# Certified deformable rockfall barriers: tests, design and installation


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ABSTRACT
Rockfall barrier manufacturers test and certify their structures in accordance with the European Guideline ETAG 027/2008. The guideline does not define how the different components of the tested system must be manufactured, but it ensures that the entire tested “kit” is able to withstand a certain impact. After a short introduction of the ETAG 027, the paper underlines the main differences between test and real in-situ conditions, and introduces the new design approach proposed by the UNI 11211:4/2012. Moreover, the installation criteria are analyzed in order to define the best cost-effective fence. In conclusion, some considerations on the anchoring systems are presented.

RÉSUMÉ
Les producteurs des écrans pare-pierres testent et certifient leur structures en suivant la Ligne Guide Européenne ETAG 027/2008. Celle-ci ne définit pas comment les différent composants de la barrière doivent être fabriqués, mais assure que le « kit » testé est capable de contenir un certain impact. Après avoir introduit l’ETAG 027, l’article se focalise sur les différences principales entre les conditions qu’on trouve dans les stations d’essais et celles qu’on a vraiment sur chantier. Il introduit le nouveau approche de calcul proposé par UNI 11211:4/2012 et il analyse les critères d’installation afin de pouvoir choisir l’écran avec les meilleures avantages cout-bénéfices. En conclusion, des considérations sur les systèmes d’ancrage sont faite.


## 1 HIGH ENERGY ABSORPTION ROCKFALL BARRIER

Rockfall barriers are commonly used to provide rockfall protection along roads, highways and railways, in open pit mines, for residential areas and worksites. They are classified as passive mitigation systems. In fact, they do not affect the source area, but they mitigate the instabilities effects arresting the rock masses trajectories or reducing their falling velocity and energy. This category typically includes also debris flow barriers, embankments and hybrid fences.

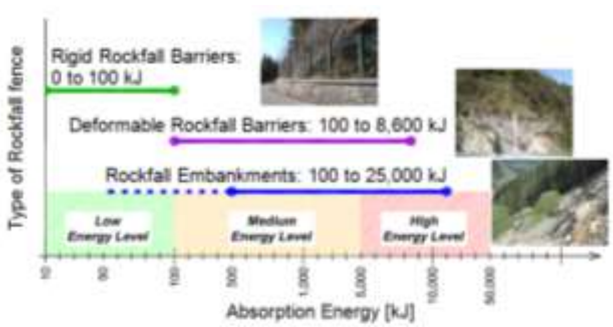


Figure 1. Correlation between the energy level and the type of rockfall barriers (Grimod at al., 2013).

According with the European Guideline ETAG 027 (Guideline for European Technical Approval of falling rock protection kits) (EOTA 2008) rockfall barriers may be grouped in two categories, depending on the energy level that are able to withstand: rigid barrier (with a capacity lower than 100 kJ) and deformable barrier (with a capacity higher than 100 kJ, at the time of writing the maximum capacity of a deformable rockfall barrier is 8,600 kJ – 27 tons travelling at 90 km/h). For higher energies, rockfall embankments must be used (Figure 1).

Deformable barriers are able to stop blocks with medium-high energy levels (up to 8,600 kJ), thanks to their capacity to deform. The elongation of the barrier (or fence) allows increasing the arresting time of the block ($\Delta t$) and consequently reducing the acting forces (F) against the structure (Equation 1).

$$F = m \, \Delta v / \Delta t \qquad [1]$$

Where: F = force acting against the fence after the impact, m = mass of the block, v= velocity of the block, t = arresting time of the block (for rigid barrier almost nil, for deformable fence approx. 0.15-0.40 s).

High energy absorption deformable barriers are one of the most common measure against rock falls. They are installed at a certain distance from the detachment area; therefore, as previously mentioned, they are classified as passive system. In agreement with the definition stated in the ETAG 027, a deformable rockfall barrier is a “kit” of different components, which must be able to stop a block impacting against it. The kit is composed by several elements:

1. an interception structure, generally a steel net (Figure 2);
2. a support structure, steel posts (Figure 2);
3. connection elements, such as:
   - 3.a upper longitudinal cable (Figure 2);
   - 3.b lower longitudinal cable (Figure 2);
   - 3.c upslope bracing cable – if any (Figure 2);

3.d lateral bracing cable (Figure 2);
3.e energy dissipator devices (brakes), etc.

The structure is then fixed to the soil by anchoring systems. These elements transfer to the ground the forces developed from the impact (Figure 2: anchoring system of posts (4.a), lateral bracing cables (4.b), and upslope bracing cables (4.c) - if any). It must be clarify that, as per ETAG 027, the anchoring systems are not part of the "kit". The type and the length of these components may change depending on the site characteristics, for instance rockfall fences are never installed in the same type of soil (i.e. rock, loose soil, concrete, etc.). Thus, these elements cannot be standardized like the elevation part of the fence.

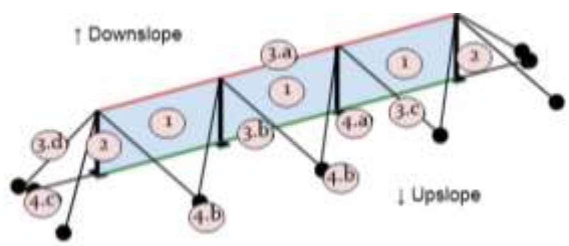

Figure 2. Components of a rockfall barrier.

## 2 ETAG 027

In order to understand and be able to compare the behaviour of rockfall barriers, the European Organisation for Technical Approval (EOTA) issued in 2008 the ETAG 027. Even if there are also other guidelines available worldwide, (e.g. American Recommendations – AASHTO 2003; Swiss Guideline – WLS 2001) the European is the strictest one. Nowadays, this guideline is essentially the only test and construction framework utilized by manufacturers and it is also starting to enter in the mentality of designer who can clearly specify the performances of rockfall barriers. ETAG 27 (and the related European Technical Approval –ETA– and CE marking) represents a milestone for the rockfall barrier market, because it gives the possibility to compare the performances of different fences and it ensures the quality of the certified product. For these reasons ETAG 27 presently constitutes the base for tenders all around the world. .

### 2.1 The crash test

ETAG 027 has standardized all the procedure to carry out the full-scale crash tests. It defines:

- Shape, minimum dimensions and density of the tested block;
- Dimension of the tested barrier: it must have at least 3 functional modules (3 spans);
- Impact features: the block must impact the barrier in the center of the middle span;
- Minimum impact velocity of the block: no lower than 25 m/s (approx. 90 km/h);
- Test field has to be able to accelerate the tested block to the minimum impact velocity; it can be on a vertical or inclined slope. No interference between the block and the soil are admitted before and during the impact;
- Two tests must be performed considering the Maximum Energy Level (MEL, i.e. 3,000 kJ) and the Serviceability Energy Level (SEL = 1/3 of the MEL, i.e. 1,000 kJ). These two tests must be carried out on 2 different barriers A and B, which present the same energy level as well as the same geometrical and mechanical characteristics:
  A. First launch at the MEL: on barrier A. To pass the test, the stopped block cannot touch the ground before the barrier reaches its maximum elongation (Figure 3);
  B. Second launch at the SEL: on barrier B;
  C. Third launch at SEL: again on barrier B. This launch must be done on the same barrier of B). No repairs are allowed between the two consecutive tests. Moreover, the 2$^{nd}$ launch can be carried out only if the residual height (Figure 4) of the barrier, previously crashed by the 1$^{st}$ SEL impact, measure at least the 70% of the nominal height of the tested fence (before the impact). During this second SEL launch the barrier simply has to withstand the falling block.


Figure 3. Deformable rockfall barrier tested at the Maximum Energy Level (MEL = 8,600 kJ) according to ETAG 027 (type of fence: RMC 850/A, height = 7.0 m).

### 2.2 The test measurements

In order to uniform the behaviour of the different tested barriers, the European guideline defines the parameter that must be measured during the SEL and MEL test. In this way, the comparison between 2 different barriers with the same energy capacity is easy and above all standardized. In term of performances the following measurements must be done:

- Maximum dynamic elongation of the interception structure: maximum downhill deformation measured parallel to the reference slope during the impact (Figure 4);
- Residual height ($h_R$): minimum distance between the lower and the upper longitudinal cable, measured orthogonally to the reference slope after the test and without removing the block from the interception

structure. The $h_R$ is expressed as a certain percentage of the nominal height of the barrier ($h_N$), which is the distance between the upper longitudinal cable and the connection line between the base of the posts, before the impact, and measured perpendicular to the reference slope (Figure 5 and Figure 6);

- Forces applied on the anchoring systems;
- Photos and description of the damages occurred in the rockfall barrier.

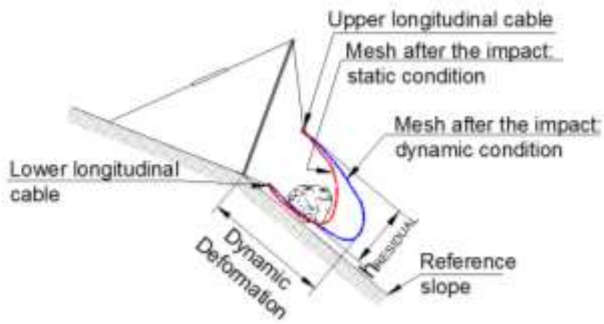


Figure 4. Measurement of the dynamic elongation and the residual height of the barrier, after the impact.

ETAG 027 classifies the barriers in 3 categories based on the residual height: when $h_R \geq 50\%$ of the nominal height ($h_N$), the fence is classified in Category A; if $30\%\ h_N < h_R < 50\%\ h_N$ the barrier is in Category B; and if $h_R \leq 30\%\ h_N$ the barrier is in Category C.

## 2.3 Barrier comparisons

ETAG 027 does not define how the different components of the tested system must be manufactured and/or assembled, but it ensures that the entire tested kit is fit for stopping an impact of a block that develops a certain energy level (i.e. 3,000 kJ). In this way, it is quick and easy comparing the performances of different structures (from different producers) with the same nominal energy capacity. For instance it is possible to compare two or more different 5,000 kJ barriers analyzing the most important parameters to be considered during the design: maximum dynamic elongation, residual height, lateral gaps and efforts transmitted from the structure to the anchoring systems during the impact.

In these terms, manufacturers implement their rockfall barriers in order to satisfy the minimal requirements of ETAG 027 (logic of the technology), as well as the economic aspects (market needs). The consequent result is that fences are pushed to their proper limits. Therefore, their margin of safety might be reduced. For example, a deformable rockfall barrier able to withstand an impact of 5,000 kJ, theoretically, could fail a test at 5,001 kJ.

This logic has several consequences:

1. Producers are encouraged to develop cost-effective structures, by reducing the materials cost (economic reason) and increasing the performances (safety reason). Thus, this concept can be translated in more researches, innovations and competition too;
2. Designers may easily know the resistance limits of the barriers available on the market. In fact, before ETAG 027, the real performances of rockfall fences were pretty much unknown and doubtful;
3. The problem of the safety margin of the barrier is transferred to designers, who must introduce new design approaches to choose the right nominal capacity of the designed fence (see chapter 3);
4. All the fundamental performances are recoded and demonstrated by the full-scale tests. Any declaration of higher safety margin (or better performance) must be validated in accordance with the guideline. Without the certification (European Technical Approval – ETA), issued by an EOTA member after the crash test, manufactures are not able to declare any performance on their barrier;
5. The kit is comprised of elements of various sizes and configurations depending on the required energy capacity and manufacturer. The combination of these elements does not necessarily mean that a structure with heavier (oversized) components has a higher performance capacity than one which is made up of lighter parts but is assembled more efficiently.

Table 1. Comparison between 4 (four) 5,000 kJ fences produced by different manufactures. The values reported are extracted by the European Technical Approvals (ETA), and are referred to the MEL tests: maximum deformation, residual height, and weight of the beam constituting the post.

| Manufacturer | Max. elongation[1] | Residual height ($h_R$) and Category[2] | Beam weight[3] |
|---|---|---|---|
| Manufacturer 1 | 6.50 m | 70% of $h_N$[4]: Category A | 50.5 kg/m |
| Manufacture 2 | 8.62 m | 65% of $h_N$[4]: Category A | 155 kg/m |
| Manufacture 3 | 8.15 m | 61% of $h_N$[4]: Category A | 88.6 kg/m |
| Manufacture 4 | 12.30 m | 34% of $h_N$[4]: Category B | 39.0 kg/m |

[1]Measured considering the dynamic condition.
[2]Category according to ETAG 027.
[3]Referred to the weight of the beam which constitute the post (without any added elements, plate, welded components, etc.). If the fence has more than one type of post, the value in Table 1 define the heaviest one.
[3]$h_N$ is the nominal height of the fence (all the manufacturers listed above tested their barrier with $h_N$ = 6.0 m).

From Table 1, it is possible to underline that there is not any correlation between the dimension of the structure (dimension of the post) and its performance. As shown, the second lightest barrier (Manufacturer 1) has the best performances in term of both residual height and dynamic elongation. While, the manufacturer with the biggest structure (manufacturer 2) has a good residual height, but its elongation is approx. 35% (2.0 m) more than the shortest one available on the market. This fact is strictly connected to the assembling procedure of the components of the kit and on the efficiency of the braking elements of the fence. Both these characteristics differ between the producers.

### 2.4 Residual height

In order to evaluate the protection level of the area after the first impact on the barrier, designers should know the exact residual height of the fence. It is mandatory to use a rockfall barrier with the highest residual height. In this way the high of the interception structure does not decrease significantly after an impact. Thus, the probability that further blocks may jump above the impacted barrier is reduced.

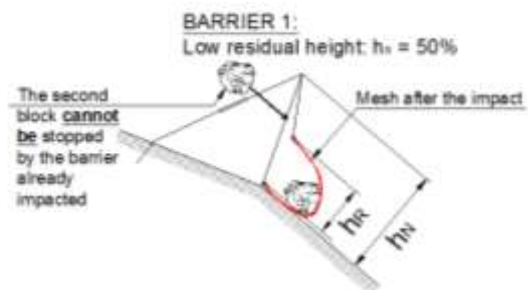


Figure 5. Example of a barrier with a residual height = 50% (classified in Category A according to ETAG 027/2008).

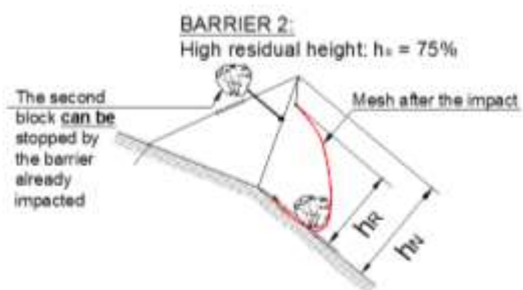


Figure 6. Advantage having a high residual height of the barrier. Example of a barrier with a residual height = 75%, (classified in Category A according to ETAG 027/2008).

Figure 5 and Figure 6 show 2 examples of barriers classified in Category A, according to ETAG 027. It can be remarked that if both the barriers are impacted by the same block (same energy and same size) the barrier in Figure 5, with a residual height equal to 50%, has a lower safety margin compare to the one shown in Figure 6, characterized by a residual height of 75%. For example, according to Table 1, the 5,000 kJ barrier produced by the "manufacturer 1" is strongly recommended.

The analysis of multiple impacts can be done comparing the probabilistic distribution of the height of the trajectories with the residual height of the barrier chosen in the design. The graph below explains how this analysis may be carried out. This specific example shows that, after the first impact, the reliability of the simulation drops from 95% to 70% of the bounce heights on the slope. This means that the probability that a block may overpass the structure increases from 5% to 30%.

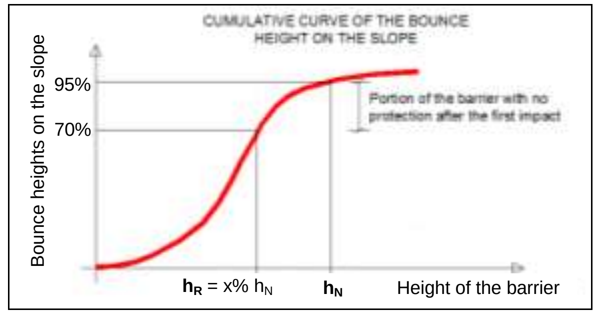


Figure 7. Reduction of the protection level after the first impact: the barrier height is reduced from the nominal value to the residual value.

### 2.5 Dynamic elongation

The maximum dynamic elongation of the fence plays an important role too during the design process (Figure 8). Barriers with a small deformation can be placed closest to the structure to be protected. This is a big advantage in the sites where the space available or the accesses to the slope are restricted. For instance, considering Table 1, the 5,000 kJ barrier produced by the "manufacturer 1" is suggested in all these situations where the distance between the fence and the protected area is limited.

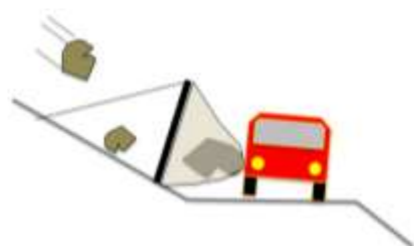

Figure 8. Example of a barrier with an elongation higher than the minimum space available between the fence and the road. The effect of the barrier is neglectable.

## 3 DESIGN

### 3.1 Rockfall simulations

At the base of rockfall barrier designs, rockfall simulations must be performed in order to define the trajectories of the potential unstable blocks along the slope. The aim of these analyses is defining, in every point of the slope, the statistical distribution of energy, velocity, height of the bounces and end points of the falling masses.

The input data necessary for the rockfall trajectories analysis are defined based on: geomechanical surveys, in order to characterize the unstable area and identify the number and the dimension of the potential falling blocks; geological surveys, in order to identify the different soil present on the slope; and finally, topography surveys, in order to identify the geometry of the study area and the exact location of the unstable rocks.

Rockfall simulation are generally performed with commercial software available on the market (i.e. RocFall, CRSP, Rock falls 3D), which may use different calculation approaches. For instance, Lumped Mass Analysis (LMA) is being used extensively. For a lumped mass model, the normal coefficient of restitution (Rn: parameter that depends on the material property of the soil, and it ranges between 0.1 to 0.2) and tangential coefficient of friction resistance (Rt: experimental parameter that depends on the slope material and the vegetation, and it ranges between 0.5 to 1.0) must be defined. Moreover, the rock is considered as dimensionless point mass. Nowadays, new methods have been implemented to offer a more realistic behaviour of the falling blocks. For example, the Rigid Body Impact Mechanics (RBIM) model introduces the effect of the size and shape of the rock and its interaction with the slope. It uses the soil material parameters Rn, Rt, dynamic friction coefficient ($\mu$: tangent of the friction angle, obtained with experimental data) and the rolling friction (Chai et al., 2013).

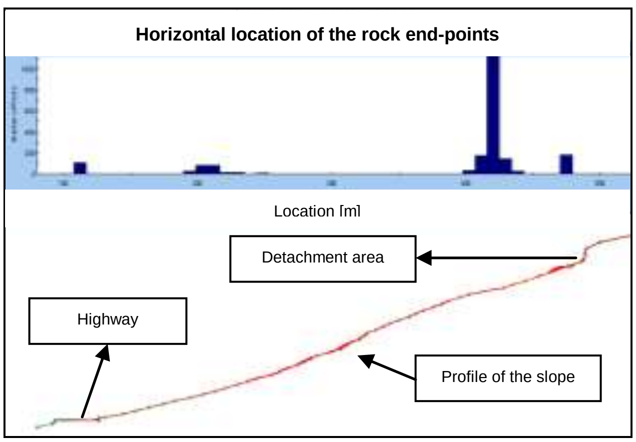


Figure 9. Example of back analysis. Statistical distribution of the horizontal location of the rock end-points; Y-Axis: number of rocks; X-Axis: location in meters (RocFall rel. 4.050).

Irrespective of the model used during the analysis, in order to have reliable results, rockfall simulation must consider at least 1,000+ trajectories (Giani, 1997; UNI, 2012). Moreover, back analyses are always recommended to validate the input data used on the simulation: the statistical distribution of the end-points (defined with the simulation) should match the real distribution of the block on site. As shown in Figure 9, from the back analysis is possible to define the statistical distribution of the end-points recorded on site. For instance, in that specific case 15% of the blocks stopped in the first 20 m from the detachment area, 60% in the next 30-40 m, 20% in the following 150-200 m, and only 10 blocks (approx. 5%) reached the highway downslope.

## 3.2 Installation aspects

The simplest and easiest way to design a deformable rockfall barrier consists in comparing the energy level calculated during the rockfall simulation analysis, with the results obtained by the full-scale crash tests (ETAG 027). For example, if the numerical rockfall trajectory analysis shows energy equal to 1,850 kJ in the location where the barrier has to be placed, therefore an ETAG 027 certified barrier able to withstand more than 1,850 kJ (i.e. 2,000 kJ) must to be chosen. Moreover, if the height of the rock bounces defined with the simulation is 3.8 m, the chosen barrier must be higher than that value (i.e. 4.0 m). Finally, the distance between the fence and the protected area must be higher than the maximum dynamic elongation of the fence (i.e. according to Table 1, > 6.50 m if the chosen barrier belong to the manufacturer 1).

Unfortunately, this simplified calculation approach presents a lot of uncertainty related to the reliability of the input data used for the simulation, to several installation issues and, above all, to the differences between the configuration, and then the behaviour/performance, of the tested and the barrier installed at the job site.

Figure 10. Examples of installed barriers. Top-left: barrier impacted by several blocks in different part of the fence. Top-right: barrier longer than 30 m with upslope concavity. Bottom-left: barrier with posts placed not at the same level. Bottom-right: barrier with posts installed without the same inclination.

Designers must know that the crash tests are performed in ideal conditions, which are completely different from the in-situ one. Here below some of the main characteristics of the tested barrier are presented:

- length 30 m: only 3 spans (functional modules) compose the fence;
- impact in the center of the barrier;
- only one block impact the barrier at the MEL, and 2 at the SEL;
- no planimetric deviations;
- no difference between the levels of the posts.

In the reality (in-situ) the facility configuration never occurs, in fact (Grimod at al., 2013):

- the length of the barrier can vary from 10 to 100+ meters (suggested length 70-80 m) (Figure 10);
- the fence can be impacted at any point (on the top rope, on the post, on the lateral span, etc.) (Figure 10.top-left and Figure 11);
- multiple blocks (with different energy levels) may hit the structure: multiple impacts constitute one of the most severe condition for a barrier, especially when they involve two or more functional modules (Figure 10.top-left);
- planimetric distortions are frequently remarked on site: lager deformation may occur if the deviation of the barrier present upslope convexity, in the other hands, if the alignment present upslope concavity, the barrier may tilt uphill (Figure 10.top-right);
- differences in post elevations may modify the barrier behaviour, because it induces anomalous stress conditions: low stresses are remarked on the smallest diagonal of the functional module, and high stress are remarked in the longest one (Figure 10.bottom-left);
- differences on the post inclination may occur for irregular slope morphologies (Figure 10.bottom-right).

Figure 11. Full-scale test on a 2,000 kJ (RMC 200/A, height 4.0 m). The test was performed following the ETAG 027 requirements, but using only 2 functional modules instead of 3.

### 3.3 Design at the Limit States

Since the full-scale crash tests are not able to describe the barrier behavior for all the real impact conditions, the test must be considered as an index test. Therefore, the rated energy capacity of the fence must be considered nominal (Brunet at al., 2012).

In order to study the real behaviour and define the technological limits of their fences, some manufacturers perform full-scale crash tests, according to ETAG 027, modifying some of the requirements described in the guideline. For example, tests with only 2 functional modules (Figure 11), or with multiple impacts, or impacted on the posts, etc., have being carried out. Unfortunately, all these tests are extremely expensive ($ 50,000-100,000 / ea) and it is almost impossible describing all the potential configurations that may happen in real cases. For these reasons, in January 2012 the Italian Standard Organization (UNI – Ente Nazionale di Unificazione) issued the UNI 11211:4 (UNI 2012), which contain the methodology to design passive rockfall fences using the Limit State Design (LSD) approach.

According to the UNI 11211:4, the design of a rockfall barrier can be done considering the Ultimate Limit State (M.E.L. approach) or the Serviceability Limit State (S.E.L. approach). In both cases the Limit State Design (L.S.D.) approach introduces some partial coefficient: load coefficients, which increase the driving actions on the barrier, and reduction coefficients, which reduce the resistance of the structure.

#### 3.3.1 Energy of the barrier

The equation at the base of this new design approach is:

$$Esd < E_{BARRIER} / \gamma_E \qquad [2]$$

Where: Esd is the design energy level developed by the block against the barrier; $E_{BARRIER}$ is the energy absorbed by the barrier, as defined with the crash test carried out according to ETAG 027 (MEL or SEL); and $\gamma_E$ is the safety coefficient related to the energy level adopted during the design and the length of the barrier (Table 2).

Esd is defined with the classical formula of the kinetic energy multiplied by a safety coefficient $\gamma_R$ (Table 2), which considers the human risk. In the formula the spin effect of the falling rock can be neglected, because it has been highlighted (Arndt, 2009) that this value is only the 10-15% of the total energy; therefore it can be compensated by the introduced partial safety coefficients.

$$Esd = (½\ M_d\ v_d^2)\ \gamma_R \qquad [3]$$

Where: $M_d$ is the design mass of the block; and $v_d$ is the design velocity of the block.

Designers must define the design mass and velocity as following:

$$M_d = (Vol_B \cdot \gamma)\ \gamma_{VOL} \cdot \gamma_\gamma \qquad [4]$$

$$v_d = v_t \cdot \gamma_{Tr} \cdot \gamma_{Dp} \qquad [5]$$

Where: $Vol_B$ is the volume of the design block; $\gamma$ is the unit weight of the rock; $\gamma_{VOL}$ is the safety coefficient related to the precision of the geomechanical survey to define the size of the block (Table 2); $\gamma_\gamma$ is the safety coefficient related to the evaluation of the unit weight of the rock (Table 2); $v_t$ is the velocity calculated with the rockfall simulation and considering the 95° percentile of the velocities; $\gamma_{Tr}$ is the safety coefficient related to the reliability of the rock fall simulation (Table 2); and $\gamma_{Dp}$ is the safety coefficient related to the quality of the topographic survey (Table 2).

#### 3.3.2 Height of the barrier

The minimum height of the barrier has to be defined considering the design height ($h_d$) plus an upper free border, where the block cannot impact ($f_{min}$).

$$H_{tot} \geq H_d + f_{min} = (H_t \cdot \gamma_{Tr} \cdot \gamma_{Dp} + R_{block} \cdot \gamma_{Rb}) + f_{min} \qquad [6]$$

Where: $H_{tot}$ is the nominal height of the tested barrier according to ETAG 027; and $H_d$ is the design height of the trajectories; $f_{min}$ is the safety zone (upper free border) that cannot be impacted (usually $f_{min} \geq 50$ cm); $H_t$ is the height of the trajectories defined with the numerical simulations and considering the 95° percentile of the heights; $R_{block}$ is the average radius of the design block; and $\gamma_{Rb}$ is the safety coefficient on the radius of the block (Table 2).

### 3.3.3 Distance between the barrier and the protected zone

The minimum distance between the barrier and the protected area ($D_A$) is determined as follow:

$$D_A \geq D_b \cdot \gamma_d \quad [7]$$

Where: $D_b$ is the maximum dynamic deformation of the barrier, measured after the crash test at the MEL; $\gamma_d$ is the safety coefficient related to the energy level adopted during the design, the length of the barrier and the barrier-span impacted by the boulder (Table 2).

Table 2. Values of the partial coefficients, according to UNI 11211:4-2012 and authors' experience.

| Symbol | Notes | Value |
|---|---|---|
| $\gamma_E$ | SEL approach : | 1.00 |
| | MEL approach and fence with more than 3-spans : | 1.20 |
| | MEL approach and fence with less than 3-spans (where 2 parallel barrier are placed) : | 1.20 |
| | MEL approach and fence with less than 3-spans (where only 1 barrier is placed) : | 2.00 |
| $\gamma_R$ | Place rarely frequented, with low value and easy to be repaired : | 1.00 |
| | Place rarely frequented, with medium value and easy to be repair : | 1.05 |
| | Place frequented, with high value and difficult to be repaired : | 1.10 |
| | Place highly frequented, with really high value - or strategic - and impossible to be repair (i.e. hospital, school, etc.) : | 1.20 |
| | From a risk analysis : | T.B.D. |
| $\gamma_{VOL}$ | High accuracy survey to define the dimension of the blocks : | 1.02 |
| | Without any survey : | 1.10 |
| $\gamma_\gamma$ | Generally suggested : | 1.00 |
| $\gamma_{Tr}$ | Rockfall simulation based on back analysis : | 1.02 |
| | Rockfall simulation based on literature : | 1.10 |
| $\gamma_{Dp}$ | High accuracy of the topographic survey : | 1.02 |
| | Low accuracy of the topographic discretization : | 1.10 |
| $\gamma_{Rb}$ | Suggested by UNI 11211:4-2012 : | 1.00 |
| | Generally suggested by authors : | $\gamma_{VOL}$ |
| $\gamma_d$ | SEL approach : | 1.00 |
| | MEL approach and fence with more than 3-spans : | 1.30 |
| | MEL approach and fence with less than 3-spans : | 1.50 |
| | MEL approach and possible trajectories impacting the lateral spans : | 1.50 |

### 3.3.4 MEL or SEL?

ETAG 027 and UNI 11211:4 introduce an innovative concept for the absorption energy of the fence. Therefore, consultants may do their rockfall barrier designs at Serviceability or Ultimate Limit States.

SEL (Serviceability Limit State Design) is normally used in order to reduce the maintenance costs of the barrier, when the site is vulnerable to multiple impacts and a very low risk is admitted. This approach is obviously the most expensive, because it is necessary to use a barrier with a capacity 3 times higher than the minimum required, but on the other hands it can increase significantly the safety condition of the area. A typical application of a SEL-design is at the entrance of the tunnel portals (Grimod et al., 2013).

MEL (Ultimate Limit State Design) is normally adopted when there is a low frequency of rock falls or only one boulder is expected to fall, if the maintenance can be easily done and/or if the risk level admitted is high. Using this approach, the initial cost of the structure is certainly lower than the one designed at the SEL, but the maintenance cost can be higher and the safety level is surely lower. Typical uses of rockfall barriers designed at the maximum energy level could be for temporary works, or installations at the base of a re-profiled slope, as often happens in mining applications (Grimod et al., 2013).

## 3.4 Field installation experiences

During the choice of a rockfall barrier the priority must be focused on the performances of the barrier, as described in the previous chapters (fences with high residual height and low deformation must be preferred). However, the installation aspects ought to be taken into consideration as well as the global cost of the intervention.

Throughout the conception of rockfall barriers consultants usually do not think about the installation. Nevertheless, during the design phases it must be clear that these structures are generally installed on remote areas, characterized by very steep slopes, limited accesses, and where powerful machinery cannot operate. Indeed, in order to facilitate the installation, helicopters are normally used to transport the different components of the barrier: anchors, cables, nets and posts. Additionally, in these zones workers are often exposed to rockfall hazards, so it is often mandatory operate as quickly as possible.

In order to reduce the installation issued, several manufacturers have developed their barriers including features to make the installation faster, easier and safer, reducing the time on site. For instance, hereafter some of the major features adopted by produces are listed: steps on the posts (Figure 12), to simplify the access at top of the structure; support struts on post footplate (Figure 12), to facilitate the elevation of the post and maintain the post in the proper position without fixing the bracing cables; interception structure directly connected to the longitudinal cables and/or posts, in order to reduce the installation time of the net; light brakes directly included on the ropes, to reduce the number of connection elements to apply on site; etc.

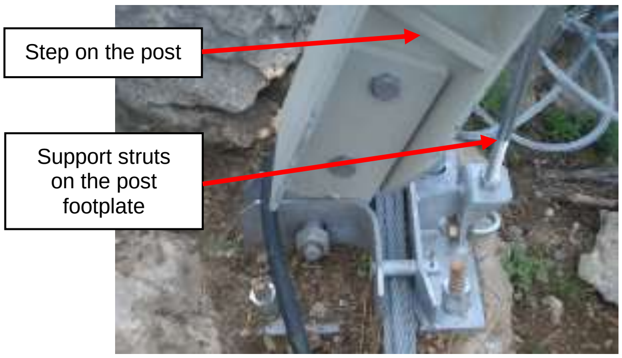


Figure 12. Example of devices to help the installation: steps on the post and support struts on post footplate.

From the authors' experience, one of the most critical operations during the barrier installation is the positioning of the posts on the footplate. This procedure is normally realized using cranes or helicopters (Figure 13), which have limits due to the maximum allowable load. In fact, for economic reasons, a lot of contractors prefer to use barriers with light posts which are easier and safer to put in place compare to those barriers with large and heavy beams. Moreover, light structures allow using small helicopters, which are cheaper and easier to maneuver. For instance, field experiences confirm the difficulties to install heavy posts (weight > 500 kg) with helicopters, which may be easily destabilized, above all if wind conditions occur. Consequently the risk for the crew present on the ground can dramatically increase.

Figure 13. Installation of the barrier post using helicopters.

As previously discussed on the paper, and as reported in Table 1, it has been clarified that light rockfall barriers are not necessarily less performing than fences with oversized components (e.g. posts, cables, etc.). In fact, light structures cannot be considered less safe or robust than other "overdesigned" structures.

As per example, it is possible to compare two 5,000 kJ barriers produced by 2 different manufacturers: "manufacturer 1" and "manufacturer 2" (see Table 1). Considering the standard height of a 5,000 kJ, which is generally 6.0 to 7.0 m, it is possible to underline the different total weight of the beams of these two fences. For manufacturer 1, the total weight of the beam is 303 to 353.5 kg, while for manufacturer 2 is 930 to 1,085 kg. This remarkable difference (more than 3 times) may induce the increasing of the installation problems on site for the heaviest fence. Moreover, in this specific case, the performances (according to ETAG 027) of the barrier produced by manufacturer 1 are higher than the ones of manufacturer 2. This aspect confirms the fact that big structures may be weaker and less performing than smaller one.

### 3.5 Design of the anchoring systems

During the full-scale tests, manufacturers have to measure the forces transmitted to the foundations during the impact. Usually the systems to measure the forces on the foundations consist on a data logger connected to different load cells disposed on all the main foundations of the barriers: post bases, upslope cables and lateral cables. Even if ETAG 027 requires that foundations forces must be measured during the full-scale tests, the guideline does not define the foundations of the barrier as a component of the rockfall kit. The reason is due to fact that barriers are never installed in the same type of soil (loose soil, rock, etc.), thus every barrier should have its proper anchoring system.

Barrier foundations should be designed considering the forces directly measured or calculated by the crash test (Turner et al., 2009). Foundations must be designed taking into account the forces transmitted to the structure during the MEL impact (for both the Serviceability and Ultimate Limit State Design) (Table 3), the geotechnical parameter of the ground and the national standards.

The anchoring systems of the rockfall barriers can be divided in 2 categories:

- Bracing cable anchors (lateral and upslope, if any): the pull-out forces act on this anchoring system. Usually double-legs cable anchors are used. They perform very well due to their flexibility and capacity to follow the direction of the pull-out force, which are never aligned to the direction of the anchor. For soils difficult to drill, other solutions may be adopted (e.g. self-drilling hollow bars);
- Post anchors: are generally composed by steel bars and/or micropiles, depending on the type of soil. They have to contrast the compression and shear forces transmitted by the structure.

Table 3. Values of the forces acting on Maccaferri 8,600 kJ (RMC 850/A) fence during the MEL crash test. Designers should consider these loads for their designs.

| Type of anchoring system | Value | Type of stress |
|---|---|---|
| Post | 626 kN | Compression |
| | 436 kN | Shear |
| Upslope bracing cable | 292 kN | Pull-out |
| Lateral bracing cable | 294 kN | Pull-out |

The anchor systems are considered passives, because they start to work only if they are stressed by the impact, no pre-tensioning is required. They are installed in drilled-holes and they are full grouted along their entire length in order to develop the maximum friction anchor-grout and grout-soil (bond stress). The length and the diameter of the anchors, as well as the drilling diameter, depend on the design requirement (Grimod et al., 2013).

Many times problems arise for the post foundations, because they are usually built where heavy machineries cannot operate and where the material transportation is very difficult. In these cases, these foundations become more expensive than the barrier itself and the intervention with rockfall barriers might be rejected because it is not cost-effective. Moreover, when a severe impact strongly damages a barrier, for safety reasons, the whole structure, including the foundations, must be replaced.

Several field experiences show that when the barrier is stressed at its maximum capacity (MEL), the damages are very severe. Therefore, re-build a new barrier is cheaper and safer than fix the impacted one. Even if after a large impact the damages seem to be light or negligible, the probability of micro ruptures on cables, posts, meshes and connection components is very high. Therefore, the barrier anchors could suffer of any type of cracks especially on the pins connecting the footplates. Opposite is the fence behaviour hit by a SEL impact. In this case, the damages are usually small and the required maintenance is negligible. The anchoring systems usually do not have any damages and rarely anchors need to be replaced.

It can be underlined that, thanks to the flexibility of the whole barrier made of steel cables and mesh, the post foundations could be designed accepting settlements. Strong concrete plinth designed for MEL impacts, appears really redundant and not cost effective. Moreover, the stiffness of the concrete plinth might cause issues on the fence, because the bottom of the post is not able to deform as much as the upper portion. Thus, a "deformable" foundation helps to dissipate energy and make the barrier safer. This concept forces structural engineers to change drastically their mentality during rockfall barriers designs. In these terms, the concrete plinth have to be thought as aimed at getting a regular support surface and make easier the installation of the footplate. Its construction should be fast and easy in any environmental condition. The plinth contribution to the bearing capacity of the footplate may be negligible. With this approach, the contribution of the foundation concrete block can be neglected and settlements should be considered acceptable even if they are too large that those usually considered acceptable for a standard building foundation.

The steel bars must directly connect the footplate to the ground (Figure 14-right). If the barrier is installed in a uneven soil, a small concrete plinth (generally 50x50x50 cm) is foreseen to give a flat base to the post (Figure 14-left). In these cases, the bars must pass throughout the small plinth in order to allow the support of the footplate and in the meantime, to make the foundation more flexible. Using flexible anchors the risk of ruptures on the footplate and of the collapse of the barrier is reduced. In this way, the rockfall fence can maintain an appreciable residual height, and consequently increase the level of safety after the first impact.

Figure 14. Example of post base systems. Left: a small concrete plinth has been realized to give a flat base to the post. Right: the base plate is directly installed on the ground.

This thesis was supported by several case studies analyzed worldwide. Barriers with "light post anchoring systems" were able to withstand impacts higher than the nominal one of the fence (e.g. Figure 15: km 425 HWY A3, Municipality of Scilla, Italy). It has been reported that the weakness of the footplate, which sunk into the ground, allowed dissipating the energy of the impacted blocks.


Figure 15. Settlement of the footplate after the impact. The vertical ($\Delta$y = approx. 200 mm) and the horizontal ($\Delta$x = approx. 50 to 100 mm) displacements of the base plate represent a benefit for the energy dissipation of the fence.

This concept is effective in these fences with upstream cables. In fact, the upslope bracing cables are able to transmit the stopping force from the interception structure directly to the soil reducing the efforts on the post. Furthermore, the benefit of this new design approach is obtaining cost-effective structures able to dissipate energy, increase their performances during the impact, and be easily repaired if an impact occurs

According to the concepts highlights in this paragraph, it is possible to state that instead of “post foundation” it would be better to talk about “post base system” or “post anchoring system”. The system should be designed not as a massive foundation able to adsorb completely all the impact forces but like a light base that can accept deformations and displacements during the impact.

## 4 CONCLUSION

Rockfall barrier manufacturers test their structures in accordance to the European Guideline for Technical Approval (ETAG 027) issued in 2008 by the European Organisation for Technical Approval (EOTA). Nowadays, the guideline represents a milestone for the rockfall market worldwide, because it defines a standardized methodology that producers may follow to test their fences at the full-scale. Barriers that pass the full-scale test may obtain the European Technical Approval (ETA), which is an official document reporting all the performances of the barrier during the test. ETAG 027 is essentially the only test and construction framework utilized by manufacturers and presently it constitutes the base for tenders worldwide.

The European Guideline does not define how the different components of the fence must be produced and/or assembled, but it ensure that the entire tested “kit” is able to stop a certain energy level. In this way, it is easier and quicker comparing all the performances of different structures (from different manufacturers) having the same nominal energy capacity.

According to ETAG 027, the tested deformable rockfall barrier must be impacted in only one specific configuration. In fact, the test-block (having predefined shape and weight) must hit the center of the central span of the fence (composed by 3-spans) with a velocity no lower than 25 m/s (approx. 90 km/h). Unfortunately, real in-situ conditions are normally extremely different from those at the test facility: rockfall events frequently generate multiple impacts, which may stress the barrier in any point (i.e. impact on the post, lateral span, upper longitudinal cable, etc.). Therefore, the design of these types of structures is really difficult and complex.

The simples and easiest way to design a rockfall barrier consists in comparing the energy level calculated during the rockfall simulation analysis with the results obtained during the crash-tests. This calculation approach presents a lot of uncertainties related to: the reliability of the input data used for the simulation, several installation issues, as well as, the differences between the configuration and the performances of the tested and the installed fence. To consider all the technical limits of the installed structures, a new design approach was introduced with the Italian Standard UNI 11211:4 (2012), which introduces the concept of the Ultimate and Serviceability Limit State. The forces acting on the fence are increased by partial load coefficients, while the resisting capacity of the fence is decreased by partial reduction coefficients. These coefficients allow estimating the needed energy and height of the fence as well as its minimum distance from the protected area.

Moreover, during the design it must be known the location where the rockfall fences will be built: often remote areas, characterized by very steep slopes, limited accesses, and where powerful machineries cannot operate. Additionally, in these zones, workers are frequently exposed to rockfall hazards. Thus, light barriers, simple to install and with modest anchoring systems, are preferred to heavy and complex fences, founded on large concrete plinth. The paper clarified that light rockfall barriers are not necessarily less performing than other with oversized components. In fact, crash-tests results and real impacts show that some of the lightest barrier available on the market may offer lower elongations and higher residual heights.

Even if the anchoring systems of the rockfall fence are not considered part of the tested kit (according to ETAG 027), these elements are really important for the global behavior of the barrier. In fact, they must be able to dissipate themselves the energy, in order to reduce the damages on the fence during an impact, as well as, the maintenance costs. Therefore, light anchoring systems that may accept deformations and settlements are preferred to massive foundations able to totally absorb the forces transmitted during the impact.

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