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

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

Keywords: *double line rockfall barreier, net fence, probabilistic trajectory analysis, mitigation measures.*

1. Introduction

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

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

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

2. Method

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

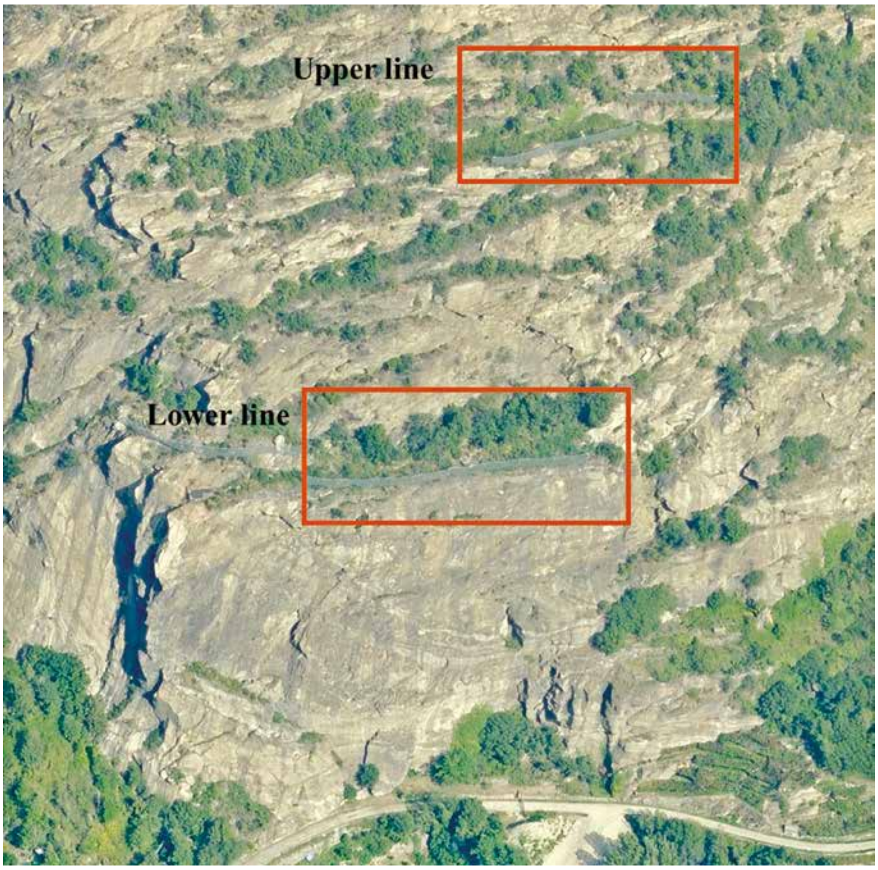

Fig. 1 – Double line system (Valle d'Aosta, Italy).

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

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

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

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

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

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

Tab. 1 – List of symbols.

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

follows tab. I

Symbol	**Meaning**
Trajectory Analysis TA2	
N^*	Number of simulations
v_i	Initial velocity of the simulations $v_i = \gamma_v \sqrt{v_{k,u}^2 - \frac{2E_{b,l}}{m_k \gamma_{E,b} \gamma_m \gamma_v^2}}$
$\overset{*}{n}_{i,l}, \overline{\overset{*}{n}_{i,l}}\ \overset{*}{n}_{a,l}, \overline{\overset{*}{n}_{a,l}}, \overset{*}{n}_{s,l}$	Number of simulation intercepted, not intercepted, arrested, not arrested, stopping before the lower line, respectively, pertaining to TA2
$\hat{\beta}$	% of blocks arrived in the lower location pertaining to TA2, $\hat{\beta} = \frac{\overset{*}{n}_{i,l} + \overline{\overset{*}{n}_{i,l}}}{N^*} = \beta$
Trajectory Analysis TA1 + TA2	
$\overset{+}{n}_{i,l}, \overline{\overset{+}{n}_{i,l}}$	Number of simulation intercepted and not intercepted by the lower line, respectively, pertaining to TA2 but scaled to consider that $N^* \neq \overline{n_a}$. $\overset{+}{n}_{i,l} + \overline{\overset{+}{n}_{i,l}} = \hat{\beta}\alpha_1(1-\alpha_2)\mathrm{N}_1$
δ	% of blocks, among those arrived, not intercepted by the lower barrier $\delta = \frac{\overline{n_{i,l}}}{n_{i,l} + \overline{n_{i,l}}}$
q	Percentile to consider to compute the characteristic value of the velocity in the lower line
$v_{q,l}$	Characteristic value of the trajectories velocity, for the design of the lower line, in a double net system.

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

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

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

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

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

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

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

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

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

2.1. Applying the method in the common practice

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

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

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

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

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

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

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

$$h_i = \gamma_h \, h_{k,i,u} \tag{7}$$

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

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

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

3. *Example of application*

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

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

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

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

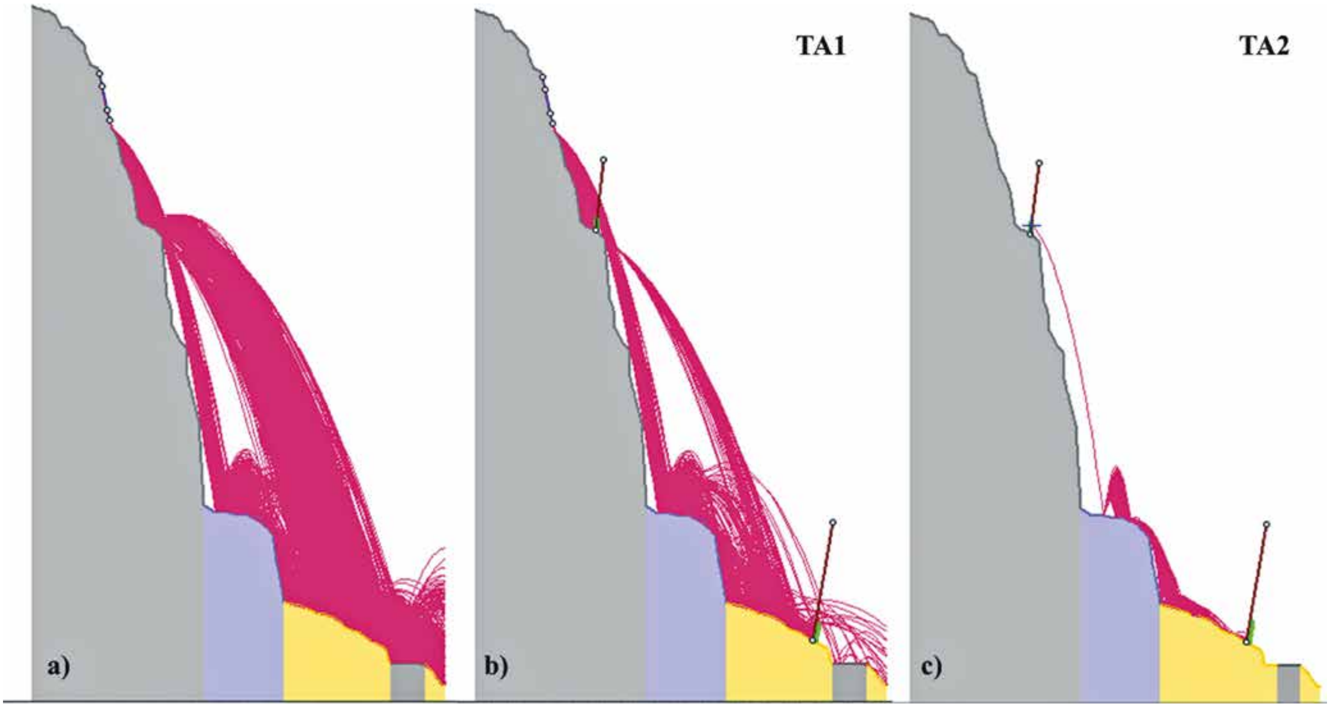

Fig. 2 – Trajectory analyses in the considered path (RocFall v8.017). See Table 2 for details on input parameters: a) without barriers, b) TA1 with a physical barrier with infinite capacity in the upper line locations, and a physical barrier in the lower line, c) TA2. Red lines state as collectors, while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

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

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

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

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

Symbol	Value
General	
m_k	5400 kg
γ_m	1.02 (-)
γ_v	1.04 (-)
γ_h	1.04 (-)
$\gamma_{E,b}$	1.2 (-)
$h_{b,u}$	5 m
$E_{b.u}$ (= E_{MEL})	1000 kJ
$v_{b,u,max}$	16.73 m/s
$h_{b,l}$	6 m
$E_{b,l}$ (= E_{MEL})	2000 kJ
Trajectory Analysis TA1	
N	1000
$n_{s,u}$	0
N_1	1000
$v_{k,u}$	25.40 m/s
$h_{k,u}$	8.21 m
$n_{i,u}$	645
$\overline{n_{i,u}}$	355
$n_{a,u}$	611
$\overline{n_{a,u}}$	34
α_1	3.4 %
α_2	35.5 %
$n_{s,l}$	250
$n_{i,u}+\overline{n_{i,u}}$	105
$v_{k,l}$	16.86 m/s
$h_{k,l}$	9.68 m
$v_{k,i,l}$	16.72 m/s
$h_{k,i,l}$	4.95 m
$n_{i,l}$	86
$\overline{n_{i,l}}$	19
$\tilde{\beta}$	29.6 %
δ	18%
$n_{a,l}$	86
$\overline{n_{a,l}}$	0
Trajectory Analysis TA2	
N^*	1000
$v_{k,i,u}$	23.23 m/s
v_i (Eq. 6)	10 m/s
$h_{k,i,u}$	3.33 m
h_i (Eq. 7)	3.46 m
$n^*_{i,l}+\overline{n^*_{i,l}}$	20
$\hat{\beta}$	2%
$v_{k,l}$	11.01 m/s
$h_{k,l}$	1.41 m
$v_{k,i,l}$	11.02 m/s
$h_{k,i,l}$	1,29 m
$n_{i,l}$	20
$\overline{n_{i,l}}$	0
Trajectory Analysis TA1 + TA2	
$n^+_{i,l}+\overline{n^+_{i,l}}$	1
$v_{k,l}$	16.21 m/s
$h_{k,u}$	9.47 m
$n_{i,l}$	89
$\overline{n_{i,l}}$	17
$v_{k,i,l}$	15.03 m/s
$h_{k,i,l}$	4.95 m
δ	16%
q	0.54
$v_{q,l}$	12.84 m/s
$n_{a,l}$	89
$\overline{n_{a,l}}$	0

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

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

Conclusion

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

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

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

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

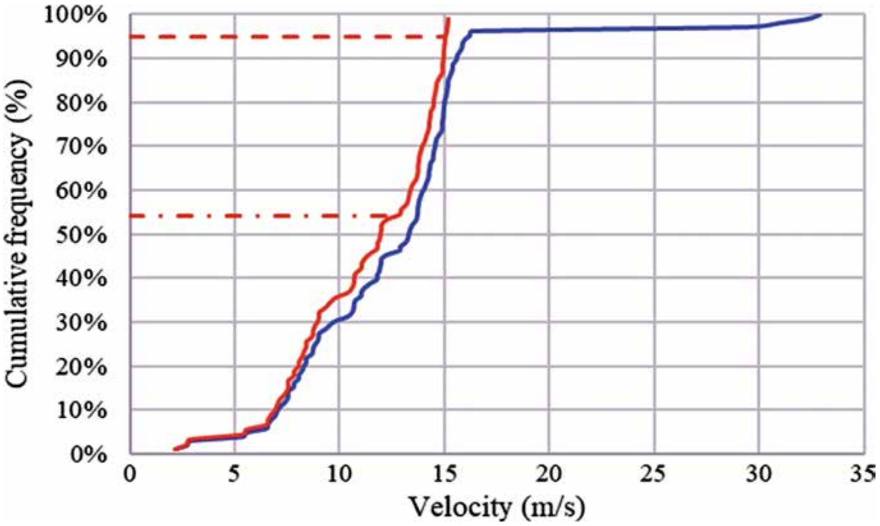

Fig. 3 – Cumulative frequency distribution of the velocity. The blue line represents the distribution of all blocks passing in the lower line position, while the orange considers the only blocks intercepted by the loer barrier. The dotted line refers to the 95th percentile, while the dash-dotted line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

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