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Maintenance and risk management of rockfall protection net fences through numerical study of damage influence

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ABSTRACT. Rockfall protection net fences are key protection systems in mountainous areas worldwide to ensure the safety of infrastructures, roads and urban areas. Maintenance of these products is fundamental for public administrations in order to guarantee risk mitigation. This paper deals with the assessment of the installation problems and damages induced by ageing of rockfall protection net fences, using numerical modelling in order to evaluate the influence of these issues on their behavior. A percentage of the residual efficiency is assessed as a useful tool for risk analysis and maintenance planning.

KEYWORDS. Rockfall protection net fence; Rockfall; Explicit numerical modelling; Residual risk; Maintenance.

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INTRODUCTION

Protection net fences play an essential role to reduce rockfall risk of infrastructure, roads and residential areas against rockfall within acceptable values.

Since their installation requires important investments for public administrations, procedures have been developed to quantitatively evaluate risk reduction obtained with these devices and to allow a comparison with other technical solutions for an optimal choice [1-5].

Moreover, the presence of already installed protection devices on the slope has to be considered in the risk assessment and their efficacy in time has to be correctly evaluated, in order to do not overestimate or underestimate their effect [6-8].

Therefore, it is very important for these evaluations to take into account maintenance issues with the aim of evaluating how time and ageing influence efficiency of net fences since public administrations are interested in assessing how long a certain investment ensures the needed risk mitigation. This evaluation allows them to schedule an appropriate maintenance management, taking into account available resources.

Despite the highlighted relevance of the influence of damages induced by ageing and installation problems on the behavior and efficiency of rockfall protection net fences, there is a lack of data in technical literature on this topic. Moreover, there is currently no predictive method that could be used to estimate the performance of damaged rockfall protection fences and there is great difference in the technical recommendations for the maintenance provided by producers.

The behavior and effectiveness of rockfall protection net fences was tackled both by full scale tests [9-13], especially after the development in Europe of the ETAG 027 standards [14-16], by pseudo-static analyses [17] and by numerical modelling [18-28] but a complete analysis of aged rockfall net fences has not been performed.

For this reasons, in this paper the influence of damages and installation problems on the efficiency of rockfall protection net fences has been studied by using numerical modelling. The assessment of the possible damages and installation problems has been performed based on an analysis of data obtained during a site survey in the Alps reported by Dimasi et al. [29]. The numerical simulation was therefore developed with the simulation of a standard impact, according to ETAG027, with different conditions able to simulate different degree of ageing or damages on the various elements of the structure. These models allow to determinate the possible reduction of efficiency and to compare the behavior of the deteriorated and not deteriorated rockfall protection net fences. The simulation is performed with a FEM model of a rockfall protection net fence of nominal energy of 3000 kJ. The model is assessed using the results of experiments on full-scale prototypes whose data were obtained from Gottardi and Govoni [11].

NUMERICAL MODEL OF THE NET FENCE

The numerical model was developed using the software ABAQUS/Explicit 6.13. This software has an explicit finite element formulation allowing to simulate non-linear dynamic events such as the impact of a block on a net fence. The studied net fence is a commercial product with a Maximum Energy Level (MEL) of 3000 kJ and the full scale data reported by Gottardi and Govoni [11] were used for back analysis.

The support structure of this net fence has four HEA200 steel posts, 5 m high, restrained at the base by cylindrical hinges allowing rotation in the upstream-downstream direction. The interception structure is made of a principal steel ring net; each 350 mm ring is connected to six nearest rings. The connection structure comprises two longitudinal upper cables and two longitudinal lower cables, eight upstream cables and four lateral cables. Each cable has a diameter of 20 mm. The longitudinal cables are free to slide on the posts in the longitudinal direction. The net fence is provided with tubular energy dissipating devices, one on each upstream cable and three on each longitudinal cable.

Fig. 1 shows a photo of the net fence.

Figure 1: Photo of the studied rockfall protection net fence.

In the numerical simulation, the support structure was modelled with 3D-2node beam elements, with a HEA200 cross section. These elements had linear elastic behavior with Young's modulus of 210 GPa while the cables, the energy dissipating devices and the net were modelled with 3D-2node truss elements that cannot withstand flexural stresses.

The material assigned to the cables had elasto-plastic behavior with Young's modulus of 150 GPa in the elastic part of the curve and of 5 GPa in the plastic one. The yield strain was set at 0.001 and the ultimate strain at 0.006, which corresponds to an ultimate stress of 1770 MPa.

The behavior of the cable connected to the energy dissipating device is complex due to the behavior of the energy dissipating device. The cable withstands the force until the activation force of the dissipating device is reached (at about 45 kN in the studied case), then the deformation of the material composing the device starts, and the constitutive relationship is governed by this phenomenon. Once the maximum displacement of the energy dissipating device is reached, the system follows again the cable behavior. To simulate this behavior a tri-linear law was assigned to the material of energy dissipating devices. The first part had Young's modulus of 63 GPa, the second one had Young's modulus of 1.4 GPa and the last part had same behavior of the cables, with Young's modulus of 150 GPa and ultimate stress of 1770 MPa.

Also the numerical simulation of the ring net behavior is complex, due to the high number of interactions between the rings that slide and deform during the impact. Therefore, following Nicot et al. [18], the net was modelled with an equivalent hexagonal net, with hexagon sides of 350 mm. Each vertex of the hexagon is the center of one of the six rings connected to the central ring. The interaction between two rings is modelled by the truss elements connecting the vertices. The material assigned to the elements composing the equivalent net had tri-linear behavior, described by three different Young's moduli. The Young's modulus of the first part was of 170 GPa, till a strain of 0.001 is reached. The Young's modulus of the second part was of 4GPa, until a strain of 0.25, and the Young's modulus of the final part was of 170 GPa.

This constitutive behavior was assessed numerically simulating the real scale tests reported by Gentilini et al. [24].

The block impacting the net was simulated as a polyhedral non-deformable element, with the same geometry of that foreseen ETAG 027 standards and the impact speed was of 25 m/s.

In the numerical model, the posts were restrained at the base by a cylindrical hinge allowing rotation on the longitudinal axis while spherical hinges simulated anchorages of the cables to the ground and to the top of the posts. The longitudinal cables were free to slide on the top and on the basis of the posts in the longitudinal direction but were constrained in the other directions. In the model, the net was not allowed to slide on the longitudinal cables, differently to what happen in the real net fence. This simplification was necessary in order to reduce computational complexity of the simulation. Fig. 2 illustrates the general sketch of the model.

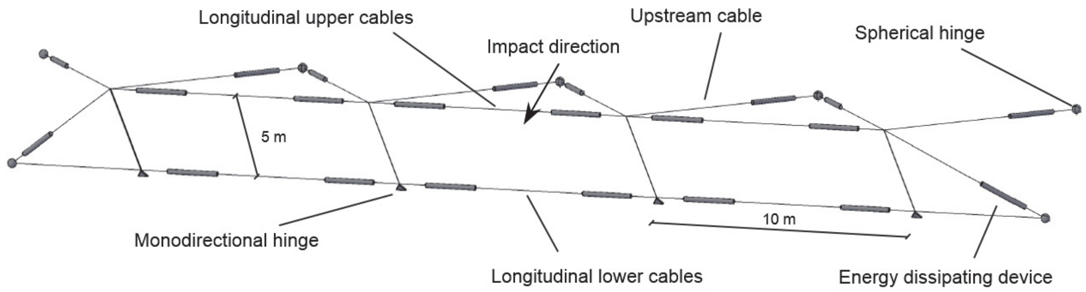

Figure 2: Drawing of the modelled rockfall protection net fence.

	MEL Test		**SEL Test**	
	Real scale test	**Numerical model**	**Real scale test**	**Numerical model**
Breaking time (s)	0.30	0.32	0.26	0.22
Maximum elongation (m)	5.35	5.38	3.90	3.73
Final elongation (m)	4.80	5.05	3.20	3.35
Residual height (m)	3.55	3.34	3.95	3.71

Table 1: Comparison between the real scale test and the results of the numerical simulation.

In the simulation the energy level foreseen by ETAG027 standard MEL and SEL tests were performed and the results of the simulations were compared to the data obtained by real scale tests reported by Gottardi and Govoni [11].

As can be seen from Tab. 1, the numerical model well reproduced the results of the real scale tests. In the simulation, the breaking time is evaluated as the first time the velocity of the block becomes zero and the maximum elongation is the maximum distance between the initial position of the net and the position of the net at the breaking time measured parallel to the slope. The final elongation was the same distance evaluated at the end of the test, i.e. at 6 s from the first contact of the block with the net. The residual height is the minimum distance between the lower and the upper longitudinal cables at the end of the test.

Fig. 3 compares model deformation during MEL test at six different times: particularly t = 0 s is the first contact of the block with the net, t = 0.36 s is the breaking time and t = 6.00 s is the test end time. Fig. 4 shows the plastic strain in the central panel of the net during the simulation; it is possible to see that the highest deformations occur in the contact area of the block with the net, then the deformation extend to the panel with a cross shape and this result is very close to what was observed in real tests [10,11].

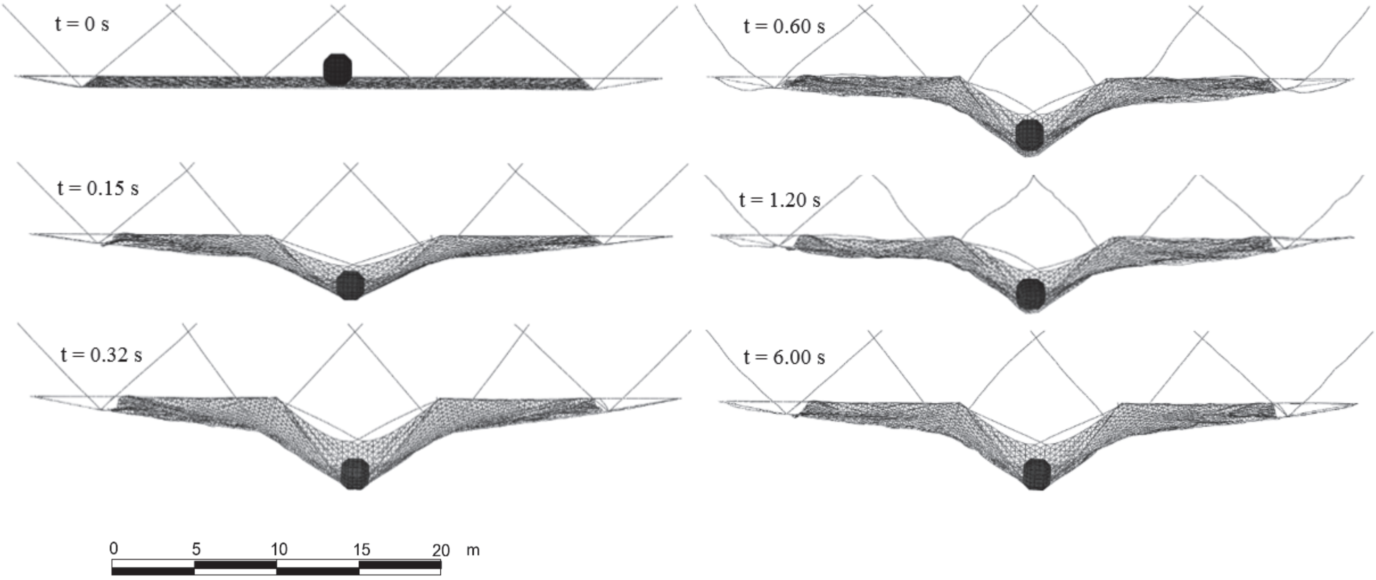

Figure 3: Numerical modelled net fence during the MEL test.

NUMERICAL SIMULATION OF DAMAGES

In order to evaluate the influence of the problems detected during the site survey [29], the numerical model was modified to reproduce damaged conditions. These conditions represent the most common local damages and the ones that were most frequently highlighted by the site survey [29]. The model has not the ability to take into account a reduction of the overall properties of the net barrier since them can be difficulty described and the research has been focused on those damages that can be modelled as the removal of a structural rope or an incorrect assembly of one or more elements of the barrier itself.

Specifically, these conditions are:

- damages to the upstream ropes or to the clamp connections; these situations can be due to installation of the clumps not in accordance with the regulations in force [31] in terms of number, distance and torque applied to the fastener or to damages of the connections and of the ropes caused by impacting blocks;
- damages to the anchorages, such as failure or under efficiency of the anchorages due to wrong installation or damaging during the device life;
- installation geometries different from those prescribed by the producer; this is a common issue for to the geometry peculiarity of many sites; in the site survey several cases have been observed ranging from barriers with short and sub-horizontal upstream ropes to barriers with extremely long upstream ropes.

Time-dependent damages to the barriers can be related to corrosion on ropes and clip connections. Nevertheless, in the barriers analyzed during the site survey, corrosion affects only some of the secondary metallic elements, but not ropes.

This is due to the non-aggressive environment of installation (usually C1-C2 following UNI EN ISO 9223 [32]) and to the protection nowadays used against corrosion (zinc and zinc-aluminum coatings) that ensure the durability for the life span of the protection devices.

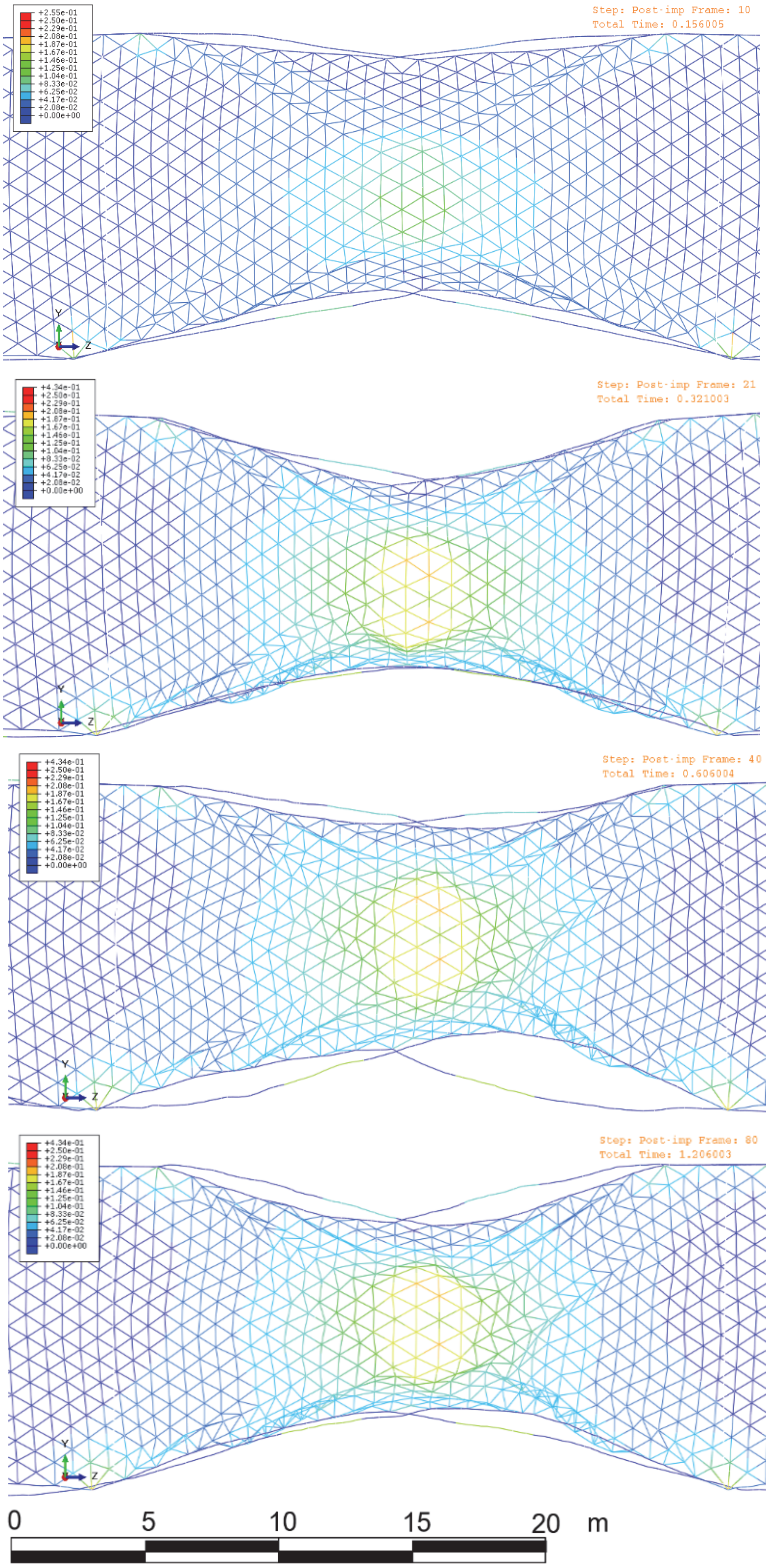

Figure 4: Comparison of the plastic strain in the central panel of the original model at different times during the impact. Time is in seconds [30].

Therefore, the six models set up for the research are:

- models from (a) to (d) simulate the failure of connections made by rope clips of the upstream cables, due to installation problems or to clip corrosion. In the numerical models, this kind of damages has been simulated simply removing one of the upstream cables from the computation i.e. the connection is not working and thus the cable cannot withstand any stress.

  Moreover, models (c) and (d) simulate also the failure of one anchorage of the upstream cables due to a not correct grouting. In the numerical model this possibility is simulated removing from the simulation the cables that are restrained by that anchorage.
- model (e) and (f) reproduce the effect of different installation geometry due to local conditions. The goal of these models is to study the influence of anomalous geometrical installations with reference to the one tested following the ETAG027 geometry.

  Model (e) represents a case with short and horizontal upstream cables. The original model has oblique upstream cables of 7.7 m while in this model they are horizontal with a length of 5.7 m while model (f) reproduces the effect of very long upstream cables. The upstream cables of this model are 20.0 m long. In the numerical model, only the geometry and length of upstream cables have been changed from the original model. (Fig. 5).

On these six modified models impact tests were performed at different energy levels aiming to identify the maximum energy the modified net fence can withstand without failure of one of the principal elements. Failure of cables and energy dissipating devices was established when one of these elements reached a plastic strain bigger than that correlated to the ultimate stress. Since the model uses an equivalent net, the ultimate stress of the net was unknown, for it may be different from that of the real ring net. Therefore, the equivalent net was considered failed if at least one of the elements composing the net reached a plastic strain bigger than the maximum recorded during the MEL simulation.

Once the maximum energy the modified model can withstand has been defined, the residual efficiency (r_{ef}) of the net fence can be evaluated as

$$r_{ef} = \frac{E_{MW}}{E_{nom}} (\%)$$

where E_{MW} is the maximum energy the net fence can withstand and E_{nom} the nominal energy of the net fence according to the ETAG 027 classification. The values of residual efficiency of the models are reported in Tab. 2.

Model	Problem simulated	Maximum energy withstood (kJ)	Residual efficiency (%)
a	Failure of one clip connection or of one upstream cable	3000	100
b	Failure of one clip connection or of one upstream cable	3000	100
c	Failure of two clip connection or of two upstream cable or of an anchorage	2900	97
d	Failure of two clip connection or of two upstream cable or of an anchorage	3000	100
e	Short and horizontal upstream cables	2400	80
f	Long upstream cables	2600	87

Table 2: Summary of the results of the numerical simulations.

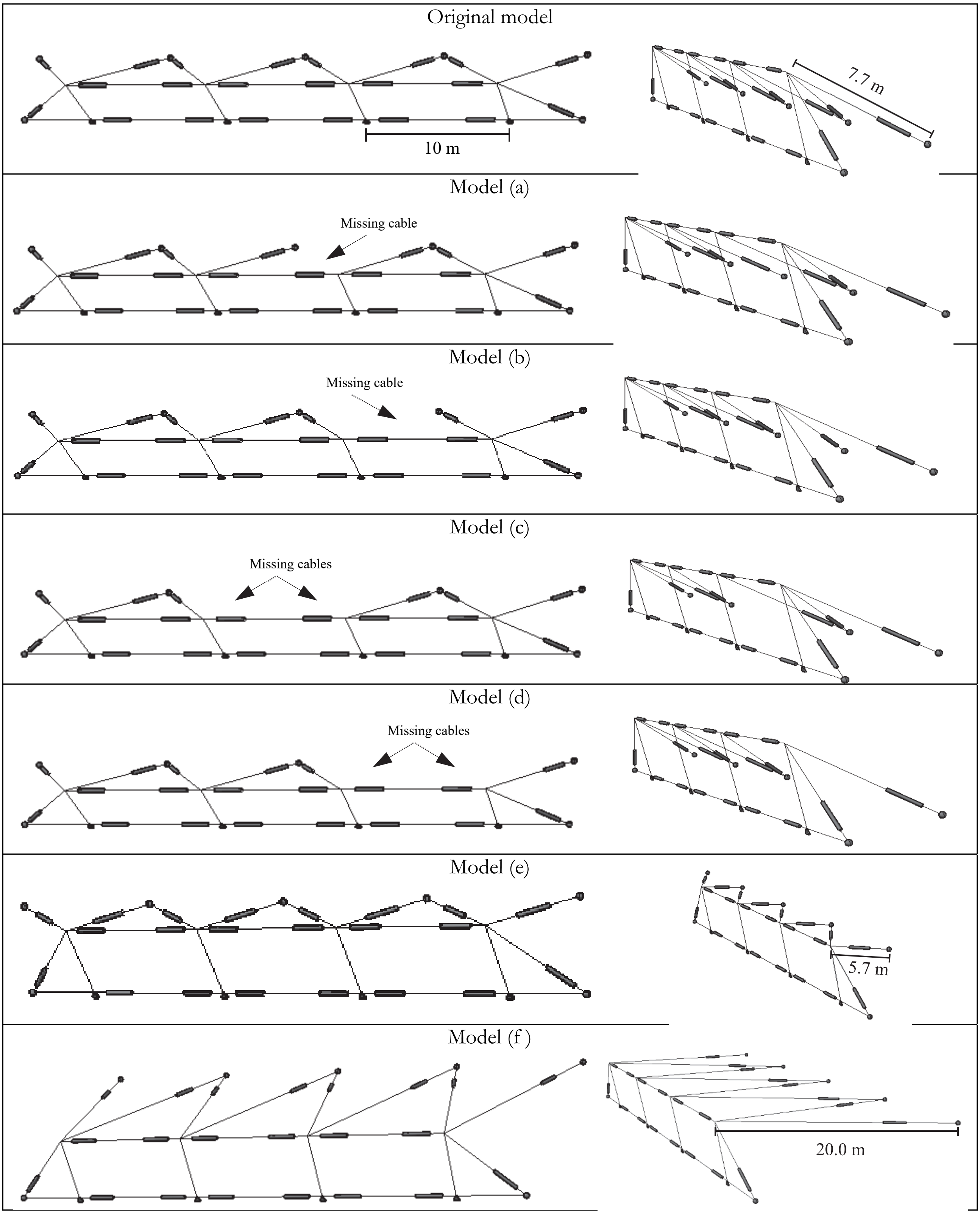

Figure 5: Drawing of the original and modified models of the rockfall protection net fence.

The most important results obtained comparing the six numerical models are:

- in models (a), (b) and (d) the modified net fence fulfilled the test at 3000 kJ without failure of any element, while in model (c) at an impact of 3000 kJ the net reaches a plastic strain higher than the maximum recorded during the original model MEL test in the contact area. Therefore, the net is considered failed. Repeating the simulation with an energy of 2900 kJ no failure has been produced. Based on these results the residual efficiency for model (a), (b) and (d) is of 100% while it is of 97% for model (c).
  Moreover, the simulations show a variation in the behavior of the net fence in terms of maximum elongation. In the damaged models the maximum elongation of the net fence increased, up to the 20% in model (c) (Fig. 6), while the final elongation is almost the same of the original model. This result is very important in terms of correct positioning of the net fence on the slope. The increase of maximum elongation is due to the absence of the upstream cables involving a lower stiffness and lack of constrains of the system.

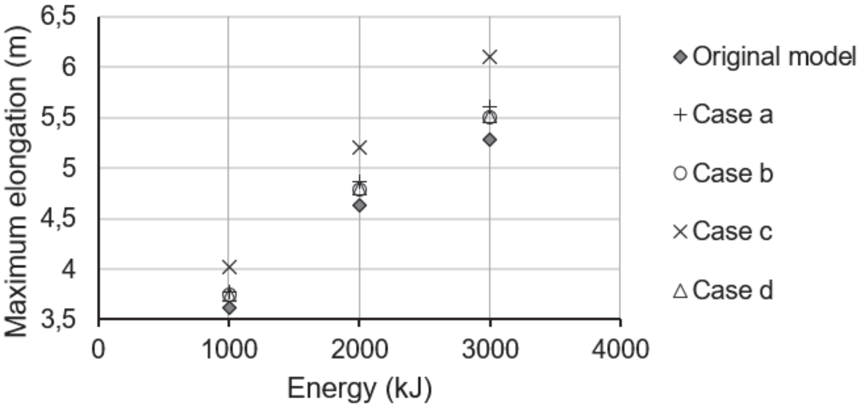

Figure 6: Comparison of the maximum elongation of the original model and of models (a), (b), (c) and (d).

- in model (e), the net, the lower longitudinal cables and the two energy dissipating devices of the upstream cables convergent to the central anchorage get to failure for an impact energy of 3000 kJ. These failures were due to the higher stiffness due to the shorter upstream cables. Repeating the simulations with lower energy, the model withstood an impact with an energy of 2400 kJ with residual efficiency of 80%.
- in model (f), the longitudinal cables failed at an impact of 3000 kJ. In this condition, the energy dissipating devices of the upstream cables were not activated. This behavior may be explained considering that longer upstream cables involve lower stiffness and so the cables were less charged. Consequently, the energy coming from the impact concentrated on the other elements of the net fence and particularly on the longitudinal cables. The model withstood an impact at 2600 kJ, with residual efficiency of 87%.

These results allow to say that after some time of ageing or when the net fence has been not correctly installed the energy it can withstand is lower than that assessed in the ETAG027 classification. Therefore, residual efficiency value should be considered in rockfall risk analysis in order to take into account in this process the deterioration and installation conditions of the net fence.

When making the design of a protection by net fences, the choice of the product is usually based on the statistical analysis of the rockfall trajectories and on the evaluation of the rock block size to be stopped.

Therefore, based on the statistical evaluation of the computed speeds and height of trajectories in correspondence of the protection device to be installed, it is possible to assess the maximum energy to be stopped and consequently choose the optimal product. After this analysis, it is possible to assess the number of blocks that cannot be stopped and, based on this number, it is possible to assess the residual risk. Risk analyses are usually started taking into account the number of blocks that exceeds the barrier capacity or jumps over it and, consequently, reaches the object to be protected [3]. As a consequence, the risk mitigation is directly affected by the percentage of block stopped by the net fence i.e. its efficiency. An incorrect installation can reduce the ability of the barrier to stop the block and consequently a higher percentage of blocks can pass. The analysis has allowed to quantify this value for a set of frequent defects or ageing conditions.

Taking as an example, the procedure proposed by Peila and Guardini [3], the key parameter in the evaluation of the probability in the analysis is the number of rockfall events that can affect the infrastructure per year (N_r). A protective device reduces the probability of occurrence of the event, i.e. induces a reduction of the number of blocks affecting the road, that can be estimated as

$$N_r^{'} = (1 - C) \cdot N_r$$

where N_r is the number of blocks reaching the road without the protection device, $N_r^{'}$ those reaching the road with the device and C is the catching capacity of the device. The catching capacity is the percentage of blocks that the device can stop.

The requested catching capacity should be evaluated through the trajectories analysis and the design block assessment. The residual efficiency proposed above describes the energy the damaged barrier can withstand compared to the nominal one. Therefore, it can easily be taken into account in the risk analysis modifying the previous equation as follows

$$N_r^{'} = (1 - C \cdot r_{ef}) \cdot N_r$$

The residual efficiency reduces the catching capacity, i.e. increases the number of blocks reaching the road ($N_r^{'}$), with an obvious increase of the rockfall risk. Therefore, in the design, the effect of a damaged barrier can be considered in the trajectories analysis simulating a barrier with a reduced ability to stop a certain energy and allowing more blocks to go through.

CONCLUSIONS

The influence of damages induced by ageing on the behaviour of a rockfall protection net fence is analyzed using numerical modelling. A site survey on many net fence installations located in North of Italy allowed to point out the most relevant problems related to ageing of rockfall protection net fences after installation and suggested how to set up the numerical models.

The main goal of the analyses is to show how damages of the components can affect the efficiency of the products and therefore reduce their ability to stop falling blocks. To develop this assessment six different numerical models of a commercial net fence have been studied and an assessment of the residual efficiency has been developed. This value may be included in rockfall risk analysis allowing to take into account the conditions of a damaged or aged device. In this procedure the residual efficiency value should be used to reduce the catching capacity of the net fence increasing the number of falling blocks that might impact against the structure to be protected and consequently correctly considering in the risk analysis the presence of aged net fences on the slope. It is important to highlight that all the risk analysis procedures have as an input datum the number of blocks impacting the structure.

Moreover, this appraisal allows owners to plan maintenance or refurbishment works and establish priority between different protection devices, knowing when the reduction of efficiency induces a risk higher than the accepted threshold value.

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