



HAL
open science

Sensitivity Analysis of the Global Response of Flexible Rockfall Barriers

Cyril Douthe, Chloé Girardon, Romain Boulaud

► **To cite this version:**

Cyril Douthe, Chloé Girardon, Romain Boulaud. Sensitivity Analysis of the Global Response of Flexible Rockfall Barriers. *Geosciences*, 2022, 12 (2), pp.75. 10.3390/geosciences12020075 . hal-04309097

HAL Id: hal-04309097

<https://hal.science/hal-04309097>

Submitted on 27 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Sensitivity analysis of the global response of flexible rockfall barriers

Cyril Douthe^{1,†,*} , Chloé Girardon¹ and Romain Boulaud¹

¹ Laboratoire Navier, École des Ponts ParisTech, Univ. Gustave Eiffel, CNRS

* Correspondence: cyril.douthe@univ-eiffel.fr; Tel.: +33-16415-3740

† Current address: 6 & 8 avenue Blaise Pascal, 77420 Champs sur Marne, France

Abstract: Protection barriers against the fall of boulders and rocks are structures with non-linear mechanical behaviour that make the study particularly complex. In this paper, the understanding of an experimentally observed variability is investigated numerically using a non-linear spring-mass equivalence. First, key figures of the experiments on which this study is based are detailed. Then, the numerical model for the dynamic simulation of the barrier deformation under impact is presented. Finally the variability due to block-related parameters and then net-related parameters are explored and evidence the role of the cables geometric stiffness in the global response of the fence.

Keywords: Rockfall barrier; Structural Engineering; Brake activation threshold; geometric stiffness.)

1. Introduction

The risk due to falling rocks and boulders is all the greater because it is difficult to predict it, as well as to anticipate the trajectory or energy of the block [1]. Passive protections must therefore be designed to be able to stop the fall of blocks alongside more or less large areas of instability. These protections often take the form of nets supported by edge cables and posts attached to the cliff [2].

Mechanical understanding of these rockfall protections is difficult: non-linear and dynamic behaviours, in a context of large displacements and irreversible mechanisms to dissipate energy, make the study of these barriers all the more complex. A series of test campaigns were conducted: by rolling rocks along the slope (Muraishi *et al.* [3], McCauley *et al.* [4]); by moving them along a cable (Peila *et al.* [5], who proposed semi-empirical design methods based on their measurements of the maximum deceleration) or launching them vertically (Gerber *et al.* [6] and Muraishi and Sano [7]) as well as the experiments of Grassl *et al.* [8] in partnership with the Swiss company Geobrugg. Experimental tests for a better understanding at the net scale were conducted by Trad [9] and Bertrand *et al.* [10].

Some of these experiments may be realistic but cannot be controllable and thus difficult to repeat. Others are well repeatable, but the rotating component of the speed is missing. Therefore, a standardisation of experimental test protocols was carried out (ETAG [11]) which sets out a 1:1 test protocol and a series of results to be achieved in order to validate a barrier and allow its commercialisation in the European Union. Impacts are defined by their kinetic energy E_c . A MEL impact ("Maximum Energy Level") corresponds to an energy E_c ; a SEL impact ("Service Energy Level") corresponds to two successive energy impacts of $E_c/3$. These two types of impact are centred in the central module of the barrier. The ETAG standard also defines the shape of the module and requires an impact velocity of at least 25 m/s. A review of approval of flexible rockfall protection systems was recently provided by Volkwein *et al.* [12] and outlined some general features on the response of such structures over a large variety of kits.

Citation: Douthe C; Girardon C; Boulaud R Sensitivity analysis of the global response of flexible rockfall barriers. *Geosciences* 2021, 1, 0. <https://doi.org/>

Received:
Accepted:
Published:

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Submitted to *Geosciences* for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

39 This barrier validation protocol leads to a questioning of its representativeness
40 under more general conditions - without a safety coefficient, external elements are not
41 taken into account, as well as the possibility of non-central impacts (Toe *et al.* [13]). In
42 addition, these validation experiments are very expensive; a realistic numerical study is
43 therefore useful to ensure the feasibility of the experiment. A number of models have
44 been presented in the literature. The following list is non-exhaustive. Rockfall barrier
45 models have been developed by Nicot *et al.* [14], where ASM rings are modelled by
46 a node which is located at its centre. The interaction between the rings is modelled
47 by imaginary bars joining all the rings. Volkwein [15] suggests a four-node mechanical
48 model of ring. It is made of two parts: two diagonal tension only springs and one
49 circumferential spring. A recent publication by Boulaud and Douthe [16] has however
50 shown that the modelling choice for the net had few influence on the global response
51 of the structure which was mainly governed by the architecture of the barrier and
52 the supporting cable behaviour. Non-standard studies have also been carried out, by
53 Hambleton *et al.* [17] about the perforation of the net by the block or by Coulibaly *et al.*
54 [18] on variability on curtain effect or consecutive impacts.

55 In this article, a brief synthesis of the experimental results on which the present
56 study is based will be presented first and complement some aspects of the results pub-
57 lished in [19]. Then, the numerical model in the form of a non-linear spring-mass system
58 will be introduced. Afterwards, a statistical analysis of the results will be carried out
59 according to a parameter related to the boulder: its impact position. Next, a sensitivity
60 analysis will be conducted using parameters related to the barrier: the prestress in the
61 edge cables, as well as the brake threshold. A discussion on the order of magnitude of
62 variations induced by the different parameters will conclude the paper.

63 2. Presentation of the experimental set-up

64 The present study was partly supported by the C2ROP programme¹, a french national
65 project which seeks both to bring together stakeholders in the field of rockfall risks
66 and to create a platform of operational resources, in particular through two experimental
67 campaigns carried out in 2016 and 2019 which are abundantly detailed in Olmedo, I
68 *et al.* [19]. The experimental analyses conducted here are based on the data collected
69 from these campaigns, which consist of 1:1 scale tests of block drops on a rockfall barrier
70 described below (see set-up photo in Figure 1).

71 2.1. Rockfall barrier architecture

72 The protective barrier used in the tests and numerical simulations is made up of
73 three modules (2.75 m x 5.00 m each) anchored perpendicular to the cliff. The size of
74 the net is 2.75 m high (direction y in Figure 4) and 15.0 m long (direction x below). This
75 barrier consists of a net formed by intertwined anti-submarine rings (ASM4 made of
76 rings with a diameter of 275 mm and strand of 7.5 mm), as well as ten edging cables (12
77 mm)- four on each side parallel to the cliff (cables 1, 5, 6 and 8 at the base of the posts
78 and cables 2, 3, 4 and 7 at the top of the posts) and one on each lateral edge (cables 9 and
79 10). The entire structure, which consists of the cables and the net, is anchored to the cliff
80 by means of four steel posts, each head of which is held by struts anchored to the cliff.
81 The geometry of the barrier is shown on Figures 2.

82 The upstream and downstream sides are symmetrical for the edge cables. The
83 outer cables (4, 5, 6, 7 in Figure 2) connect the lateral anchor to the head of the central
84 post. The central cables (1, 3 in Figure 2) connect the heads of the first and third post.
85 In the neighbourhood of the second post, the net is thus linked only to cables 1 and 3,
86 so that when the net is impacted it can deform softly around the post avoiding stress
87 concentration in the net. Symmetrically cables 2 and 8 run from second post to the fourth
88 post, without touching directly the third post. Each cable is hence partially connected

¹ website : <https://www.c2rop.fr/>



Figure 1. Top view of the experimental set-up (by courtesy NGE fondations).

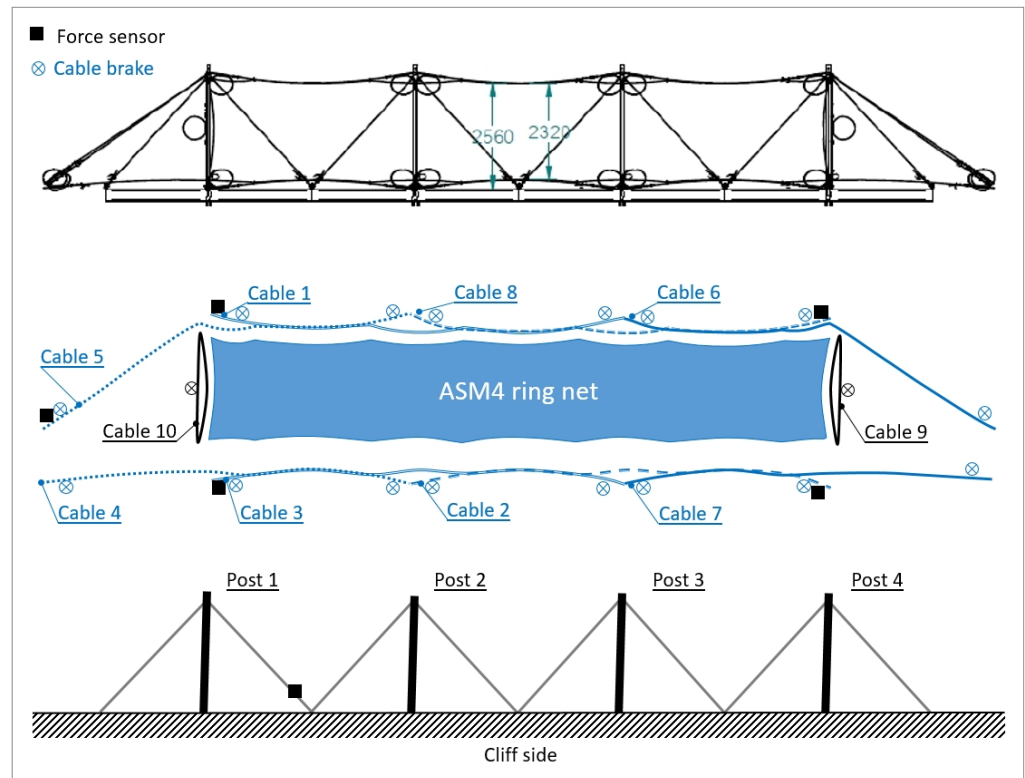


Figure 2. Architecture of the experimental flexible-barrier. Top: Technical drawing from above of the barrier by courtesy NGE fondations. Middle: Decomposition of the supporting cable and of their weaving with the ASM4 ring net. The circle at cables end represent the brakes ("snake" brake provided by NGE fondation), the black square the force sensors. Bottom: Supporting structures made of post and struts.

89 to the net, and free at the pole heads. Thus, with this assembly, the net is held by two
 90 cables in its module centres and by one cable near to the posts.

91 The barrier works as follows: a block is intercepted by the net, which deforms. The
 92 net slides along the edge cables (Boulaud *et al.* [20]) which deform. When the stress in
 93 these cables reaches a threshold force F_s , friction brakes (so-called "snake brake" by the
 94 provider NGE fondation which are shown in Figure 3) activate. In practice, the stress
 95 in the edge cables are not uniform and one cannot foresee which end will be the most
 96 solicited. Therefore, one brake is set at each end for all the cables, except the lateral
 97 cables 9 and 10 which form closed loop and require thus only one brake. The block stops
 98 finally when all the kinetic energy is dissipated.

99 2.2. Measuring devices

100 For each test of the two campaigns, a number of force sensors were attached to the
 101 cables between the brake and the anchor (each sensor corresponds to a canal indicated in
 102 Figure 2). All the central cables (labelled 4, 5, 6 and 7 in Figure 2) were hence monitored,



Figure 3. Image of the so-called snake brake provided by NGE foundations: it is made of two steel plates connected by a series of bolts through which a cable is braided at both end of the loop (by courtesy NGE foundations).

1203 plus one strut between the cliff and the head of the second posts (see Figure 2). The
 1204 acceleration of the block was recorded by an accelerometer within the block. After
 1205 impact, the residual height and final brake elongation were measured on the deformed
 1206 structure.

1207 Then, each block fall was filmed with high speed cameras: one with a top view, one
 1208 with frontal view. When the quality of the video allows it, digital image correlation (DIC)
 1209 could be used to retrieve the block position through time as well as the brake elongations
 1210 as a function of time. This manual operation introduce some intrinsic variability which
 1211 has been quantified performing the same measurement 4 times for 4 different videos.
 1212 The resulting relative deviation of the maximum block displacement is 4.5% which seems
 1213 acceptable considering the variability on the other variables.

1214 2.3. First campaign

1215 The first set of tests during this campaign consists of two impacts centred on the net,
 1216 with the same impact energy $E_{MEL} = 270$ kJ. For the second set of tests, three consecutive
 1217 impacts (with the removal of the block from the net before the next impact) occurred,
 1218 with an impact energy for each of $E_{SEL} = 90$ kJ, *i.e.* a third of E_{MEL} . The structure was
 1219 not repaired between the three impacts.

1220 The main objectives of this campaign were first to investigate the reproducibility of
 1221 experimental results and second to investigate the hypothesis that the effect of successive
 1222 impacts compared with the effect of one impact with an energy equal to the sum of
 1223 successive impacts ($3SEL \equiv MEL?$).

1224 2.4. Second campaign

1225 During the second test campaign, five different impacts took place (the first one on
 1226 an isolated module, the other four on the complete barrier):

- 1227 1. An impact centred on a structure composed of a single net instead of three, with an
 1228 impact energy $E_1 = 270$ kJ [*individual module*]
- 1229 2. A centred impact with a pre-loaded net, with an impact energy $E_2 = 270$ kJ [*pre-*
 1230 *loaded impact*]
- 1231 3. A slightly off-centre impact, with an impact energy $E_3 = 270$ kJ [*off-centred impact*]
- 1232 4. An impact on a side net, with an impact energy $E_4 = 270$ kJ [*lateral impact*]
- 1233 5. An impact centred in the central module following a first impact in the lateral
 1234 module, with an impact energy $E_5 = 90$ kJ [*consecutive impacts*]

1235 The location of these impacts are reported in Figure 4. The main objective of this
 1236 second campaign was to investigate if the impact conditions of the Standard were
 1237 unfavourable when compared to other more realistic impact conditions.

1238 3. Main results of the experimental campaigns

1239 3.1. First campaign

1240 The results of the first campaign are synthesised in the Table 1 below.

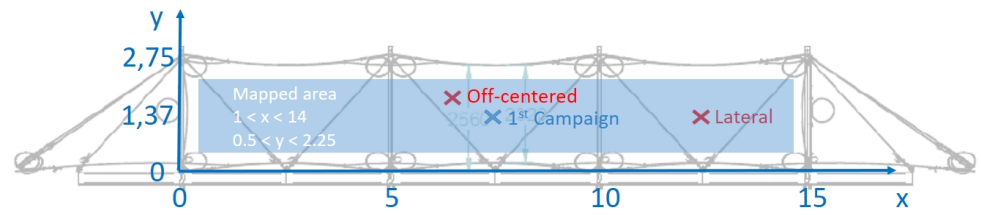


Figure 4. Location of impacts in the two experimental campaigns, as well as zone mapped by the numerical simulations (a margin of 0.5m (resp. 1m) is taken along the long edges (resp. lateral edges) to avoid direct interaction of the block with edge cables).

Table 1: Characteristics recorded for each of the two MEL and three SEL impacts - first campaign.

test	MEL 1	MEL 2	SEL 1	SEL 2	SEL 3	SEL _{tot}
theor. energy	270 kJ	270 kJ	90 kJ	90 kJ	90 kJ	3*90kJ
total brake elong. (eq. energy 25kN)	828 cm (207 kJ)	1136 cm (284 kJ)	348 cm (87 kJ)	288 cm (72 kJ)	256 cm (64 kJ)	892 cm (223 kJ)
maximal displacement	4.44 m	5.05 m				
residual height	1.4 m	1.2 m	1.5 m	1.1 m	0.9 m	

141 It is observed that the resulting data differs significantly for the two MEL tests:
 142 there is a 13 percent difference between the two maximum displacements reached by the
 143 block, as well as a 31 percent difference in the total brake elongation. Considering that
 144 the brake threshold is constant and equal to 25kN (as specified by the manufacturer),
 145 this difference in the brake elongation can be interpreted in terms of energy dissipated
 146 by the brakes. Following this reasoning for MEL2, this equivalent energy is higher than
 147 the impacting energy, which is not possible and indicates that the average threshold
 148 values must have been lower than 25kN in this case.

149 Considering then the three successive SEL tests, it appears that the energy dissipated
 150 by each test diminishes progressively with the number of tests. This can be easily
 151 understood by the fact that, test after test, the geometry of the fence changes and
 152 becomes more efficient to resist vertical forces. Indeed, while the net deforms, the edge
 153 cables incline so that consequently the vertical component of the forces in the edge cables,
 154 which are given by the brake threshold, increases. And if the vertical component of the
 155 cable forces increase, the vertical reaction on the block increases and the kinetic energy
 156 dissipated for a given elongation also. Therefore, the additional brake elongation (or
 157 energy dissipated by the brakes) diminishes with each impact increment. Notice that
 158 the total energy dissipated by the three SEL test is comparable to MEL1 and MEL2. This
 159 confirms the idea that what drives the barrier response is the impacting energy.

160 3.2. Second campaign

161 Table 2 then shows the results of the second campaign. It is observed that the impact
 162 characteristics vary greatly from one test to another: a twofold variation in the total
 163 brake elongation and a maximum block displacement variation of nearly 40%.

164 This variability may depend on many factors. Non-exhaustively, one can mention
 165 the location of the impact of the block, the pre-stress in the edge cables or the uncertainty
 166 on the effective brake activation threshold. Yet, force sensors had been installed on the
 167 main cables during the tests and pre-stress measurement had been conducted before
 168 the impact. Before conducting the sensitivity analysis, experimental data on these two
 169 characteristics are presented.

Table 2: Characteristics recorded for each of the five test impacts for the second campaign.

test	indiv. mod- ule	pre-loaded	off-centred	lateral	consecutive
location	$x = 7.5\text{m}$ $y = 1.37\text{m}$	$x = 7.5\text{m}$ $y = 1.37\text{m}$	$x = 6.1\text{m}$ $y = 1.8\text{m}$	$x = 13.4\text{m}$ $y = 1.37\text{m}$	$x = 7.5\text{m}$ $y = 1.37\text{m}$
total brake elong. (eq. energy 25 kN)	581 cm (145 kJ)	579 cm (145 kJ)	1210 cm (303 kJ)	474 cm (119 kJ)	670 cm (168 kJ)
max. displ	4.74 m	4.19 m	5.08 m	4.18 m	3.48 m
res. height	1.36 m	no data	1.01 m	0.94 m	no data

170 3.3. Analysis of the prestress distribution in the cables

171 The ring net and their supporting cables have no bending rigidity. Therefore, to
172 resist gravity load, they need to be prestressed during the set-up of the fence in order
173 to build a quasi horizontal barrier perpendicular to the cliff. The curvature of the edge
174 cables (that can be seen in Figure 2 for example) is directly associated with the ratio
175 between the distributed gravity load induced by the ring net and the prestress in the
176 cable. The level of this prestress is relatively low for two reasons: first to be easily set by
177 workers and second to let the highest possible margin with brake thresholds.

178 During these two test campaigns, 47 prestress values were thus measured thanks
179 to an arbalest with an accuracy of $\pm 2\%$ [21]. To establish a distribution law for the
180 prestress, it is necessary to ensure independence between values. However, the barrier
181 consists in an hyperstatic structure, with a relatively high level of hyperstaticity: when
182 one pulls on one cable, the tensions in the others vary. It is therefore preferable to take
183 the pre-stress values for each cable individually from each test (these values are indeed
184 independent), to identify for each cable the distribution law characteristics (through the
185 various experiments). Then from the identified prestress distributions, one can determine
186 an average distribution law which is shown in Figure 5 with the characteristics displayed
187 in Table 3.

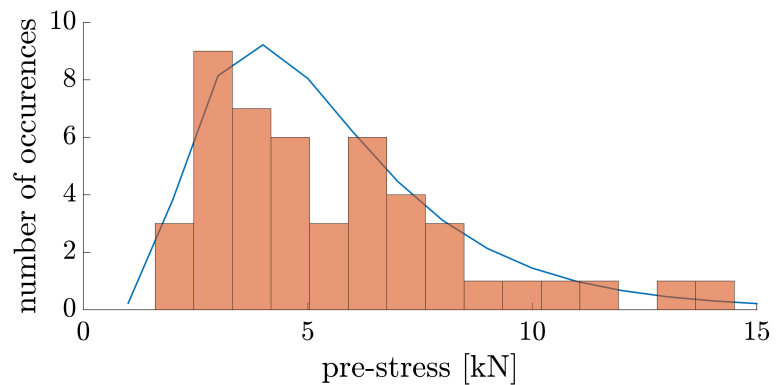


Figure 5. Distribution of experimentally measured prestressing forces in all the cables.

A log-normal distribution of parameters $\mu = 1.60$ and $\sigma^2 = 0.25$ is defined ($x > 0$):

$$f_X(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \cdot \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right) \quad (1)$$

188 The average value of this distribution is 6.2kN , slightly higher than the value obtained
189 by direct averaging of the recorded data which was of 5.6kN . The standard deviation is
190 about 3.0kN .

191 3.4. Analysis of brake activation threshold distribution

192 In the same way, during these two campaigns, 27 usable brake activation threshold
193 values were identified. The force values are obtained directly from the force sensor data

Table 3: Pre-loading distributions

Standard deviation	Average	Expected value
3.0 kN	6.2 kN	5.6 kN

194 whose location is indicated on figure 2. To obtain the complete force/displacement
 195 curve, digital image correlation is used to measure the distance between brake anchor
 196 points on images from the high speed camera. The time correlation is made manually
 197 by combining the force/time curve and elongation/time curve. Usable data of brake
 198 threshold are then found when data are available from three sources: data from force
 199 sensor, visibility of brake on the high speed camera images, data of prestressing force.
 200 Four typical force-displacement diagrams are displayed in Figure 6. These values are all
 201 independent.

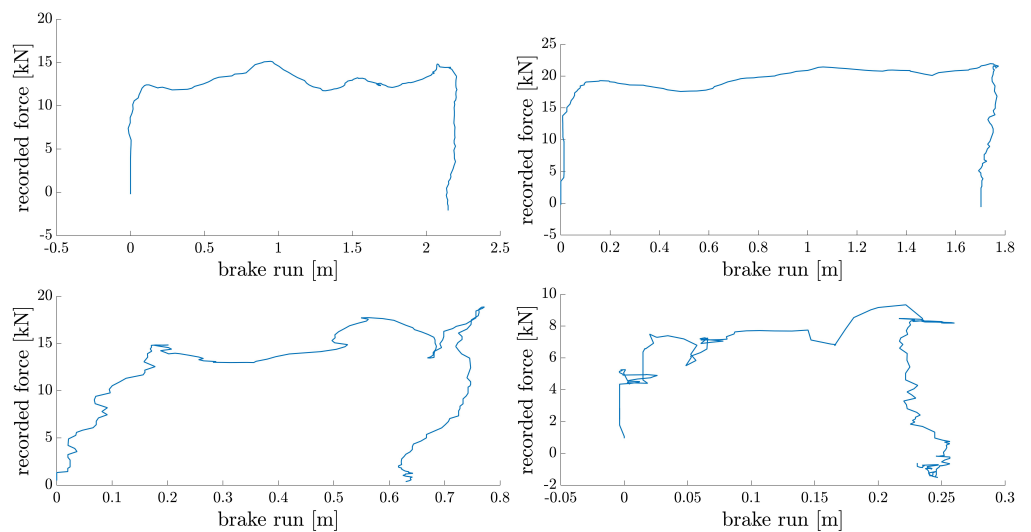


Figure 6. Four Force-Displacement diagrams used to determine brake activation thresholds. *For left to right, and top to bottom* : Off-centred impact, cable 3; Off-centred impact, cable 1; Lateral impact, cable 2; Consecutive impact, cable 8 - Pre-stress is taken into account.

202 The brake threshold distribution in Figure 7 with the characteristics displayed
 203 in Table 4 is determined from these values. A log-normal distribution of parameters
 204 $\mu = 3.22$ and $\sigma^2 = 0.15$ is defined.

Table 4: Brake activation threshold distributions.

Standard deviation	Average	Expected value
10.8 kN	27.0 kN	27.0 kN

205 The average value is close to the theoretical threshold defined by the manufacturer
 206 (25kN). One observes however that the dispersion is very large (around 40%) which
 207 means that the hypothesis, currently admitted in numerical models, that all threshold
 208 values are equal, suffers some serious limitation as already suspected from the equivalent
 209 energy deduced in Table 1 and 2. How this dispersion precisely influence the response
 210 of the barrier is the purpose of the propose paper. However, before conducting the
 211 numerical sensitivity analysis, it is necessary to present the numerical model used in the
 212 study, which is done in the coming section.

213 4. Non-linear spring mass system

214 The starting point of the numerical model is a code that was already used for
 215 rockfall barrier in two previous publications by the authors [16,20] and which is therefore

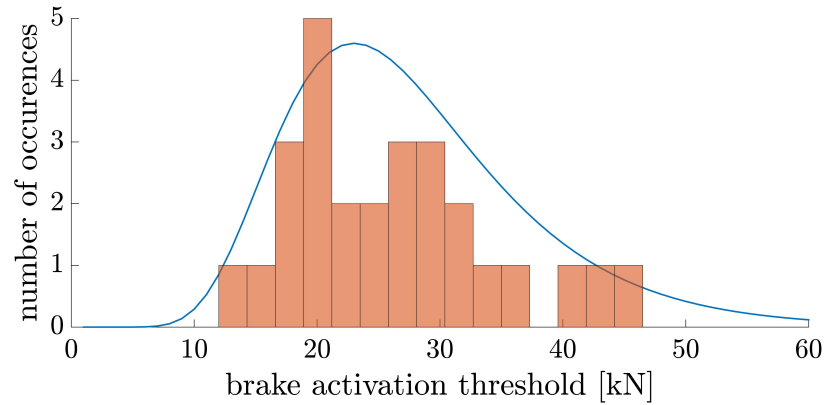


Figure 7. Distribution of experimentally measured brake activation thresholds.

216 not recalled here. This tool is based on quasi-static calculations conducted by the
 217 dynamic relaxation method (Day [22]), an algorithm which is suited for the study of
 218 static equilibrium of structures with large displacements (Douthe and Baverel [23]).

219 4.1. A dynamic model based on finite differences

220 The mass of the net is distributed and about 7 times smaller than the mass of the
 221 block which is concentrated in one point. In a first approximation, one could thus
 222 considered that the kinetic energy stored by the net is negligible compared to the kinetic
 223 energy of the block (which is completely true in the beginning where only the block
 224 moves). By there, it was decided to concentrate dynamical aspects of the barrier response
 225 in the dynamic of the block and, consequently, to consider the dynamics of the net as a
 226 second order perturbation. The system becomes hence equivalent to a mass (the block)
 227 interacting with a complex spring (the net with its supporting structures), the reaction
 228 force of the spring being calculated from a quasi-static force applied by the net on the
 229 actual position of the block. A similar approach had been implemented in Grassl [24].

230 The algorithm goes hence as follow (see Figure 8):

- 231 (i) Start from a position $u_i(0)$, speed $\dot{u}_i(0)$ and initial acceleration $\ddot{u}_i(0)$ of the
 232 block. In all the simulation, the initial velocity and initial acceleration are always
 233 taken purely vertical. Horizontal movement is allowed but is only caused by
 234 the reaction of the structure.
- 235 (ii) A small displacement is imposed $\delta_i(0) = \dot{u}_i(0)dt$, and the equilibrium solution
 236 is calculated according to the quasi-static analysis of the barrier.
- (iii) From R_i the reactions of the net on the block, the new position is calculated:

$$\ddot{u}_i(t) = \frac{R_i}{m}$$

$$\dot{u}_i\left(t + \frac{dt}{2}\right) = \dot{u}_i\left(t - \frac{dt}{2}\right) + \ddot{u}_i(t) \times dt \quad (2)$$

$$u_i(t + dt) = u_i(t) + \dot{u}_i(t) \times dt + \ddot{u}_i(t) \times \frac{dt^2}{2}$$

237 with $i = x, y$ or z the three dimensions of the block

- 238 (iv) The "brakes+cables" system following an elasto-plastic behaviour, their proper-
 239 ties are updated at each iteration.
- 240 (v) The algorithm stops when all edge cables start unloading.

241 This last issue is questionable as, when the cables start unloading, the structure is
 242 not at rest: elastic energy is still stored in the structure. It was however observed on
 243 the experimental data that, after this phase, there is no more plastic dissipation by the
 244 brakes and that the remaining elastic energy is slowly damped by the net and supporting
 245 structure by contact. In all the videos, the block is trapped by the deformed net and

246 keeps contact with it. This is the reason why this choice seemed legitimate in order to
 247 shorten computing time without losing information on the energy dissipated by the
 248 brakes.

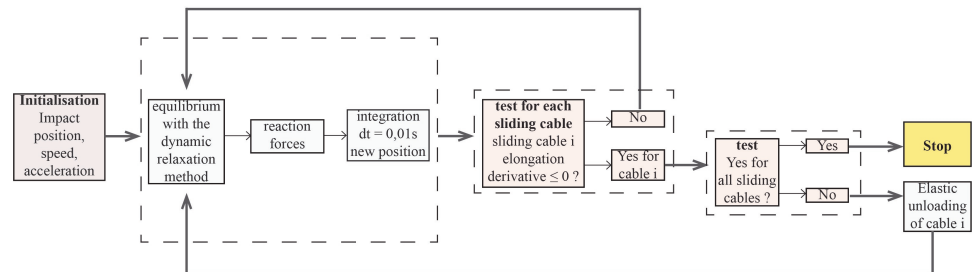


Figure 8. Equivalent spring-mass dynamic algorithm of the barrier.

249 4.2. Limitation of the structural model

250 The support cables are modelled using the sliding cable element developed by
 251 Boulaud *et al.* [20] which has no friction between the cables and the net. In this model,
 252 the only sources of dissipation are thus the brakes. This assumption is relatively strong
 253 because, in practice, part of the impact energy is dissipated by friction as documented
 254 in Coulibaly *et al.* [25] on a simple cable example or by the net itself [9,10]. However,
 255 the friction coefficient is a parameter which is independent from other parameters
 256 concerned by the present sensitivity analysis (location of impact, prestress and brake
 257 threshold). There might be couplings or interactions between parameters, but, in a
 258 first approximation, it was considered that interactions can be neglected and that the
 259 influence of parameters can be investigated independently.

260 Concerning the ASM4 ring net model, the simplest model was chosen with a spring
 261 representation of each ring interaction similarly to what is done in Nicot *et al.* [14] or
 262 Dugelas *et al.* [26]. The influence of this modelling choice was investigated in Boulaud
 263 and Douthe [16] who demonstrated that the ring model had negligible influence on the
 264 global response of the barrier which is driven by the deformation of supporting cables.

265 Concerning contact between the block and the net, non-penetration interactions
 266 are defined on the basis of proximity conditions between net nodes and the bottom
 267 of the block. Friction between the block and the net is neglected. High speed camera
 268 images of the experiments show that this hypothesis is reasonable for impacts in the
 269 central module where the block exhibits almost no rotation movement. However, during
 270 the impact on the lateral module, one observes significant rotation of the block which
 271 necessarily implies that tangential forces are applied on its surface. The presented
 272 sensitivity analysis is thus less relevant for impact in outer part of the barrier.

273 4.3. Convergence study

274 The determination of the time step dt was done through a convergence study for
 275 an off-centred impact at $(x, y) = (10.5, 1.37)$. Considering a time step of 0.01 seconds
 276 and comparing it to a time step 10 times smaller, the difference in the calculation of the
 277 new positions is, at most, less than 2% of the value (for the position according to z). The
 278 value $dt = 0.01$ seconds is therefore considered appropriate, as shown in Figure 9.

279 4.4. Validation by comparison with a few characteristic experimental tests

280 A few tests are performed to compare the accuracy of the model over time with
 281 the experimental data. The block trajectory for the MEL test is shown in Figure 10. The
 282 numerical solution fits the MEL 2 trajectory. Qualitatively, the dropping profile is the
 283 same. Quantitatively, the comparison is difficult because of the variability between the

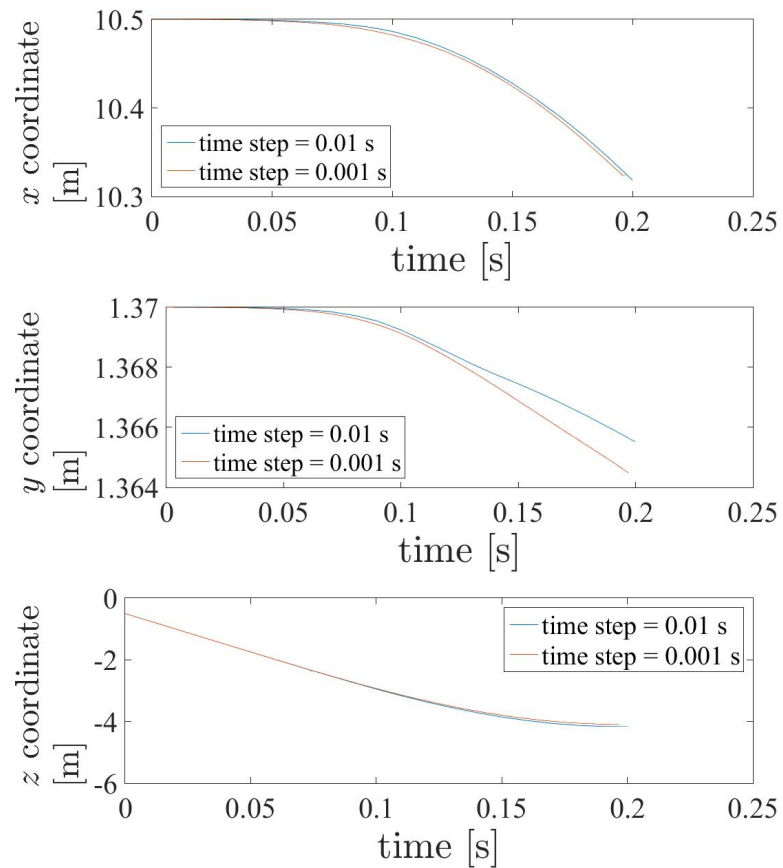


Figure 9. Position in the x , y and z directions as a function of time for $dt = 0.01$ s and $dt = 0.001$ s.

284 MEL 1 and MEL 2 tests. However, it can be concluded that the model reproduces reality
 285 quite well.

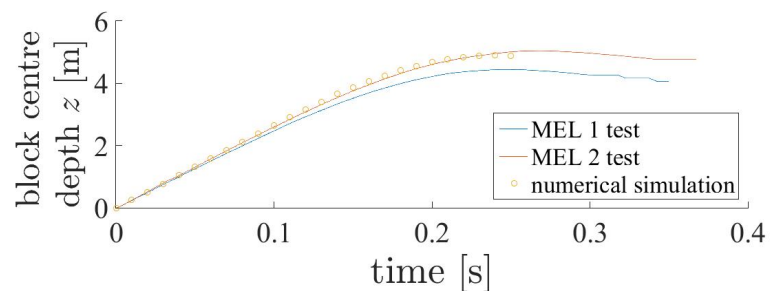


Figure 10. Displacement of the block centre as a function of time: MEL and numerical test comparisons.

286 In a quantitative approach, the total brake elongation for experimental and numeri-
 287 cal MEL tests is shown in Table 5. The numerical value is between the two experimen-
 288 tal values. The order of magnitude is thus verified.

Table 5: Total sum of brakes elongation comparison between MEL 1, MEL 2 and numeri-
 cal simulation.

test	MEL 1	MEL 2	num. simulation
total elongation	828 cm	1136 cm	1004 cm

289 Figure 11 shows the numerically obtained elongations of the brakes over time
 290 compared to the actual elongations observed on the brakes during impact (measures

291 are made using digital image correlation and visible elongation of brakes located at
 292 cables end). Qualitatively, one can see that the triggering is happening in the range $t =$
 293 $[0.05s; 0.1s]$ in both cases. One also observes that the order of magnitude of elongations
 294 seems consistent between model and experiment, the central cables being the most
 295 severely solicited. It is thus considered that the proposed simplified model is suitable to
 296 conduct the sensitivity analysis.

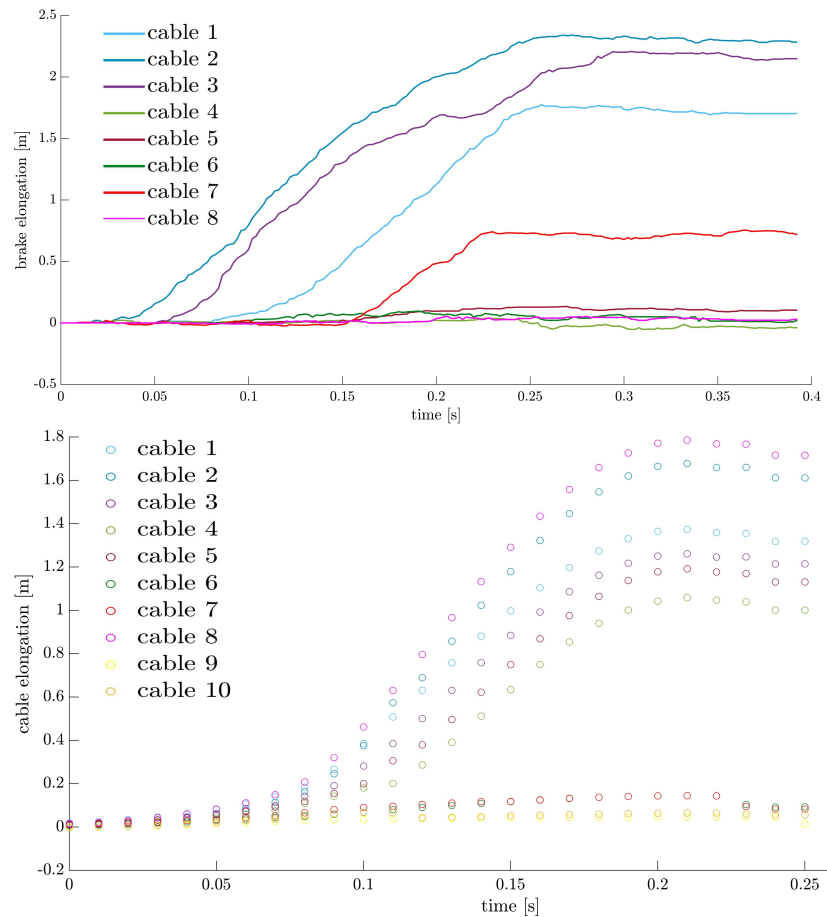


Figure 11. *Above:* Experimental brake elongation (off-centre impact) as a function of time; *Below:* Numerical brake elongation (off-centre impact) as a function of time.

297 5. Sensitivity analysis: block-related parameters

298 5.1. Impact position variability

299 The purpose of this first sensitivity analysis is to evaluate the variability of the
 300 dissipated energy, the maximum displacement reached by the block and the residual
 301 height in relation to the displacement of the impact position on the surface of the net.
 302 The aim is to map the parameters of interest, in other words, to represent the values
 303 as a function of their position on the surface of the net. The mapped area is shown in
 304 Figure 4. It runs through the three units and cover the inner part of the net. The outer
 305 part of the net consists in a 0.5m (resp. 1m) strip along the cable edges running in the
 306 x -direction (resp. y -direction) where there would be direct impact of the block on the
 307 supporting cables which are phenomena not considered in the present study.

308 Then, as the number of measurements is limited, value interpolation is necessary: it
 309 must be ensured that this interpolation is possible. The interpolation (performed with
 310 the software MATLAB©) is verified by interpolating according to the natural neighbour
 311 interpolation method between some computed values and comparing the result of
 312 the interpolation with actual computed values. The maximum error is below 3 %.

313 This assumes that the model is sufficiently stable to be able to interpolate between the
 314 calculated values.

Table 6: Difference (in percentage) between the calculated values and the values obtained by interpolation.

X [m]	Y [m]	$\frac{E_d}{E_{m,i}}$ calculated [%]	$\frac{E_d}{E_{m,i}}$ red : interpolated [%]	Difference [%]
7.5	0.5	66.94	66.94	0.0
7.5	1.37	70.18	68.69	2.13
7.5	2.24	66.58	66.58	0.0
9	0.935	75.49	75.49	0.0
9	1.805	75.54	75.54	0.0
10.5	0.5	75.69	77.84	-2.84
10.5	1.37	84.68	84.68	0.0
10.5	2.24	76.31	77.76	-1.91
12	0.935	80.03	80.03	0.0
12	1.805	79.94	79.94	0.0

315 5.2. Maximum displacement reached by the block centre during the impact and equivalent static
 316 force

317 The goal is to evaluate an average braking force, as if the braking were constant
 318 over the duration of the total energy dissipation (even if this braking is by no means
 319 constant). The amplitude of this braking is calculated as an equivalent static force $F_{s,eq}$
 320 based on the initial mechanical energy of the block $E_{M,ini}$ over the braking distance $l(t_e)$.

At the time t_e when all the energy is absorbed (either plastically by the brakes or elastically by the cables and the net), the block has moved a distance:

$$l(t_e) = \sqrt{(x(t_e) - x_0)^2 + (y(t_e) - y_0)^2 + (z(t_e) - z_0)^2} \quad (3)$$

321 The equivalent static force is then defined as follows:

$$F_{s,eq} = \frac{E_{M,ini}}{l(t_e)} \quad (4)$$

322 Where $E_{M,ini}$ is the mechanical energy of the block at $t = 0$ and with the static force
 323 oriented according to the block's displacement.

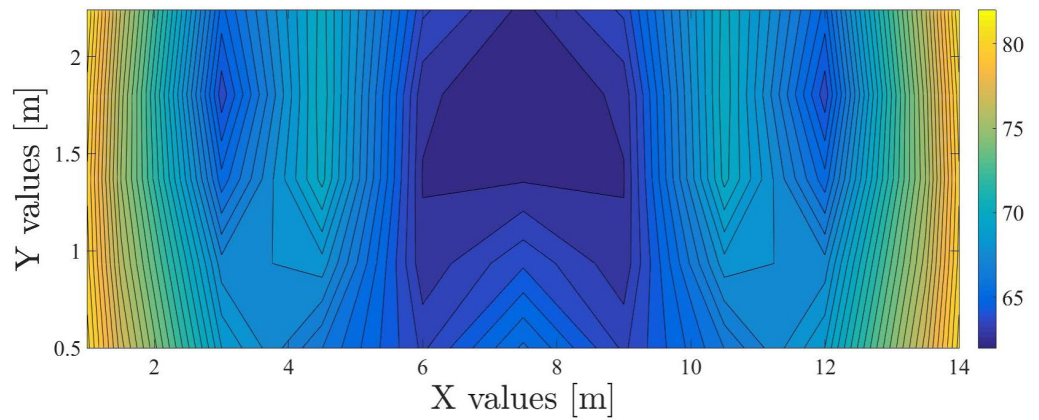


Figure 12. Mapping of the static force as a function of the impact position on the net [kN] for an impacting energy $E_{M,ini}$ of 270kJ.

324 The equivalent static force is represented according to the point of impact in Figure
 325 12. It is at its lowest in the centre of the net. The static force profile follows the stiffness
 326 of the net: it is smaller in the central (more flexible) areas of each net.

327 Figure 13 shows the map illustrating the maximum displacement reached by the
 328 block during the impact as a function of the position of the centre of the block at the time
 329 of impact.

330 The graph's appearance is very close to that of the equivalent static force. The
 331 correspondence with Figure 12 makes it possible to highlight that variations in me-
 332 chanical energy to be dissipated according to impact zones are not significant, since the
 333 displacement z is dominant to determine the static force of each point of the net. The
 334 lower the z_{max} , the smaller the rigidity of the net. It is clear that the net is more flexible
 335 near the edge than near the cliff, as well as in the central areas of the net. The impact
 336 centred in x is the most unfavourable case, but there is a variation in y : it is when it is
 337 near the edge, opposite the cliff, that the block drops the lowest.

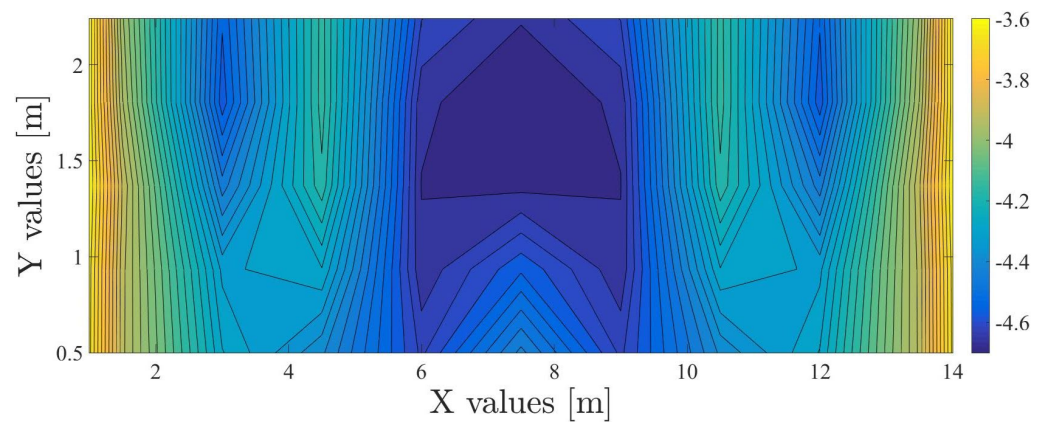


Figure 13. Mapping of the maximal displacement reached by the block centre as a function of the impact position on the net [m] for an impacting energy $E_{M,ini}$ of 270kJ.

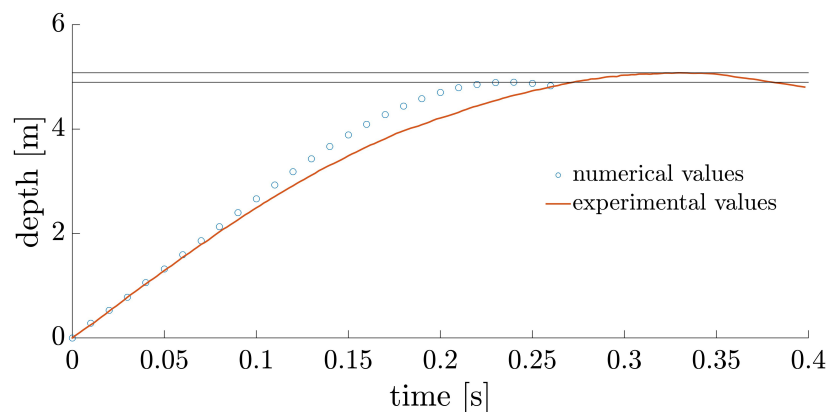


Figure 14. Off-centred impact: block's displacement according to time for an impacting energy of 270kJ.

338 Figure 14 shows the block's displacement according to time. The error on the
 339 maximal displacement z_{max} is 3.6 %. However, the impact duration is significantly lower
 340 for the numerical study than for the experimental test. This observation might be related
 341 to the lack of friction in the numerical model, as friction and the associated damping
 342 slightly delay the response of the barrier. This difference might also be related to small
 343 rotation and the associated lateral movement which are less damped than the vertical
 344 movement.

345 5.3. Total energy dissipated through the brakes

346 Figure 15 shows the ratio of the plastic energy dissipated by all the brakes at cables
 347 ends to the initial mechanical energy of the block at specific points in the net, supposing
 348 constant thresholds for all brakes. The x coordinate of the impact is therefore shown on
 349 the abscissa and the y coordinate on the ordinate. Each point is the position of the block
 350 centre at the time of impact. As a reminder, the ordinates near 0.5 correspond to the cliff
 351 side and the ordinates near 2.2 to the edge side.

352 The dissipated energies observed do not take into account the plastic deformation
 353 energy of the net (or rings).

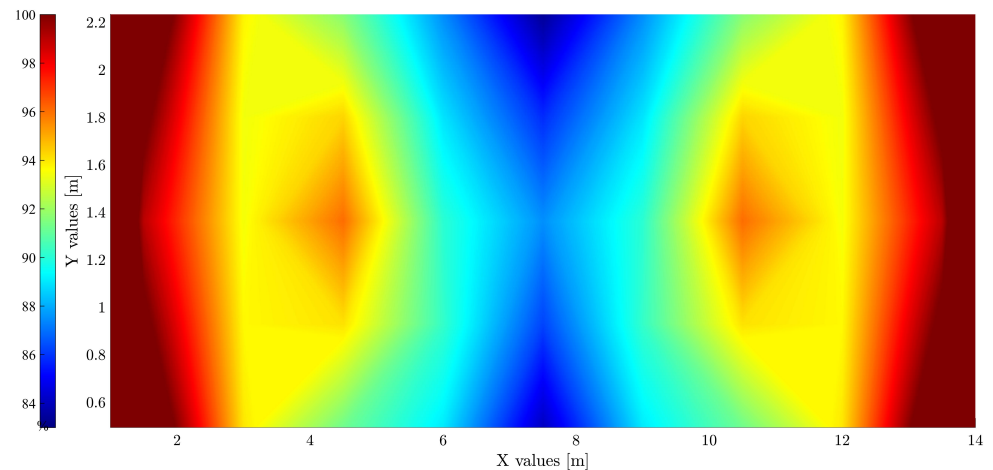


Figure 15. Percentage of plastically dissipated energy on the initial mechanical energy, supposing constant threshold of brakes for an impacting energy of 270kJ.

354 There is strong symmetry at y from the outset, despite asymmetry in reality due to
 355 cliff-side attachment points.

356 Considering that the higher the percentage of energy dissipated by the brakes, the
 357 lower the elastic energy stored by the barrier, one deduce that, in the areas where the
 358 barrier configuration or architecture has large deformation capabilities (i.e. allows for
 359 large curtain effect), the brakes suffer less. Hence, it appears on Figure 15 that in the
 360 x direction, the less demanding configuration for the brakes is the centred impact at
 361 $x = 7.5\text{m}$. In the y direction, this statement needs to be qualified: as they approach the
 362 edges, cables dissipate less energy. The impact centred in x and y is reduced from 87.6%
 363 to 83.4% for $(x, y) = (7.5, 2.24)$ and 84.1% for $(x, y) = (7.5, 0.5)$.

364 The impact which appears to be the most demanding for the brakes (*i.e.* where
 365 most energy is dissipated by them) is an impact very close to the left or right extremities.
 366 Indeed, compared to the central module, the lateral modules or extremities can mobilised
 367 the elastic deformation capabilities of only neighbour module (instead of two for the
 368 central module). Their capability to spread the load through the net is thus lower and
 369 their rigidity higher. This boundary case aside, another demanding case is the one where
 370 the impact is made near the poles (around $x = 5\text{ m}$ or $x = 10\text{ m}$) which are indeed other
 371 rigid area of the barrier. Beside, one remarks that, approaching the edges (cliff or edge
 372 side) causes less dissipation in the edge cables and brakes wherever one is on the net. In
 373 general, the maximum variation in energy dissipated is just over 15% and the most rigid
 374 areas dissipate the most.

375 5.4. Distribution of the energy dissipated between the various brakes

376 5.4.1. Analysis of numerical results

377 To go more into details, the percentage of energy dissipated plastically by each
 378 cable is represented in Figure 16. For each impact location, one can hence analyse the
 379 distribution of the energy between the various brakes and have a picture of the load
 380 paths from the impact point to the anchorages throughout the net. One remarks that:

- 381 • there are characteristic stripes on the maps, which denotes an invariance along y
 382 and the fact the the problem varies essentially according to x ;
 383 • the energy dissipation in the brakes is almost symmetrical according to y ;
 384 • on average, impact closer to the cliff result in higher dissipation (nearly 5% more)
 385 than impact on the opposite side which can be explained by the fact that the cliff
 386 side is more rigid because it is closer to the supports;
 387 • when approaching the edge at $x = 1\text{m}$ or $x = 14\text{m}$, the brakes of the edge cables
 388 dissipate more than half of the block's initial mechanical energy;
 389 • all brakes activate and dissipate significant part of the impact energy for some
 390 impact location, meaning that, in the considered structure, all brakes are necessary
 391 and will be each the most solicited brake for a given impact location.

392 5.4.2. Comparison with experimental results

393 The elongations of brakes by cable for the off-center test, in the experimental
 394 case and in the numerical case, are compiled in Table 7. These elongations are first
 395 calculated by using, in the numerical simulation, the theoretical 25 kN brake threshold.
 396 Qualitatively, one observed that the numerical model predicts well the brakes that are
 397 solicited during the impact. To to more into detail, one observe that there is a significant
 398 difference for cables 2 and 3, while this difference is reduced for all other cables. Looking
 399 at the activation thresholds measured during the experiment, for cable 2, there is a
 400 brake threshold at $F_{s,2} = 14.5$ kN and for cable 3, a brake threshold at $F_{s,3} = 12.8$ kN.
 401 By adjusting the threshold values (see last line of the table), the difference between
 402 the experimental and numerical values for those two cables falls down to comparable
 403 level. Unfortunately, the number of force sensors in the structure did not allow for the
 404 measuring of all the thresholds and it was not possible to proceed in the same way with
 405 all the cables. Nevertheless, it appears clearly that the knowledge of the exact threshold
 406 is key to the prediction of the brake elongation.

Table 7: Brake elongations by cable number for the off-centred test.

cable no.	1 edge	2 cliff	3 cliff	4 cliff	5 edge	6 edge	7 cliff	8 edge	9 lat.	10 lat.
exp. [cm]	174	340	301	75	107	0	15	198	0	0
num. [cm]	158	204	159	118	133	15	14	197	5	9
num. mod. [cm]	158	320	290	118	133	15	14	197	5	9

407 During the experiment with a lateral impact, no cliff-side cables ran. For an un-
 408 known reason, the brakes seemed to be completely blocked. There are therefore signifi-
 409 cant differences between numerical simulation and real testing. These differences are less
 410 pronounced when summing the elongations of the brakes of symmetric cables according
 411 to y , as shown in Table 8. A proportion of the energy that could not be dissipated by the
 412 blocked brakes is found in their symmetric brakes. Globally the differences observed
 413 for the brake elongations for the lateral test are comparable to those observed for the
 414 off-centred test, except for cable 10. These differences might thus be attributed to the
 415 effective threshold values of brakes.

Table 8: Brake elongations by cable number grouping cable by pairs in the y direction for the lateral impact.

cable couple	1+3	2+8	4+5	6+7	9	10
exp. [cm]	0	173	0	230	71	0
num. [cm]	29	236	12	344	269	2

To explain the very large difference in cable 9, the detailed arrangement of the net, cables and brakes is studied. It shows that these cables are looped (see Figure 2). To build these loops, the lateral cables pass through shackles with a relatively sharp angle

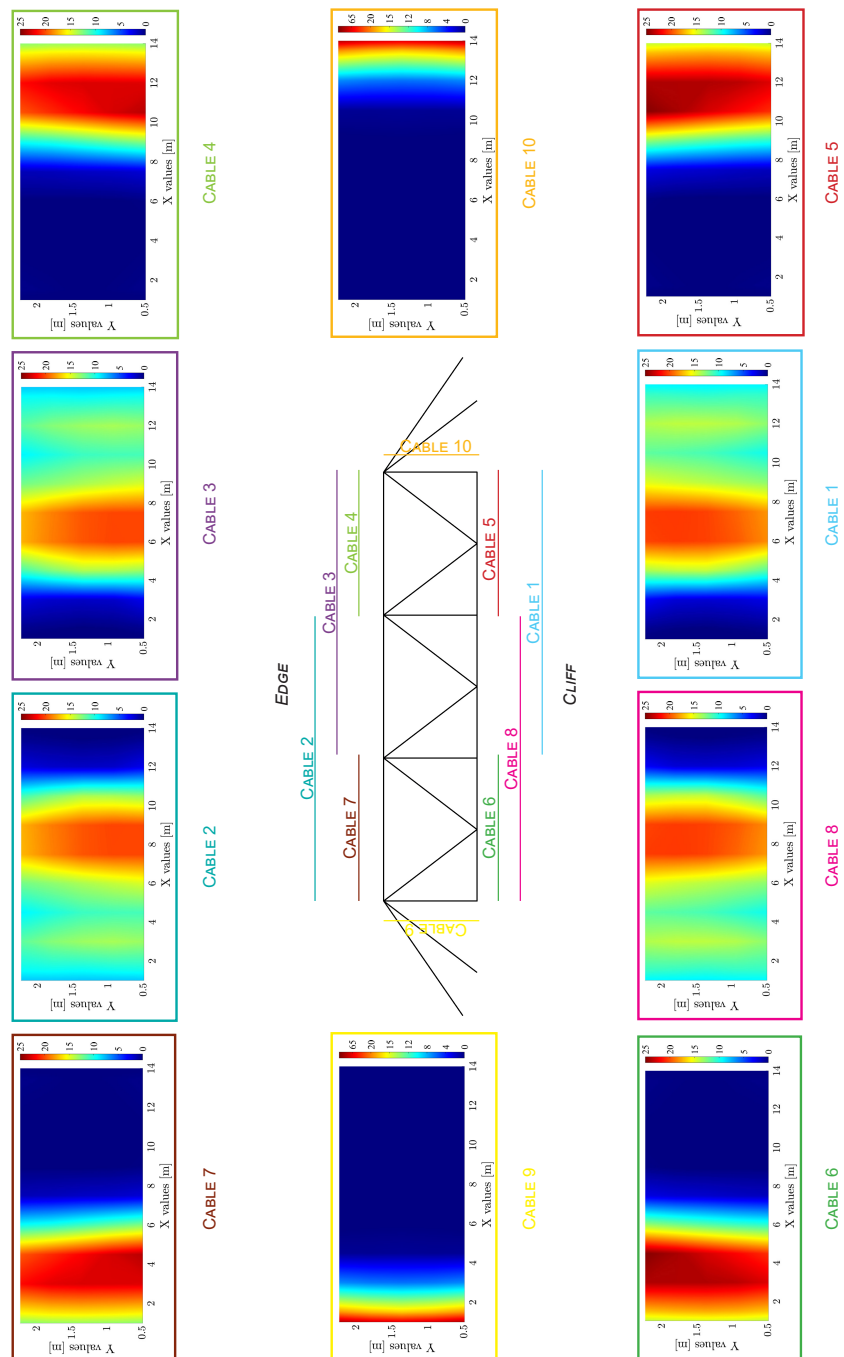


Figure 16. Percentage of the energy dissipated plastically in each cable on the initial mechanical energy, supposing constant threshold of brakes.

which hinders their sliding by friction. A more realistic numerical model is thus built by introducing friction at the head and bases of the post for these lateral cables. The force in the cable will then depend on the angle α of this cable over time and of the activation threshold F_s of the brake (see Figure 17).

$$F_s \cdot \delta + F_s \cdot (e^{\mu\alpha} - 1) \cdot \delta = F_s \cdot e^{\mu\alpha} \cdot \delta \quad (5)$$

416 with $\mu = 0.3$ the friction coefficient and δ the brake elongation.

417 Adding this adjustment to the cable behaviour of the side cables reduces the total
418 brake elongation of cable 9 by 60 %. The difference between numerical and experimental
419 elongation becomes hence comparable to other cables and can be attributed to the
420 discrepancy of threshold values (whose influence is discussed in the next section).

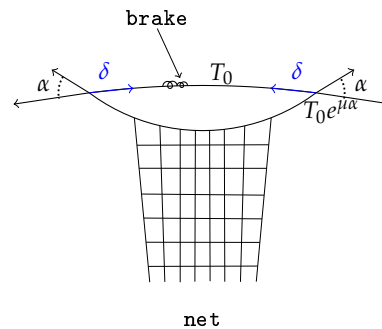


Figure 17. Detailed scheme of lateral cables (9 or 10) showing characteristic angles at shackles.

421 An attempt was then made to reproduce properly the lateral test as it is experi-
422 mentally observed: in other words, by adjusting the value of the thresholds to those
423 measured, and by putting an infinite threshold on the cables on the cliff side. As friction
424 is not taken into account in the simulation, the block can roll freely on the net and
425 eventually leave the net web (see Figure 18). By blocking on one side, a very strong
426 asymmetry is introduced which highlights the need to model the friction at the contact
427 between the block and the net when the horizontal acceleration becomes significant.
428 This should be considered in further work.

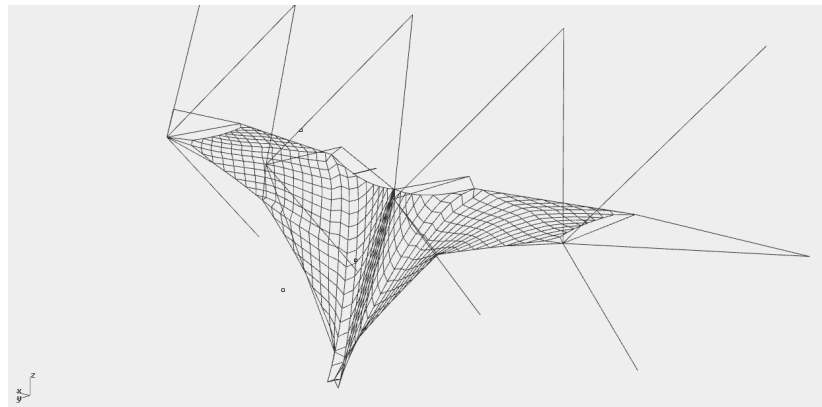


Figure 18. Net with cliff-side cables blocked and block fallen off the net.

429 5.5. Residual height h_r

430 The residual height as a function of the impact position of the block is plotted
431 on Figure 19. It represents the smallest height of the barrier taken perpendicularly to
432 the cliff when all the energy has been dissipated. To obtain these results, the previous
433 calculations are conducted one step further and the equilibrium configurations under
434 gravity load with the computed brake elongations are calculated.

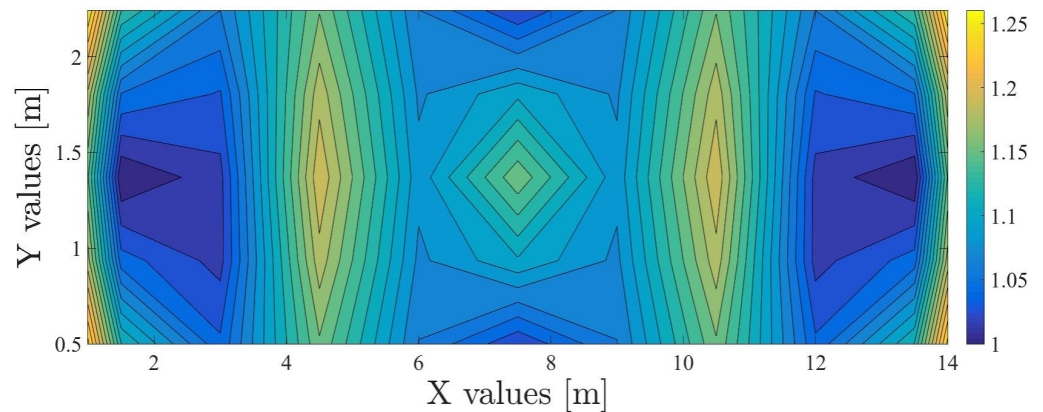


Figure 19. Mapping of the residual height as a function of the impact position on the net [m].

435 As expected, the residual height is greater in the most rigid areas (*i.e.* where the net
 436 deforms less). However, there is a local maximum for the centred impact. This can be
 437 explained by the symmetry of the system: the cables on each side are less stressed at one
 438 time, and therefore deform less plastically, while for the off-centre impact in y , the cables
 439 on one side are very stressed and deform strongly and then, when they unload, do not
 440 regain their initial length since in the plastic domain. This effect does not occur in the
 441 centre of the side nets: at this location, the length of the cable's attachment to the net
 442 is much shorter (cables 4, 5, 6, 7) than the for dissipating cables of the centred impact
 443 (cables 1, 2, 3 and 8). They can therefore stretch less in the plane (x, z) and deform more
 444 in the plane (y, z) . This results in a lower residual height (*i.e.* a higher proximity of the
 445 opposite edge cables).

Table 9: Residual height for the off-centred impact and the lateral impact.

impact	exp. height	num. height	diff.
off-centred impact	1.01 m	1.03 m	1.9 %
lateral impact	0.94 m	0.84 m	11.2 %
lateral (+ friction)	0.94 m	0.92 m	2.1 %

446 It is important to note that, in the case of impacts near the lateral edges, the notion
 447 of residual height is no longer sufficient (as shown on Figure 20). Indeed, because of the
 448 curtain effect on the side cable and of its deformation, a hole forms on the side of the
 449 barrier. It might thus be interesting for those impact to define a residual width of the
 450 barrier.



Figure 20. Side hole in the barrier after the lateral impact during the second campaign.

451 6. Sensitivity analysis: net-related parameters

452 After studying the influence of the impact position of the block, the effects related
453 to the dispersion of some of the supporting cable parameters are examined.

454 6.1. Prestress variability

455 In order to explore the influence of prestress level on the main impact characteristics
456 (energy dissipation, maximum displacement and residual height), a prestress distribu-
457 tion was randomly applied on the cables. This prestress distribution follows the law
458 determined experimentally (see section 3.3). Practically, it takes the form of a length
459 default: $\Delta l = \frac{F_{\text{pre-load}} \cdot l_0}{E_s S}$. The barrier being hyperstatic, the effective distribution of the
460 prestress at iteration $i = 1$ resulting from these length defaults is not exactly the desired
461 one. However, one can verify on a single example that the prestress only rearranged
462 marginally in the structure (see Table 10) and that the order of magnitude and statistical
463 distribution are similar. Especially, the larger the prestress level, the lower the difference
464 between the target value and the equilibrium state.

Table 10: Prestress in supporting cables: target level ($i = 0$) and practical equilibrium state ($i = 1$).

cable	input at $i = 0$ [kN]	equilibrium at $i = 1$ [kN]	difference [kN]
1	8.6	9.5	0.9
2	4.7	6.3	1.6
3	0.7	2.9	2.2
4	7.0	7.3	0.3
5	5.3	5.9	0.7
6	10.4	10.9	0.5
7	1.8	3.1	1.3
8	6.0	6.9	0.8
9	4.4	5.2	0.8
10	8.6	8.9	0.4
average	5.7	6.7	1.0

465 About ten numerical simulations are performed, the results of which are presented
466 in Figures 21 and 22. Figure 21 illustrates the variation in the amount of energy dissipated
467 by a cable for different prestress values applied to this cable in the case of a centred test.
468 It appears that the increase in the prestress of a cable has almost no influence on the
469 amount of plastic energy dissipated by this cable (dots are almost vertically aligned).
470 Indeed, during the impact, the cables rearrange and the final equilibrium is the same.
471 However, for cables with very low prestressing (typically below 3kN), the amount of
472 energy dissipated for these cable decreases significantly. Considering that the cable
473 stiffness under lateral load at the time of impact is directly linked with their geometric
474 stiffness: the higher the initial prestress, the higher the cable stiffness. Considering then
475 that the structure is hyperstatic, it is well-known that, in hyperstatic structures, stiffness
476 attracts forces. It seems thus natural that when the structure is unequally prestressed,
477 forces be attracted by the most prestressed cables, resulting in some small variations of
478 load paths through the net which has time to deform significantly before tensions in the
479 less prestressed cables reach the threshold value and start dissipating energy.

480 Notice that

481 This result is also found at global scale as shown in Figure 22: the higher the average
482 prestress level, the larger the amount of energy dissipated by the brakes (about 20%
483 increase approximately). A high global prestress level provides a higher initial stiffness
484 of the barrier which will start dissipating earlier. The global response of the barrier is
485 not modified, only the share between plastic energy dissipated by the brakes and elastic
486 energy stored by the components changes.

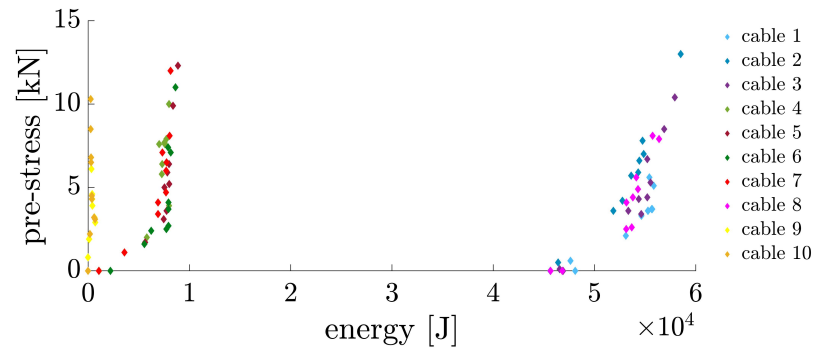


Figure 21. Locally dissipated energy according to prestress in each cable.

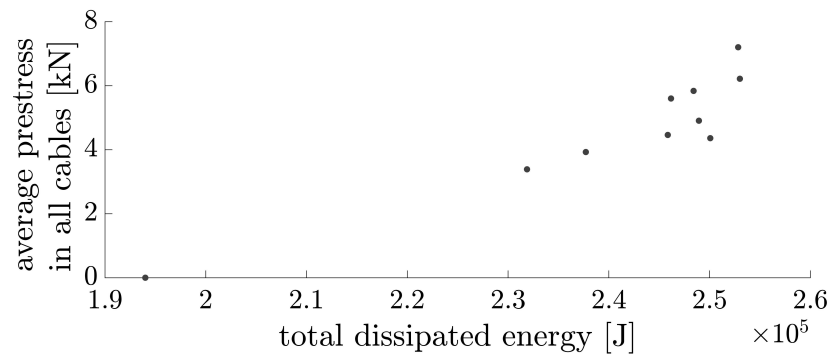


Figure 22. Global energy variation according to the average prestress in all cables.

4.87 6.2. Variability due to uncertainty on brake activation thresholds

4.88 In order to explore the influence of brake threshold variations on the main impact
 4.89 characteristics (energy dissipation, maximum displacement and residual height), a brake
 4.90 threshold distribution is randomly applied on the cables. This threshold distribution
 4.91 follows the law determined experimentally (see section 3.4).

4.92 The local study of the influence of the threshold is shown in Figure 23, where for
 4.93 each cable, the energy dissipated by this cable is represented as a function of the brake
 4.94 activation threshold whose value was given by the manufacturer as 25 kN. As expected,
 4.95 one observes that the dissipated energy is almost proportional to the brake threshold.
 4.96 Variations in the dissipated energy are significant and for example, in the test sample,
 4.97 the energy dissipated by cable 8 varies from 1.70kJ (when the threshold is 5kN) to 5.2kJ
 4.98 (for threshold of 42kN).

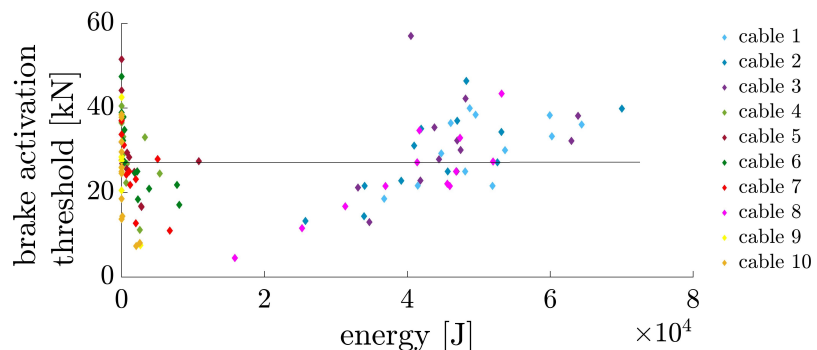


Figure 23. Local dissipated energy variations according to brake activation threshold in each cable.

4.99 Globally, the Figure 24 represents the average of the thresholds for a simulation as
 5.00 a function of the total energy dissipated during the impact. Here, it can be seen that
 5.01 the higher the average brake activation threshold, the less dissipation there is, and vice
 5.02 versa: that is, when all the brakes are triggered later, the amount of energy dissipated is

503 lower. Considering that the global deformation increases with time and, by there, that
 504 the strain energy increases with time, one might suppose that the later the triggering of
 505 the brakes, the higher the share of elastic strain energy (or equivalently the smaller the
 506 dissipated energy). Moreover, as the barrier deforms, the cables incline and the vertical
 507 component of the braking forces increase: the more vertical the braking force, the more
 508 efficient the dissipation. The dissipation being more effective, the dissipation needs are
 509 also reduced.

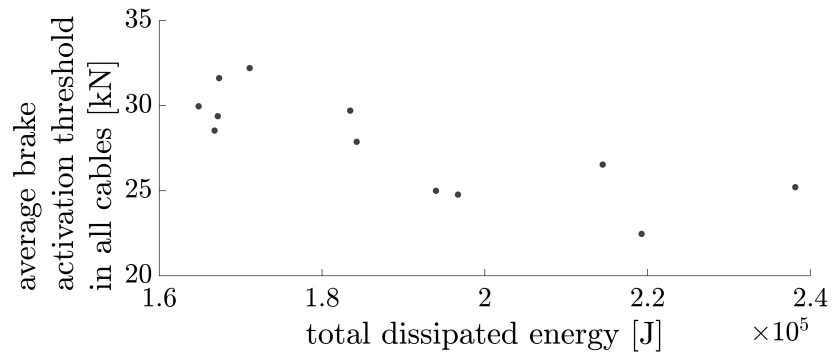


Figure 24. Global energy variation according to the average brake activation threshold in all cables.

510 This shows that the efficiency of the structure is closely linked with its geometric
 511 stiffness which combines the large deformation with the intensity of the forces in the
 512 cables, i.e. with the brake thresholds. Indeed, the geometric stiffness allies the working
 513 force in the cable with its direction change: the higher the brake threshold, the stiffer the
 514 cables; the stiffer the cables, the lower the elastic strain energy in the net and the higher
 515 the dissipated energy by the brakes.

516 7. Discussion

517 The Table 11 compiles, in percentage terms, the standard deviations and maximum
 518 deviations obtained during the series of measurements analysed in the previous sections.
 519 It can be noted that pre-stressing is indeed not a dominant factor for the variability of
 520 the results, since the standard deviations are systematically below 3%. On the contrary,
 521 the position of the block impact is significant, especially for the values of residual height
 522 and maximum displacement. The variation in the thresholds is significant as well: the
 523 maximum observed differences in the amount of energy dissipated are almost 40%.

Table 11: Variability due to impact position, prestress and brake activation threshold uncertainties.

Variable		Prestress	Brake threshold	Impact position
Energy	Std. dev.	2.9 %	13.5 %	8.1 %
	Max. dev.	8.6 %	38.9 %	26.1 %
Max. Displ	Std. dev.	0.3 %	2.7 %	8.6 %
	Max. dev.	0.9 %	8.6 %	24.2 %
Res. Height	Std. dev.	1.6 %	6.2 %	7.9 %
	Max. dev.	5.3 %	18.2 %	23.1 %

524 The variability observed in the experimental tests was very pronounced. Consider-
 525 ing the decisive parameters for the validation of a barrier, according to the ETAG, the
 526 following differences were obtained for the MEL tests alone:

- 527 • Energy dissipated : $\pm 29\%$
- 528 • Maximum displacement: $\pm 13\%$
- 529 • Residual height: $\pm 16\%$

530 Regarding the energy dissipated and the residual height, the deviation remains
531 well below the maximum differences observed numerically. The difference in terms
532 of maximum displacement, on the other hand, is very large - a few explanations are
533 possible. First, the MEL impacts, even if they are supposed to have occurred in exactly
534 the same place, can be considered to have been somewhat delayed and a variation due to
535 position is not taken into account; second, the number of measurements to provide the
536 values in Table 11, although representative, are not sufficient to make a true statistical
537 study and the range given is therefore inaccurate. Finally, the inaccuracies due to the
538 measure itself are not negligible (as stated in section 2.2, brake elongations uncertainties
539 were estimated to approximately 4.5%). Considering this, the difference between the
540 maximum displacements remains within the range defined in the Table 11.

541 8. Conclusion

542 The analysis of both C2ROP project test campaigns revealed a high variability in
543 residual height, maximum displacement and cable running values. To understand this
544 variability, a sensibility analysis was conducted numerically using a model in which
545 the dynamics of the system is implemented in the form of a non-linear mass/spring
546 system. The relevance of this model was tested and validated with comparison with
547 experimental results.

548 The first phase of the sensitivity analysis concerned the influence of the impact
549 position of the block. It was shown that, for the studied fence, each cable is important
550 and each brake is activated for some impact position (see Figure 16), so that all the
551 brakes are necessary at some points. The centred impact is, according to the study, the
552 most unfavourable (the one which exhibits the highest deformation), so that the ETAG is
553 indeed safe.

554 The second phase of the sensitivity analysis investigated: first the influence of
555 prestress applied to the edge cables, then that of brake thresholds. Concerning the
556 prestress, even if the dispersion of the values was large (more than 50%), the influence
557 was found of secondary order on the global response of the fence. Concerning the
558 variation in brake thresholds, their dispersion was smaller (less than 40%) but by far had
559 more significant influence, with a standard deviation on dissipated energy of 13.5% and
560 a maximum deviation among the simulations performed of nearly 40%.

561 Some general comments on the fence structural behaviour can hence be drawn. The
562 key issue in the design of flexible rockfall barrier is its architecture: it is the arrangement
563 of the supporting cables which drives the way the structure deforms from planar to
564 three dimensional network. The modelling choices of the net have few influence on
565 the response, provided that the sliding of the cable is correctly taken into account [16].
566 It is the architecture of the fence and the sliding that guaranty its ability to adapt its
567 geometry to the position of the impact so that it can resist the load with reasonable
568 internal forces in the system.

569 The efficiency of the structure is then principally linked with its geometric stiffness
570 which combines the working force in the cable (given by the brake threshold) with
571 its direction change. The prestress level can be seen has a kind of initial geometric
572 imperfection, like the position of the post head, the ring arrangement variation or small
573 pre-loading of the net.

574 To conclude, there is a trend in the community toward the definition of safety
575 coefficients for such protective fences. It seems thus that, beside perforation issues
576 which were not in the scope of this study, one way to improve the reliability of flexible
577 rockfall barrier would be to improve the brake reliability. Indeed, by diminishing the
578 threshold dispersion, one would reduce the dispersion of the barrier response (maximal
579 displacement and residual height) and by there, reduce the statistical consequences of
580 this dispersion on safety factors.

581 Acknowledgements

582 The authors wish to thank all the members of the national project C2ROP and
 583 particularly the members of the working group on flexible barriers for their invaluable
 584 support, namely M-A. Chanut and J. Coulibaly from CEREMA, P. Robit, I. Olmedo from
 585 NGE foundations, C. Galandrin and M. Verdet from CAN, L. Dugelas, and S. Lambert
 586 form INRAE and D. Bertrand from INSA Lyon.

References

1. Volkwein, A.; Schellenberg, K.; Labiouse, V.; Agliardi, F.; Berger, F.; Bourrier, F.; Dorren, L.K.A.; Gerber, W.; Jaboyedoff, M. Rockfall characterisation and structural protection - a review. *Natural Hazards and Earth System Sciences* **2011**, *11*, 2617–2651. doi:10.5194/nhess-11-2617-2011.
2. Yang, J.; Duan, S.; Li, Q.; Liu, C. A review of flexible protection in rockfall protection. *Natural Hazards* **2019**, *99*, 71–89. doi:10.1007/s11069-019-03709-x.
3. Muraishi, H.; Samizo, M.; Sugiyama, T. Development of a flexible low-energy rockfall protection fence. *Quarterly Report of RTRI* **2005**, *46*, 161–166.
4. McCauley, M.L.; Works, B.W.; Naramore, S.A. Rockfall Mitigation. Final Report. Technical report, 1985.
5. Peila, D.; Pelizza, S.; Sassudelli, F. Evaluation of Behaviour of Rockfall Restraining Nets by Full Scale Tests. *Rock Mechanics and Rock Engineering* **1998**, *31*, 1–24. doi:10.1007/s006030050006.
6. Gerber, W.; Grassl, H.; Boell, A.; Ammann, W. Flexible rockfall barriers development, standardisation and type-testing in switzerland. *Proc. M. Kuehne, ed., Landslides Causes, Impacts and Countermeasures. United Engineering Foundation, Inc* **2001**.
7. Muraishi, H.; Sano, S. Full-scale rockfall test of ring net barrier and components. Seminar on rock fall tests and stabilization, Davos, 1999.
8. Grassl, H.; Volkwein, A.; Anderheggen, E.; Ammann, W.J. *Steel-net Rockfall Protection - Experimental And Numerical Simulation*; WIT, 2002; p. 593. doi:10.2495/SU020141.
9. Trad, A. Analyse du Comportement et Modélisation de Structures Souples de Protection: le cas des Ecrans de Filets Pare-Pierre sous Sollicitations Statique et Dynamique. PhD thesis, 2011.
10. Bertrand, D.; Trad, A.; Limam, A.; Silvani, C. Full-Scale Dynamic Analysis of an Innovative Rockfall Fence Under Impact Using the Discrete Element Method: from the Local Scale to the Structure Scale. *Rock Mechanics and Rock Engineering* **2012**, *45*, 885–900. doi:10.1007/s00603-012-0222-5.
11. EOTA. ETAG-027: guideline for European technical approval of falling rock protection kits, 2013.
12. Volkwein, A.; Gerber, W.; Klette, J.; Spescha, G. Review of Approval of Flexible Rockfall Protection Systems According to ETAG 027. *Geosciences* **2019**, *9*, 49. doi:10.3390/geosciences9010049.
13. Toe, D.; Mentani, A.; Govoni, L.; Bourrier, F.; Gottardi, G.; Stéphane, L. Introducing Meta-models for a More Efficient Hazard Mitigation Strategy with Rockfall Protection Barriers. *Rock Mechanics and Rock Engineering* **2018**, *51*, 1097–1109. doi:10.1007/s00603-017-1394-9.
14. Nicot, F.; Cambou, B.; Mazzoleni, G. From a constitutive modelling of metallic rings to the design of rockfall restraining nets. *International Journal for Numerical and Analytical Methods in Geomechanics* **2001**, *25*, 49–70.
15. Volkwein, A. Numerical simulation of flexible rockfall protection systems. In *Computing in Civil Engineering (2005)*; 2005; pp. 1–11.
16. Boulaud, R.; Douthe, C. A comparative assessment of ASM4 rockfall barrier modelling. *Engineering Structures* **2022**, *251*. doi:10.1016/j.engstruct.2021.113512.
17. Hambleton, J.P.; Buzzi, O.; Giacomini, A.; Spadari, M.; Sloan, S.W. Perforation of flexible rockfall barriers by normal block impact. *Rock Mechanics and Rock Engineering*, 2013, Vol. 46, pp. 515–526. doi:10.1007/s00603-012-0343-x.
18. Coulibaly, J.; Chanut, M.; Lambert, S.; Nicot, F. Toward a Generic Computational Approach for Flexible Rockfall Barrier Modeling. *Rock Mechanics and Rock Engineering* **2019**. doi:10.1007/s00603-019-01878-6.
19. Olmedo, I.; Chanut, M.A.; Douthe, C.; Verdet, M.; Galandrin, C.; Dugelas, L.; Bertrand, D. Étude expérimentale multi-échelle sur les écrans pare-blocs comportement des ouvrages hors cadre ETAG27. *Rev. Fr. Geotech.* **2020**, p. 8. doi:10.1051/geotech/2020018.
20. Boulaud, R.; Douthe, C.; Sab, K. Modelling of curtain effect in rockfall barrier with the dynamic relaxation. *International Journal of Solids and Structures* **2020**, *200-201*, 297–312. doi:https://doi.org/10.1016/j.ijsolstr.2020.01.008.
21. Les collections de l'Ifsttar Méthodes d'auscultation de la structure. Mesure de forces. Mesure de la tension des câbles et armatures de précontrainte au moyen de l'arbalète principe et description sommaire. Technical report, Ifsttar, 2015.
22. Day, A. An introduction to dynamic relaxation. *the engineer* **1965**, *219*.
23. Douthe, C.; Baverel, O. Design of nexorades or reciprocal frame systems with the dynamic relaxation method. *Computers & Structures* **2009**, *87*, 1296–1307.
24. Grassl, H.G. Experimentelle und numerische Modellierung des dynamischen Trag- und Verformungsverhaltens von hochflexiblen Schutzsystemen gegen Steinschlag. PhD thesis, 2002. doi:10.3929/ETHZ-A-004446317.
25. Coulibaly, J.; Chanut, M.A.; Lambert, S.; Nicot, F. Sliding cable modeling: An attempt at a unified formulation. *International Journal of Solids and Structures* **2018**, *130*, 1–10.

26. Dugelas, L.; Coulibaly, J.; Bourrier, F.; Lambert, S.; Chanut, M.; Olmedo, I.; Nicot, F. Assessment of the predictive capabilities of discrete element models for flexible rockfall barriers. *International Journal of Impact Engineering* **2019**, *133*, 103365. doi:<https://doi.org/10.1016/j.ijimpeng.2019.103365>.