and subordinate poikilotropic calcite (Amireh, 1991; Franchi & Pallecchi 1995; Franchi *et al*. 2009). The formation can be subdivided into three main units, according to their texture, mineralogical composition and engineering classification. The Upper Sandstone, called "honeycomb sandstone", is composed of white and mauve-red, coarse to medium grained, hard and massive sandstone, capable to promote very steep slopes. It is characterized by typical cavernous weathering caused by solution of cement and consequent granular disintegration that form the typical honeycomb structures. The Middle Sandstone ("tear sandstone") consists of multi-coloured, medium to fine-grained, well-bedded and friable sandstone. Weathering is diffuse, especially by solution of the ferruginous and manganesiferous layers and cements that cause change or the rock face from red-brown to yellow and grey. Cross-bedding structures and presence of interbedded silty and clayey sands are quite common. This unit, due to anisotropy of materials, sensitive to moisture change, can promote sliding of blocks especially under saturation conditions. The Lower Sandstone ("smooth sandstone") is made of white, medium to coarse-grained, hard massive sandstone, mainly used as building and decorative sandstone. The majority of the rock monuments of Petra were almost entirely cut in the Umm Ishrin formation due to its good mechanical strength and facility to hand-carving (Amireh *et al*., 2001) (Fig. 4).

The geomorphology of the 'Siq' is the result of long and short-term factors such as tectonic uplift, erosion due to runoff, differential erosion and weathering of sandstone rocks. The mainly E-W orientation of the 'Siq' and its meandering course are a consequence of the intersection of sub-vertical faults and master joints. Along with main tectonic structures, other discontinuities in the 'Siq' rock slopes are sub-horizontal bedding planes and joints, from vertical to medium slope angle which correlated with the geomorphological evolution of the 'Siq'. Slope instability processes are conditioned by local orientation, density and persistence of discontinuities, and can affect rock blocks with variable dimension depending on types and degree of structural control. The main rock slope instability phenomena are: a) fall of loose debris (very small blocks) from the cliff edges and terraces triggered by heavy rainfall and flash-floods; b) fall/toppling/sliding of small/medium and large size blocks along pre-existing discontinuities of the rock mass. Slope failures in the 'Siq' of Petra generally occur along pre-existing discontinuities and their triggering is mostly associated with short-term factors depending mainly on climatic parameters (i.e. temperature/humidity changes) and seismicity factors (Delmonaco *et al*., 2013; 2014). In the last two decades, several landslide events, mostly rock falls and rock slides, with variable magnitude (volumes from < 1 m^3 to > 10 m^3) have occurred in the 'Siq' (2009, 2015) and in the core area of the site (2009, 2010, 2016, 2020) (Fig. 5). A brief description of such events is summarized in Table 1.

In Petra, heavy rainfall precipitation is characterized by an average yearly recurrence of 4-5 events, from October to early May, characterized by high intensity and short duration; these events can cause removal and fall of loose debris from the upper slopes and outlets of secondary channels (Delmonaco, 2016).

Based on available meteorological records and recent rock failures inventory, in the 'Siq' of Petra it is possible to estimate a yearly return time TR for debris fall as TR =4÷5 /yr whereas for rock slope failures (rock fall, rock slide) the return time can be assumed as TR =0.1÷ 0.2/yr (Delmonaco, 2016; Delmonaco *et. al*., 2017b).

Tab. I – Inventory of recent landslide events in Petra.

Location	Date	Typology	Magnitude
Siq (sector 11)	01.05.2009	Rock fall	0.025 m^3
Wadi Mu'eissra (Tomb 609)	01.03.2010	Rock-slide	70÷80 m^3
High Place of Sacrifice	14.10.2010	Rock fall	10÷15 m^3
Siq (sector 11)	29.05.2015	Rock fall	3÷4 m^3
High Place of Sacrifice	13.04.2016	Rock slide	1.5÷2.0 m^3
Treasury Plaza	19.02.2020	Rock fall	0.025 m^3

Rock slope deformation of largest unstable blocks in the 'Siq' were assessed through a wireless monitoring system installed in 2013, functioning until 2016 (Fig. 6). The wireless monitoring system was composed of 2 wire deformometers, 2 crack deformometers and 2 tiltmeters, 6 air-temperature sensors, a meteorological station, with wireless technology sensors for on-time registration and transmission of data. Displacement of the main fractures, inclination of the blocks and meteorological parameters were the main data collected by the system and sent to a main server via GPRS through a gateway located in the upper 'Siq' in front of the 'Treasury' monument. Data can be visualized on-time and further analysed through a specific software developed by EASA®.

Monitoring data during the 3-years observation have shown the dominant role of temperature in joints displacement where opening and closure of joints are strongly correlated with air cooling and heating (Fig. 7). A further analysis on the role of daily temperature oscillation in Petra in relation with recent rock falls suggest the value of ca. 15° in daily temperature difference as a possible threshold capable to promote rock failures in the' Siq' and Petra Archaeological Park Delmonaco *et al*., 2017b) (Fig. 8).

3. Consolidation works in the 'Siq'

3.1. Rationale

The engineering geological study conducted during the Phase

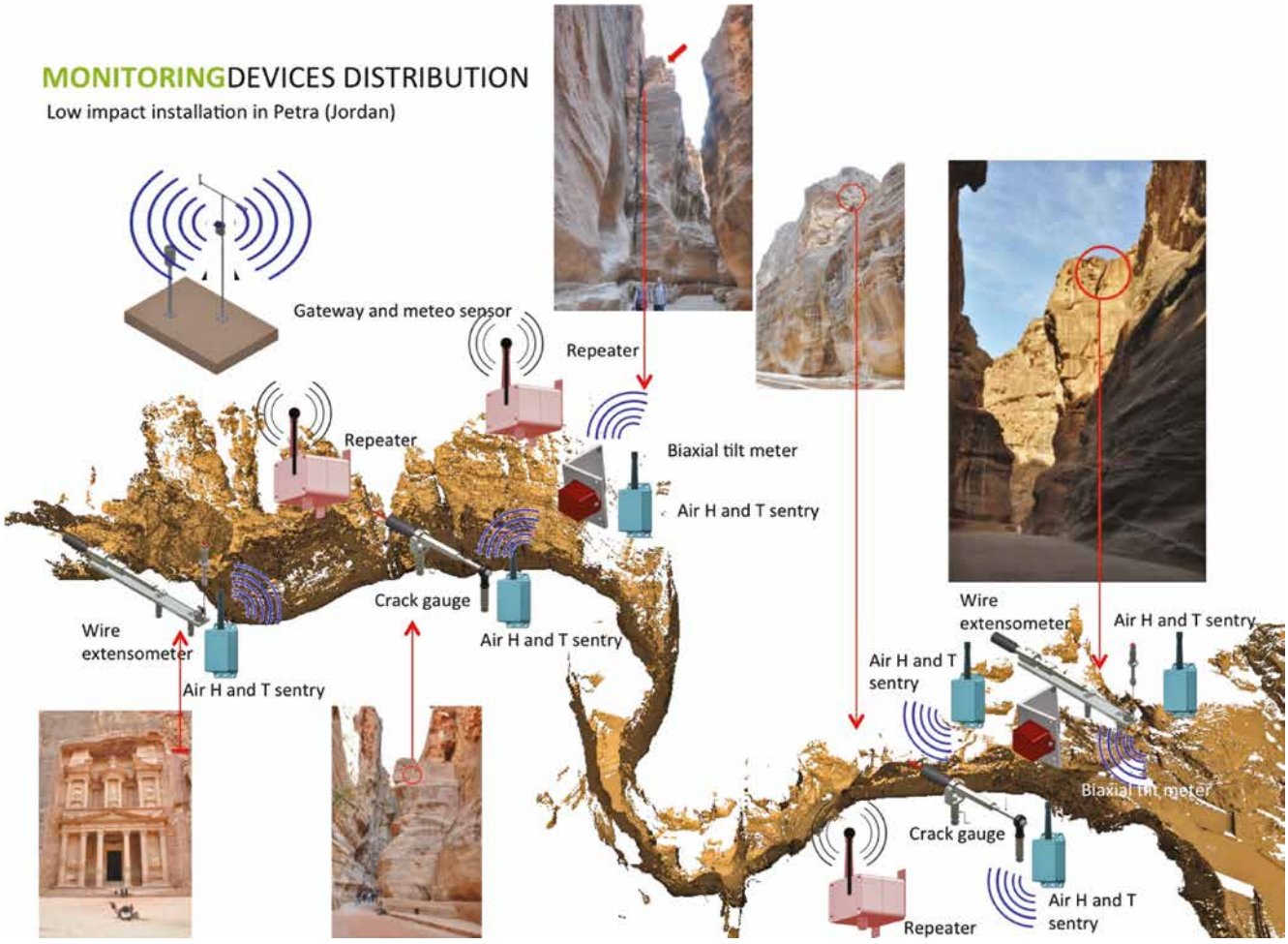

Fig. 6 – Scheme of the wireless monitoring system installed in the 'Siq' in 2013 in the UNESCO 'Siq Stability Project, Phase I.

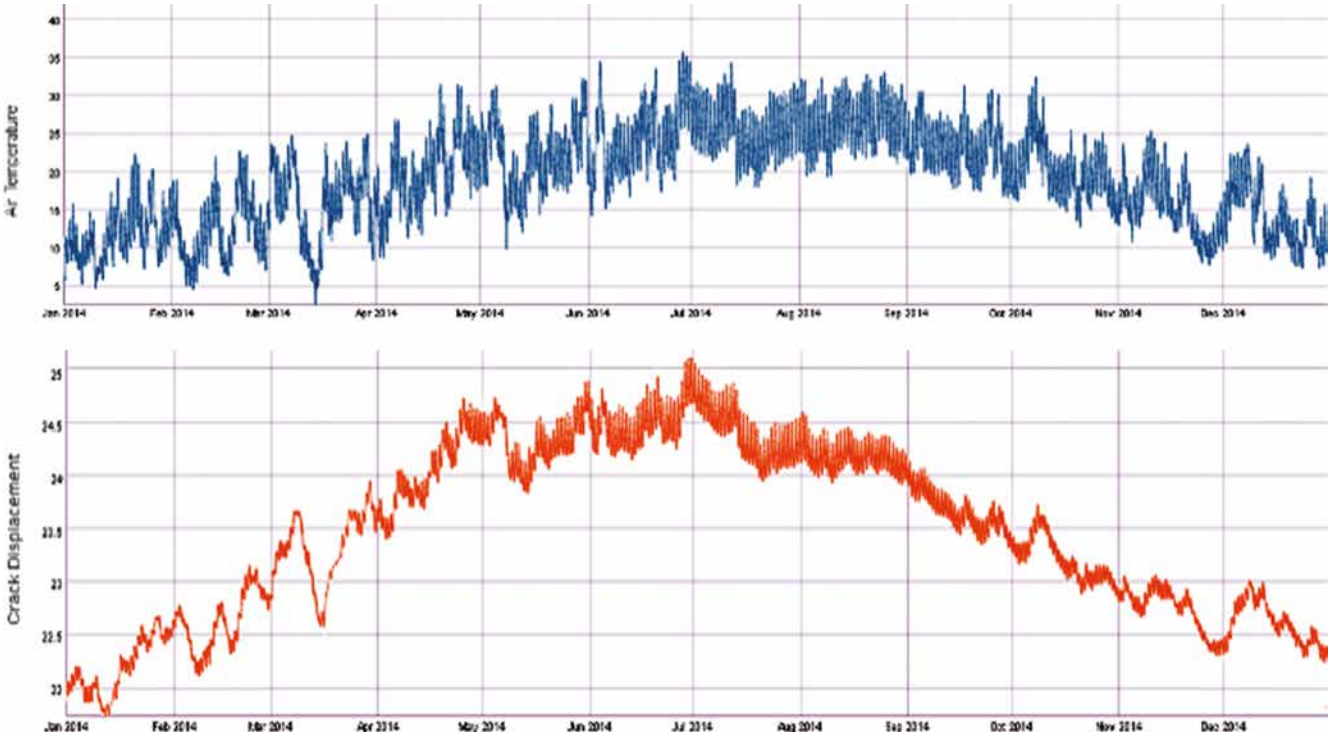

Fig. 7 – Correlation between air T° (up) and crack deformation measured in a rock block in the 'Siq'.

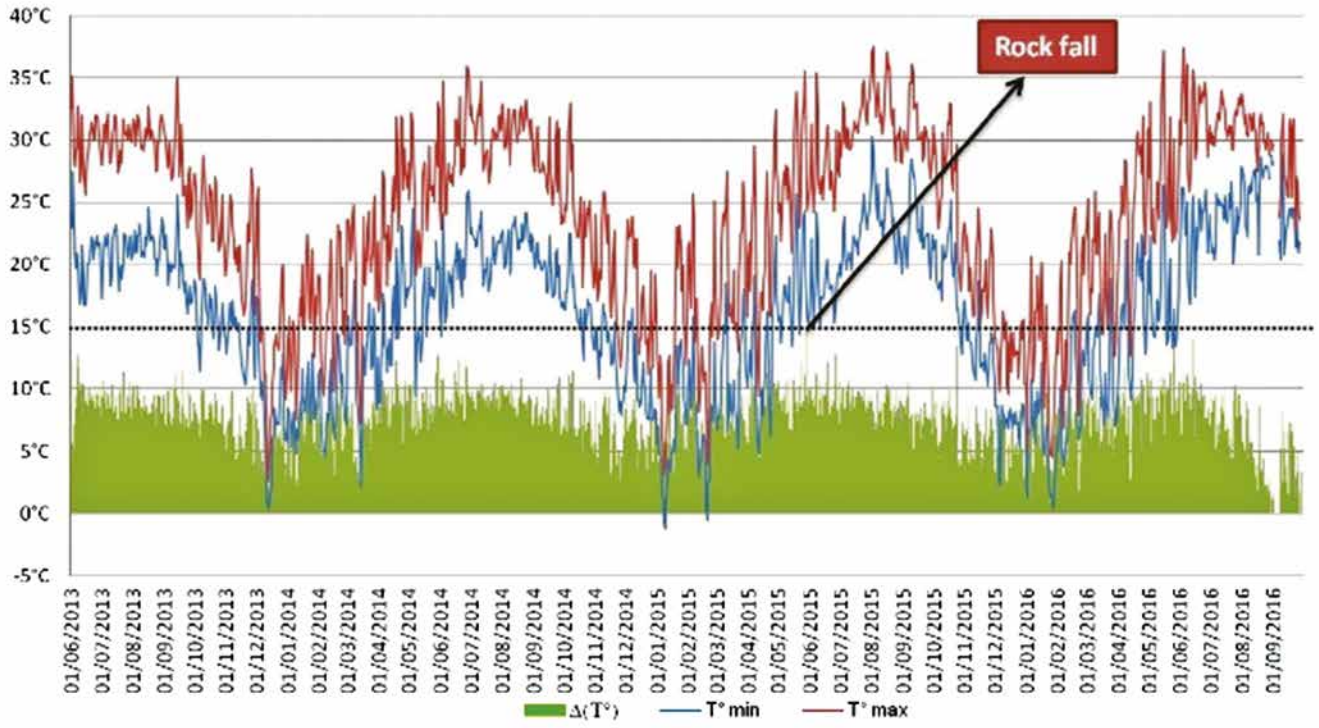

Fig. 8 – Possible threshold value (ca. 15°) correlated with air T° daily difference and rock fall occurred on May 31, 2015.

I of the UNESCO 'Siq Stability Project' by ISPRA defined and mapped most of the potentially unstable rocks outcropping along the 'Siq' slopes. The 'Siq' was divided into 14 sectors, according to the main local orientation of the path. A further and more detailed slope inspection, as part of the Phase II of the Project, was successively conducted in 2016 in the 'Siq' by Assoroccia and ISPRA with climber techniques. A series of potentially unstable zones prone to rock fall and debris flows, some of them not recognised during the previous studies, were detected and documented with detailed guidelines and preliminary design projects aimed at consolidation or mitigation of in-

Fig. 9 – Consolidation of a rock block in the 'Siq' sector 9 (2019).

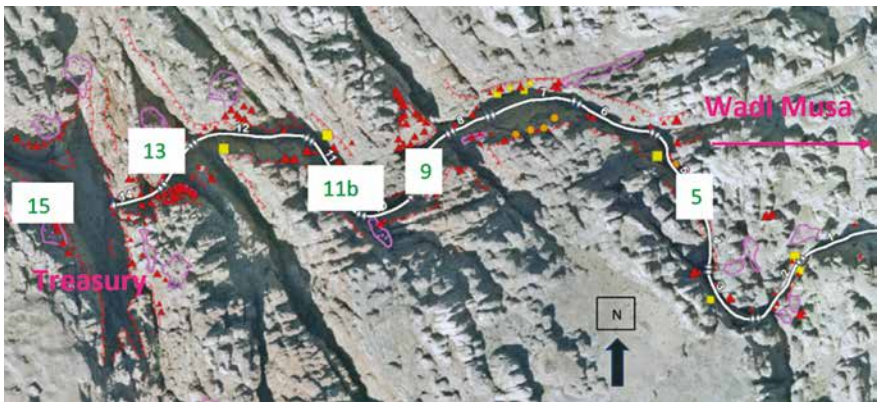

Fig. 10 – Sectors involved by consolidation works implemented in 2021 in the 'Siq'; the map reports the inventory of the potentially unstable blocks (points, squares, triangles) produced by ISPRA during the Phase I of the UNESCO 'Siq' Stability Project.

stability phenomena (Delmonaco *et al.*, 2017a). In 2018, after a first consolidation of a block in the 'Siq' sector 9 (Fig. 9), the Phase IV of the project was devoted to rock slope consolidation works of large blocks as the most challenging and difficult engineering activity so far undertaken in the 'Siq' of Petra. In July 2019, a further on-site surveys using climbing techniques was performed by the whole project team (UNESCO, ISPRA, geologists and engineers) mainly in order to: a) complete the engineering geological survey and data collection; b) install geotechnical monitoring systems; finalize the project design of consolidation works for the selected areas. Therefore, the works were implemented in the sectors 5, 9, 11B, 13 and 15 (Treasury area) in January-March 2021 by OR.BA. RI. snc and Consolrocce srl under the supervision of ISPRA and based on design projects provided to UNESCO by the aforementioned companies (Fig. 10).

3.2. Engineering geological analysis

In this paper, a detailed description of consolidation of the block located in the sector 5 is reported; nevertheless, the consolidation works undertaken in the sectors 9, 11, 13 and 15, even if technically less complex, were indeed of fundamental importance for the reduction of rock fall and debris flow hazard in the 'Siq'. The sector 5 is located approximately 500 m from the main entrance of the Siq, on the N and right side of the canyon. Here the canyon has a NNW-SSE direction (canyon rock face direction) and is ca. 80 m high. The danger is represented by a large potentially unstable rock block characterized by the base placed at an elevation of approx.17 m and the top at ca. 43 m above the ground level of the Siq path. The rock block has a W slope face exposition. Due to the narrow distance between the 'Siq' slopes, in this area the solar irradiation is quite low. The total dimension of the block is ca.1000 m^3 (Fig. 11).

Lithologically, the block is composed by sandstone belonging to the middle part of the Umm Ishrinn formation. The rock presents horizontal layers and beds of variable thickness (from few cm up to 1 m) with variable degree of strength and weathering. The base of the block, composed by cm-thick sandstone layers, is softer and strongly weathered than the upper part due to wind erosion and thermal stress (Fig. 12). The bedding planes are horizontal, locally with an inclination of 5° towards East, N90°/5°.

The block is characterized by the following main joint systems: joint set K1 N250-N70/85, joint set K2 N340-N160/85 and the rock bedding N90/5 (Fig. 13). The intersection between perpendicular, vertical joints and the horizontal bedding creates prismatic columns. The block is delimitated by a vertical joint system. The three faces exposition of the block is approx. N250-N160-N340. The surveyed discontinuities system corresponds to the main and secondary regional tectonic structures (e.g. faults, joints) (Fig. 14).

A large joint (N250-N70/70-85)

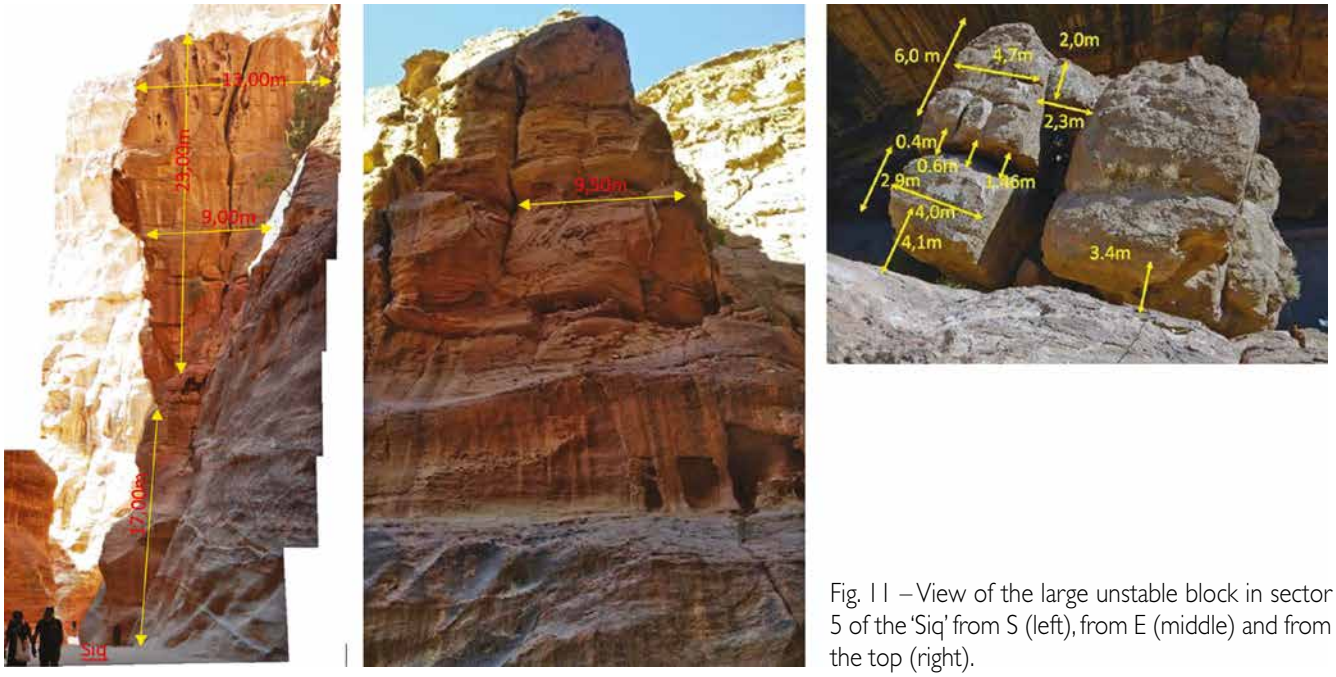

Fig. 11 – View of the large unstable block in sector 5 of the 'Siq' from S (left), from E (middle) and from the top (right).

Fig. 12 – Base of the large block located in the 'Siq', sector 5.

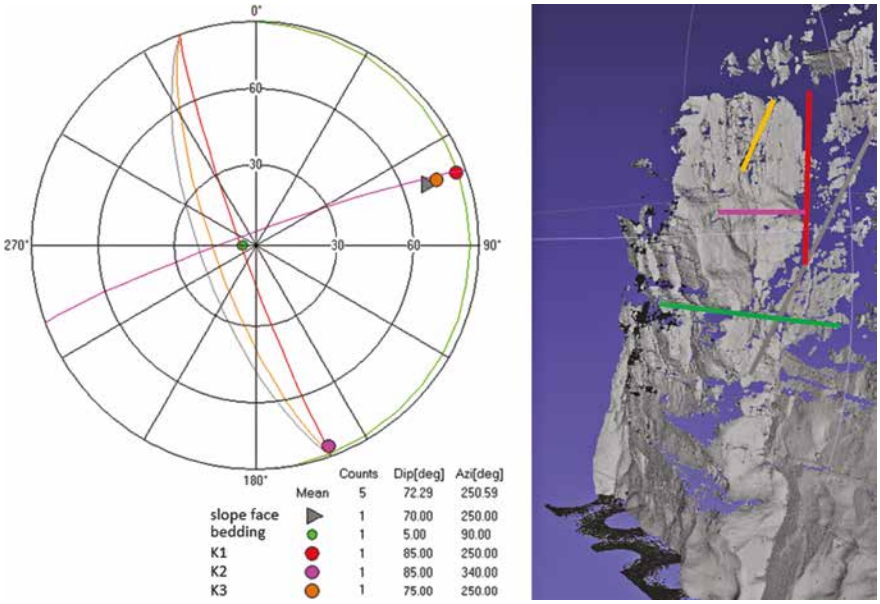

Fig. 13 – Stereoplot of the main discontinuities surveyed in the block of sector 5 (source laser scanner image: UNESCO/Zamani).

separates the block 5 from the rock slope. This sub-vertical joint is 4.10 m wide on the top of the block. South of block 5, the rock slope presents also an old sliding plane K1-1 (N250/70-80 (Fig. 15). The rock quality of the slope face can be classified as good.

The K1, K2 and K3 joint sets systems and the horizontal bedding divide the rock block 5 into five prismatic columns (a-e of Figure 16).

The Table 2 reports the main geotechnical and geomechanical data surveyed by ISPRA in the Phase I and during direct site surveys on the block carried out in 2019 where the main joint systems were also directly monitored through endo-

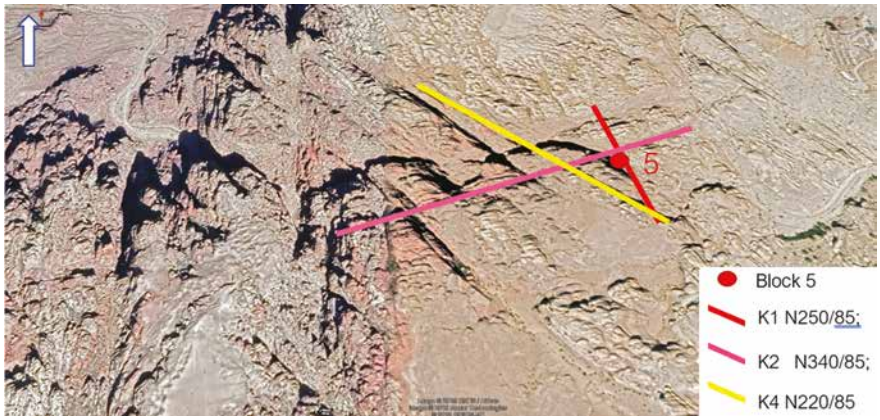

Fig. 14 – Orientation of the main discontinuities surveyed in the block of sector 5.

Fig. 15 – The arrow shows an old sliding plane surveyed S of block 5.

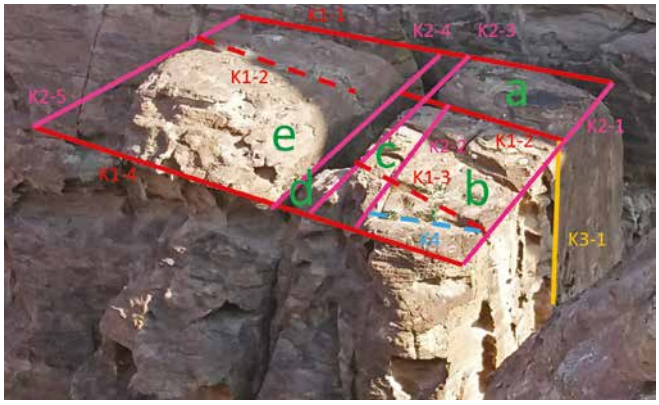

Fig. 16 – Separation of block 5 into five prismatic columnar-blocks (a-e).

Fig. 17 – Endoscope log in set K1-2 (left), jointmeter in K1-2 (right).

scope logs and jointmeter (Fig. 17 and 18).

From July 2019 to February 2021, the joint K2-4 was constantly monitored with a jointmeter and datalogger (Fig. 19). The graph shows the annual cyclical movement of the joint which is equal to 6 mm and a permanent displacement of ca. 1 mm. This movement is caused by the daily and seasonal thermal obscillations with the same trends previously shown in Figure 8. The direct monitoring of the large sub-vertical crack of block 5 undertaken in the period 2013-2016 also showed a permanent displacement of ca 2 mm. Over time, these movements can cause instability of the rock block.

A kinematic analysis for the assessment of potential failure type was performed for blocks 5a and 5b (which includes blocks 5b, 5c and 5d). The block 5e was considered as more stable and not included in the project. The joints K-1-1, K1-2, K2-1, K2-3, and K 3-1 are the perimeter faces of block 5a. The base of the block 5a is represented by the sliding plane K1-1 (N250-/70°-80°). The geological surveys and geomechanical

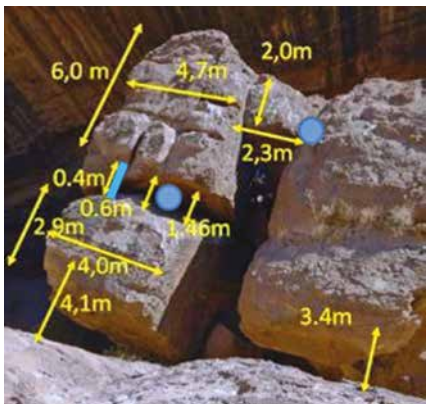

Fig. 18 – Location of jointmeter (blue line) and endoscopic logs (blue points) on block 5 (right).

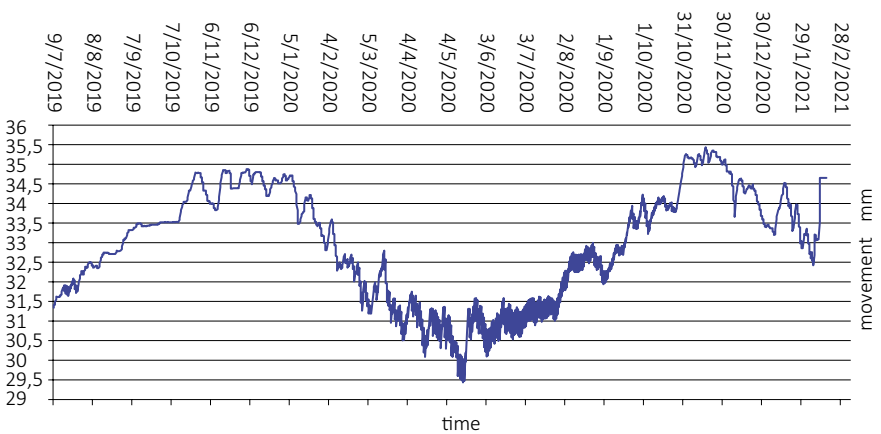

Fig. 19 – Trend of displacement of the large crack in block 5 monitored with a jointmeter (July 2019-February 2021).

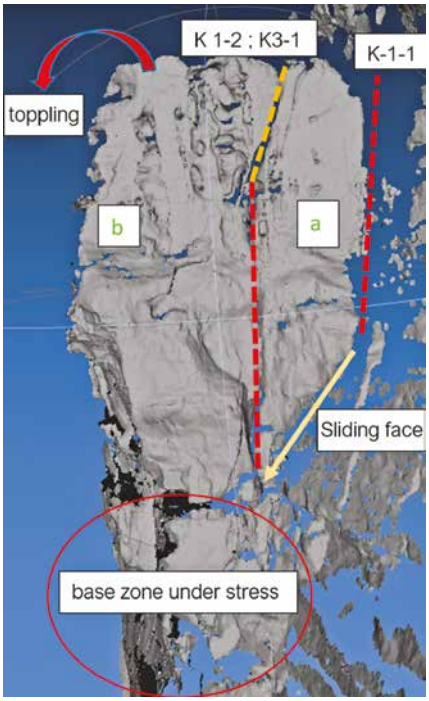

Fig. 20 – Potential failure types acting in the block 5 after kinematic analysis (3D laser scanning image from UNESCO-Zamani).

kinematic evaluations show that the block 5a could be destabilized by an initially sliding movement. The joint K1-2, K1-4, K2-1, K2-3, K 3-1 are the perimeter faces of block 5b. Along the base of the block 5b, a cm-wide vertical joints (N160°/340°-85°/90°) were detected. These joints are probably generated by the conversion of compression into tensile stress. The compression stress is provided by the weight of the upper prismatic column 5b. Kinematically, the block 5b could be destabilized by an initially toppling movement with direction N220 /N250. The blocks 5a and 5b were therefore classified as highly potentially unstable (Fig. 20).

3.3. Design phase

As an important assumption for the design phase, due to the lack of specific regulations in Jordan for rock slope consolidation works, the project design was undertaken according to the following Italian regulations and guidelines and Eurocodes:

- NTC2018;
- Eurocode 7;
- Eurocode 8;
- UNI EN 14490:2010 "soil nailing";
- UNI EN 12715:2003 "injections";
- UNI EN 1537 "anchor tie-rods";
- AICAPP recommendations;
- UNI 11211-1÷4 Rockfall protective measures;
- UNI EN ISO 17746:2016 "Steel wire rope net panels and rolls — Definitions and specifications";
- CIRIA – Rock netting systems – design, installation and whole-life management, 2018 reference manual.

In continuity with the consolidation works implemented in the previous Phase III, it was considered as fundamental to check the state and degree of maintenance of the structural elements, thus assessing the effectiveness and efficiency of the intervention, as well as of the aesthetical conditions of the works camouflage (e.g. ropes, nets) as another key aspect to take into account (Fig. 21).

The design phase of the consolidation works for each individual intervention has taken into account the complex geometries and variable volumes of the the blocks as well as their mutual interaction. This implies the choice of different consolidation technologies to be adopted and individually computed in order to optimize and calibrate the whole intervention. The meticulous analysis of the geometries, which are strictly related to the lithotype and geomechanical characteristics of the rock, allowed to proceed with a simplification of the volumetric distributions fully adherent to the reality and representative of the most probable kinematics. Consequently, any single intervention was designed and dimensioned according to the objective of consolidation, shape maintenance and masking of the visible structural elements.

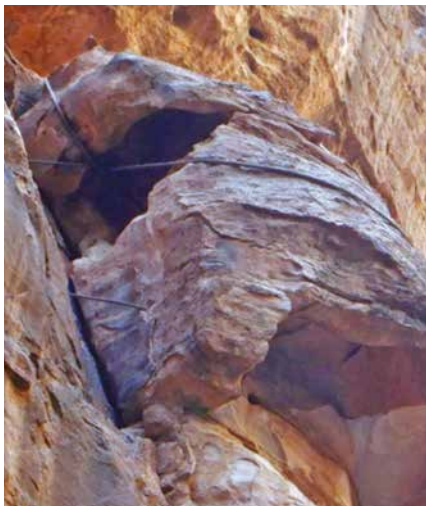

Fig. 21 – Rock block consolidated with anchored ropes in 2019 during the Phase III of the 'Siq Stability Project'.

The executive design of the slope reinforcement works has been based on the approaches and recommendations available in the technical literature (Hoek and Bray, 1981; Barton and Bandis, 1982; Bustamante, 1985; Panet, 1987; Duffy, 1992; Giani, 1992; Nicot *et al.*, 2001; Ruegger *et al.*, 2001; Cravero *et al.*, 2004; Ferraiolo and Giacchetti, 2004; Sasiharan *et al.*, 2006; Oreste, 2009; Cargnel and Cargnel, 2011; AGI-AICAP 2012).

The use of the limit equilibrium software (SWEDGE® and ROCKPLANE®) was accompanied by "hand" calculations by which the reinforcing elements (nails or anchors, bindings) were computed.

As a general approach, the high cultural and scenic values of the 'Siq's were taken into account for the consolidation methods; barbicans and reinforced concrete ribs were excluded in all cases as well as any demolition of large volume of rocks since they belong to the natural and cultural heritage of the 'Siq' due to their unicity. The minimization of the visual impact of works was also considered in the design and implementation phases of the works. All the external structural elements (e.g. ro-

pes, nets, head of anchors) where masked with different techniques. Also importantly, the continuous fruition and the passage of tourists in the working areas of the 'Siq' have been considered indispensable preconditions for the choice of the consolidation works and site safety measures.

The nailing was dimensioned for a total consolidation of geomechanical situations, while the cortical reinforcements were dimensioned to contain the release of superficial portions of the rock masses, where detected. The anchorage length of the bars is given by the sum of the foundation length (within the rock mass considered to be stable, so strength hierarchies were considered) and the free length. The free length was optimized on a case-by-case basis based on the size of the rock blocks, the morphology of the slope, and the parietal fractures present, which are very often of considerable thickness.

For individual blocks of smaller volumetry or where nailing is difficult due to the width of the frac-tures to the back of the rock bodies, it has been opted for resisting elements that are barely visible but effective for the objective, i.e., wire rope ligatures that envelop the unstable blocks and anchor into the stable rock mass with double spiroidal rope anchors.

The whole geometric shape of block 5 has been divided into two main blocks, block A and block B (pillar), both detached from the stable rock mass. Moreover, the block B has been divided into 3 distinct sectors (Fig. 22). The volumes of the single blocks are the following: block A/block 4: 150 m^3; block 1: 280 m^3; block 2: 350 m^3; block 3: 200 m^3; block B (total): 830 m^3.

In accordance with the general approach, it is assumed the consolidation of the block A has to be done by means of steel cables anchored to the stable mass since it could induce a negative thrust for the pillar. Then, for the consolidation of the pillar (block B), a mesh of deep anchor bars (portion 1 and 2) and (portion 3, where the risk of detachment of rocky elements on surface also remains) by high tensile strength steel wire rope net in addition to bindings and anchors were adopted. Consolidation steps as well have been planned to allow the highest safety conditions for operators and tourists during the works.

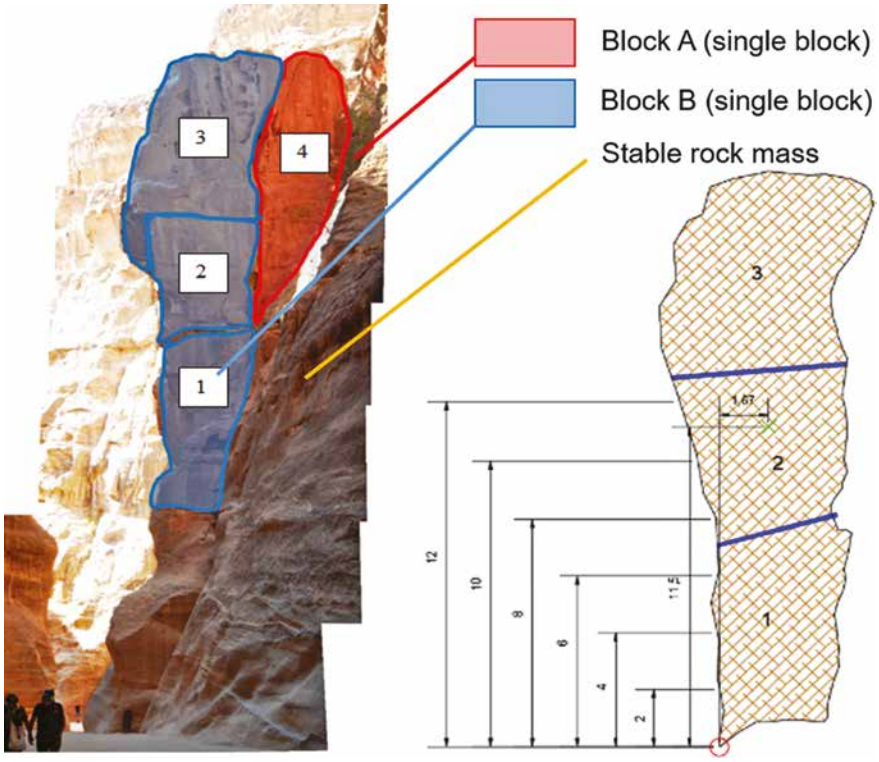

Fig. 22 – Scheme of block 5.

For block 5A subject to sliding, the mobilizing force was calculated according to the weight of the rock mass and the average inclination of the slope. A discontinuity friction angle of 41.75° was also taken into account to consider the effect of resistance to motion in the hypothesis of sliding trigger and nullification of the cohesion given by the rock bridges now existing.

Since some of the rock bars responsible for stabilizing the so-called 5B rocky mass also pass through the 5A block, we could count on their contribution for the stabilization of the rocky mass. As a precautionary measure, this contribution has not been taken into account in the verification, leaving only to bindings to counteract the destabilizing forces. From the analyses carried out, it is necessary to apply n.8 pairs of anchorages in double spiral rope ø16mm within perforation ø60mm of the length L=6m.

For the binding, steel wire ropes of diameter ø(min) 18 mm has been used in number of 2 ropes for each pair of anchors.

Under conservative conditions, in verifications conducted at equilibrium of the rigid body, only 3 m for each individual bar anchored in the solid rock have been considered. The anchors are provided in steel bar S950 / 1050 Ø32mm within a borehole Ø 90mm.

From the analyses carried out under the above assumptions, it follows that a mesh of bars 2m x 2m is necessary.

Taking into account the geometry, it was decided to create six or-

Fig. 23 – Construction of the protection net in the 'Siq'.

ders of bars with vertical spacing of 2m: the 3 lower lines, 9m long; the 2 intermediate lines, 12m long, and the upper line 15m considering that in the event of triggering instability due to toppling, the first and most stressed bars will be those above.

The steel chosen is high strength S950/1050, to have greater guarantees in case of unexpected shear stresses, which could be generated by seismic mobilization of the mass not in line with the installation of the anchors.

During the execution phase, it was also planned to put in place 4 bindings composed of steel ropes ø20mm connected to 4 pairs of anchorages in double spiral rope of 16mm within perforation ø(min) 60mm, 4.00m in length. These bindings, which are useful for the safety of workers, have not been taken into account in the calculation model, although they also have a consolidating effect.

In the planned configuration, a safety factor of FS = 1.35 is achieved.

3.4. Works implementation

The works have been initiated with the protection of the archaeological remains with sandbags and reinforced geotextile. The tourist passage was guaranteed by the construction of protective metal nets with wire ropes anchored on the two opposite sides of the canyon, consisting of wire mesh panels supporting double-twisted rock fall protection nets covered with geotextile (Figg. 23-24).

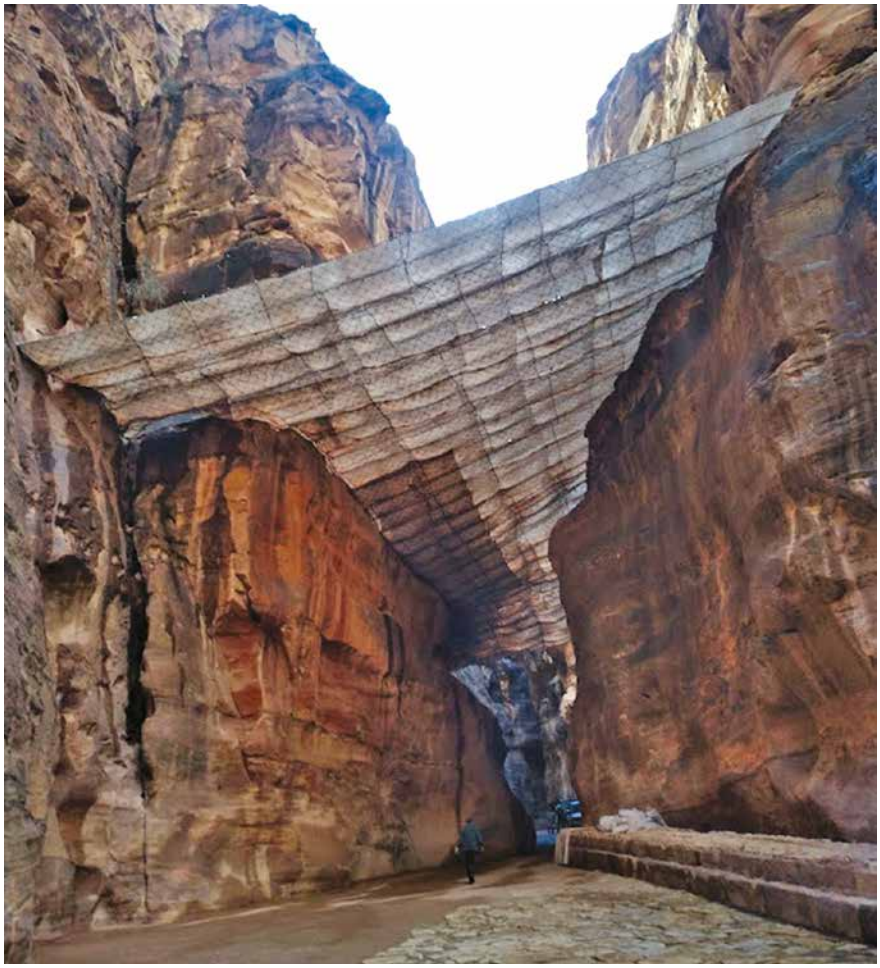

Fig. 24 – Final view of the protection net.

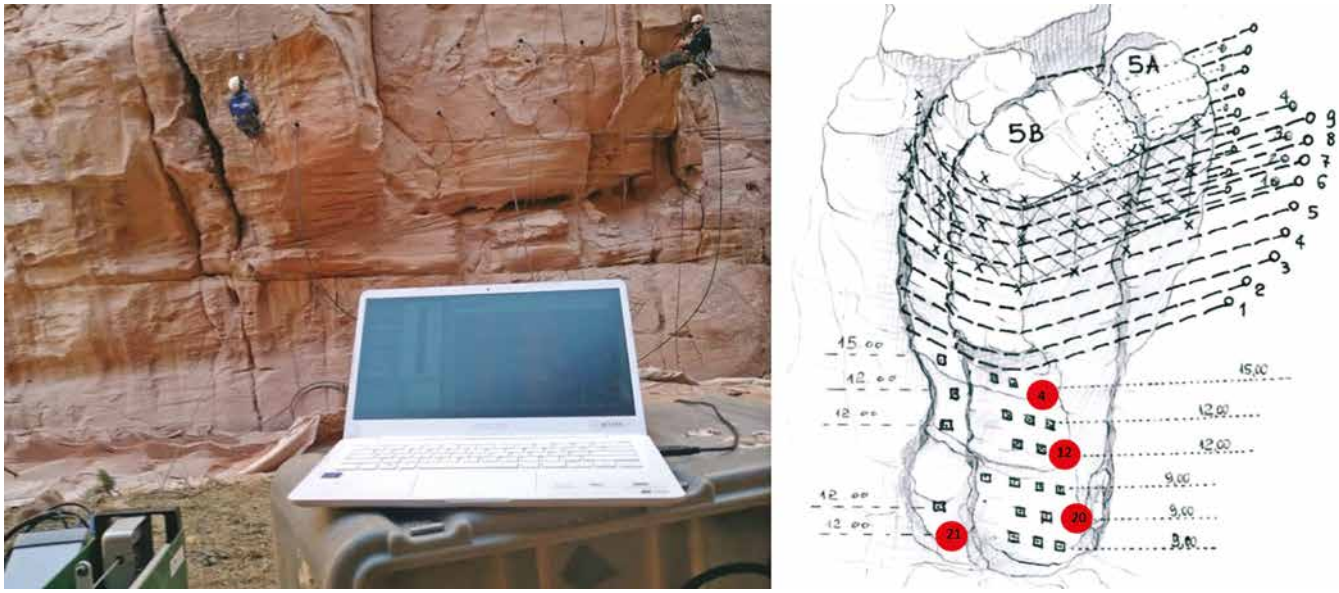

Fig. 25 – Real-time analysis with borehole optical televiewer, block 5. The red spots indicate the boreholes investigated (drawing by Elio Orlandi).

The block 5A has been consolidated with 4 ropes, and the block 5B (the more unstable block) has been consolidated with 9 ropes. The base of the block was consolidated with 24 deep anchors.

During the drilling phase for the anchoring, the rock deep joints conditions have been analyzed in some boreholes through the borehole optical televiewer OBI™ (Figg. 25-28). This optical borehole imager generates a continuous true color image of the borehole wall via an optical imaging system using a downhole CCD camera that records the image of the borehole wall in a prism. A built in high precision orientation package incorporating a 3-axis magnetometer and 3-axis accelerometer allows orientation of the images to a global reference and determination of the borehole's azimuth and inclination. The tool is fully downhole digital and runs on standard wirelines. The geomechanical analysis of the oriented borehole image can be utilized to detect presence of discontinuities, thin beds and determination of bedding dip. The real-time analysis in the block 5 detected a deeper discontinuity in the rock mass, not visible from

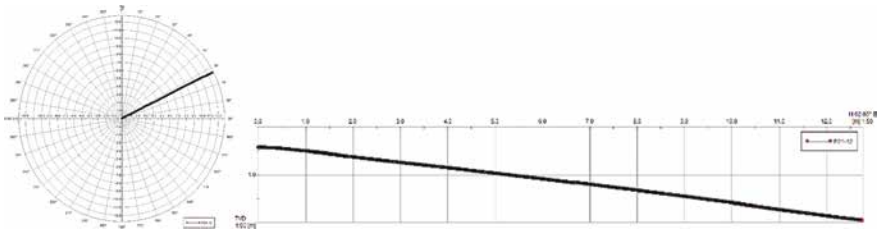

Fig. 26 – Orientation data, inclination and length of a borehole drilled in block 5.

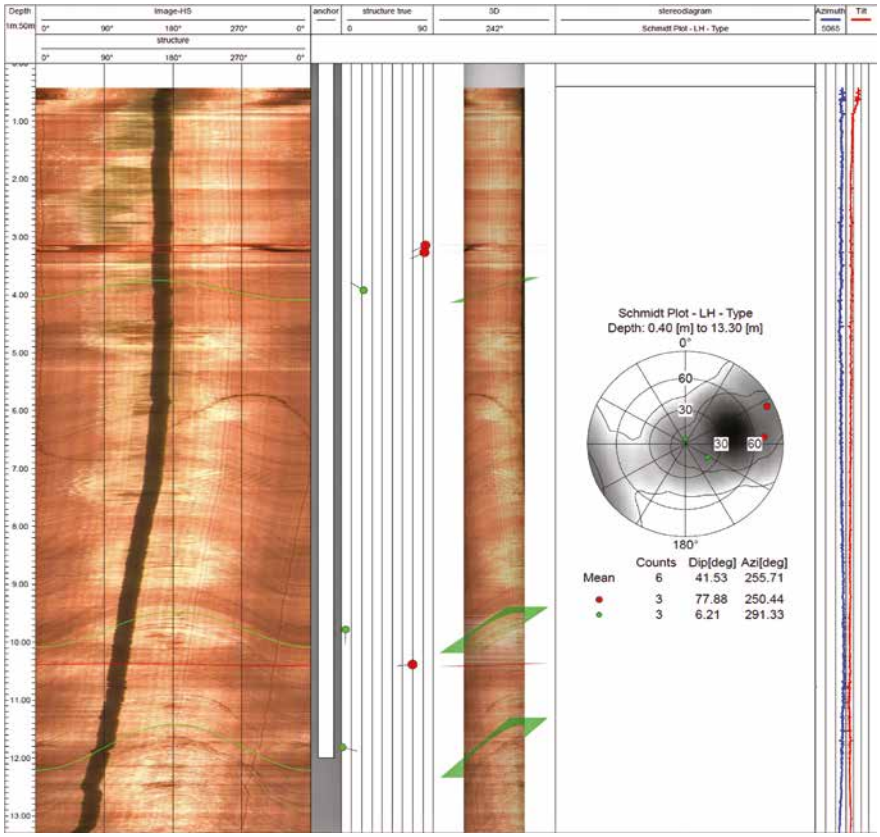

Fig. 27 – Borehole logging image.

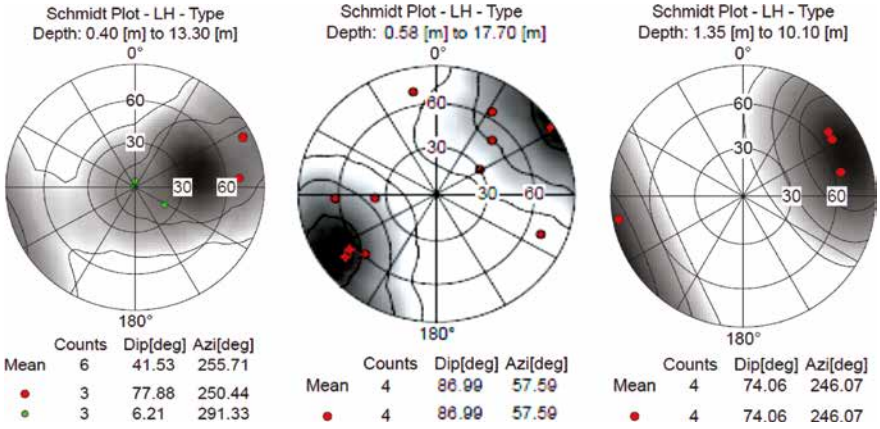

Fig. 28 – Stereoplot of joints (red spots) and bedding (green spots) detected with the optical televiewer.

outside. Due to this condition, it was decided to increase the depth of some boreholes and anchors in order to provide the highest safety conditions.

The borehole optical televiewer was also used to analyze the geostructural conditions of the rock mass where a pull-out test was carried out (Shu *et al.*, 2005). The pull-out test resulted in deformation of the system grout/bar without rupture (Fig. 29).

The drilling operations for the anchors were monitored with a vibrometer (Fig. 30) which provided data showing a negligible disturbance for the rock mass.

The operation of camouflage of the anchors works in the block 5 included the coverage of the head of the anchors with mortar mixed with local sand (Figg. 31-32).

Fig. 29 – Pull-out test implemented in the 'Siq' of Petra.

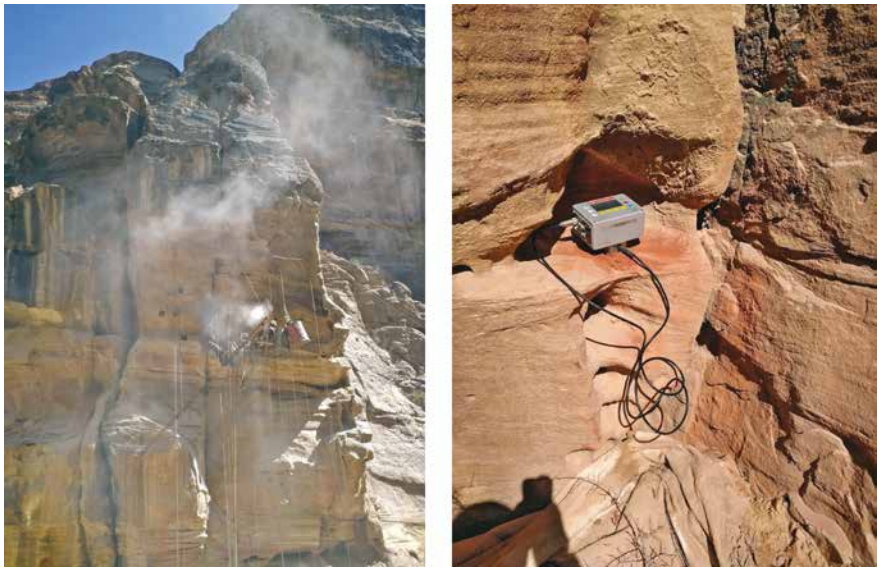
Fig. 30 – Vibrometer installed in the block 5 during the drilling operations.

4. Discussion

The paper reports the results of slope consolidation works carried out in the 'Siq' of Petra, a UNESCO World Heritage site in the framework of the UNESCO 'Siq Stability Programme'. A brief summary of previous activities conducted in Petra in the last decade highlights the need by Jordanian relevant authorities to implement direct and indirect actions for the mitigation of rock fall and debris flow in the 'Siq' to reduce the risk for tourists and the unique cultural and natural heritage of the 'Siq'. The slope consolidation works implemented in the period 2019-2021 by Italian expert rock climbers, engineers and geologists represent the last and most challenging stage of a long-term involvement and investments from UNESCO and AICS. The project design included a systematic site geological analysis and use of innovative technologies (i.e. borehole logging analysis) for monitoring geostructural rock conditions utilized for the first time in slope anchoring operations. The project works included effective safety measures for the protection of the cultural heritage and tourists in Petra since all operations were carried out during the visit hours of the archaeological site. A special attention was also devoted as much as possible to the minimization of the visual impact of the works in order to preserve the natural aspect of the site. The slope consolidation works implemented in the 'Siq' of Petra represent a unique and successful

Fig. 31 – Head of anchor covered with mortar.

Fig. 32 – Final view of block 5 front after the consolidation works.

experience conducted in a UNESCO World Heritage site subject to landslide hazard which included not only the implementation of the slope works but also capacity building and training activities addressed to Jordanian technicians and workers. Finally, it is worth of consideration the need to proceed with further activities such as control and monitoring of other critical zones in the 'Siq' potentially subject to slope instability.

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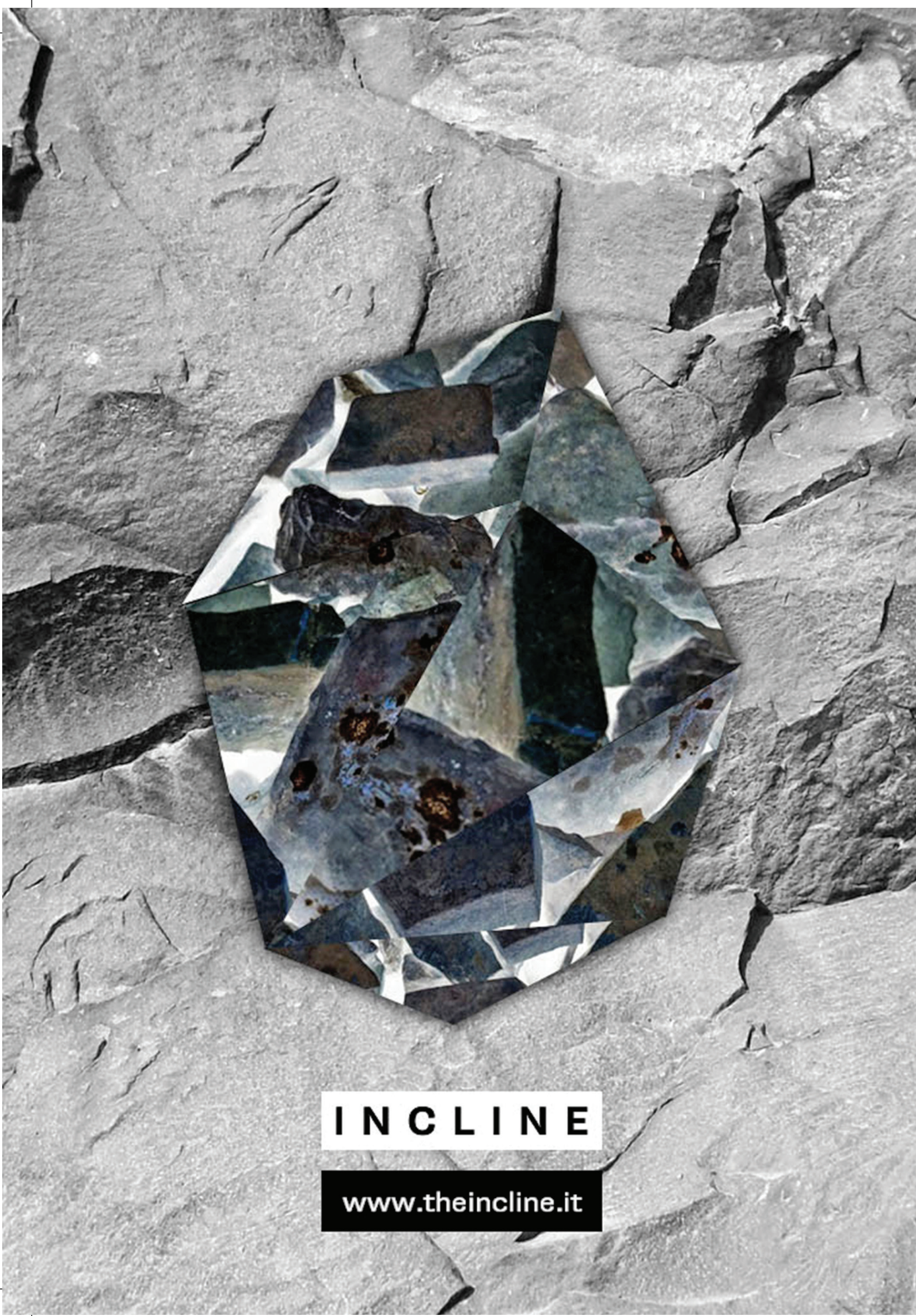
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