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A step forward in the resilience of flexible rockfall protection systems

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Abstract

Rockfall barriers are widely used worldwide to protect critical infrastructure and must safely dissipate large amounts of energy throughout their lifetime. However, current European approval procedures - followed internationally by default- are based on overly idealized test conditions, involving a single block striking the centre of the middle field at either the service or maximum energy level. This setup represents the most favourable geometric scenario and does not reflect the complexity of real rockfall events, where blocks seldom fall alone or hit the barrier centrally. Instead, actual events involve unpredictable combinations of multiple impacts, block rotation, and fragmentation, leading to highly irregular and dynamic load patterns. Consequently, standard tests fail to capture the true demands placed on barriers. This paper therefore remarks the need for improved experimental approaches, particularly tests at critical areas with eccentric, and simultaneous impacts on border fields to better replicate real field conditions. It also highlights limitations in current guidelines, summarises key insights from research and field experience, and presents new findings from recent investigations.

Keywords

Rockfall barriers, European Technical Assessments, Test in critical areas, Eccentric and simultaneous.

1 Introduction

The use of flexible steel barriers to mitigate rockfall hazards first emerged in the 1950s. Early systems were based on triangular wire rope nets (fig. 1) snow avalanche structures (Spang, 2000). In many cases, repurposed anti torpedo nets from World War II (fig. 2).



Fig. 1 Flexible avalanche structure (1950) (Spang, 2000).



Fig. 2 Mine layer ship collecting an anti-torpedo net Norfolk, Virginia 1945 (public domain).

The first use of steel wire rope nets for rockfall protection happened in 1951 in Schafberg (Switzerland), where nets previously used for blast control, was installed as single field rockfall barrier. Häfeli (ETH, Zurich) later introduced the concept of serial structures and developed design methods for flexible wire rope net snow avalanche barriers. Experience showed that snow control structures could also withstand rock impacts during snow free periods. This led Brugg AG, following Bindschädler's proposal, to adopt wire rope nets for rockfall protection. As a result, the world's first flexible rockfall barrier was installed in Brusio in 1958, protecting power lines with nets mounted on wall. A second installation followed in 1959 in Ardez, also built on a concrete wall.

2 From pragmatism to standardization

Flexible mitigation systems design always begins with analytical and numerical models. Those models are not considered valid -and the systems not considered ready for use- until they are verified through full scale (1:1) field test under real conditions, for decades this philosophy has combined practical engineering with scientific rigor. Over time, full scale testing has proven essential for ensuring system safety and reliability. Field experiments have strongly shaped the development of technical guidelines and standards. Due to testing methods have advanced more quickly than the standards themselves, they need to be treated separately. Current regulations still rely on older results, with the latest findings not yet incorporated.

3 Full-scale test methods

3.1 Historical background

The first systematic tests on protective nets were conducted in 1962 in Brunnen (near Lucerne, Switzerland).About 50 kg rockswere thrown from 45 m high, achieving minimum energies of 22 kJ, marking the beginning of the experimental characterization (fig. 3).



Fig. 3 First trial in Brunnen (1962).



Fig. 4 First vertical droptest in Brugg (1976) .



Fig. 5 Brugg barrier testing for Caltrans (1989).

In 1968, following recommendations from the Swiss Railway Company BLS, tests were conducted in which rocks of up to 1000 kg were released toward a three-field wire rope net barrier. In 1975, Brugg AG (Birr), and Heierli Engineering (Zurich), conducted rockfall experiments to support the development of new protection systems (Spang, 2000). Using a truck mounted crane, concrete blocks of up to 1000 kg were dropped freely from a height of 20 m onto horizontally tensioned wire rope nets (fig. 4). These trials marked the first documented use of braking elements. Around the same period (fig. 5), Caltrans (California Department of Transportation, USA) evaluated wire rope net barriers designed to absorb up to 200 kJ (the barriers were provided by Brugg AG, Switzerland and L'Entreprise Industrielle, France). More than 80 tests were executed with rocks ranging from 136 kg to 5900 kg, rolled down a 34° slope over 76 m (Duffy, 1990). Results showed that the barriers withstood impact energies far above their design values, and damaged components could be quickly replaced using standard equipment. This demonstrated early on that flexible barriers were a reliable and efficient rockfall mitigation option for California roadways. Beginning in 1988, Switzerland launched a new series of full-scale field experiments (more than 350 in total) which led to major advancements in barrier design (Baumann, 2002). One of the first Brugg AG test campaigns took place in Oberbuchsiten, using a procedure like the Caltrans experiments: rocks were released downslope with an excavator. Because the test slope consisted of hard rock, impact energies were significantly higher than in the California trials. Six barriers were tested using more than 100 blocks. Luis Fonseca (1995) later performed full scale tests on two flexible net barrier types at Beckenried.

A cable car launch system generated impact energies up to 250 kJ, and extensive instrumentation (including strain gauges) enabled accurate measurement of dynamic and kinetic responses. This setup offered a decisive advantage: high repeatability and precise control of impact parameters, improving the reliability of system evaluation. Collaboration among researchers and four manufacturers during this period drove rapid improvements in barrier technology, increasing energy absorption capacity from about 250 kJ in 1987 to approximately 2,000 kJ by 1998 (fig. 6).

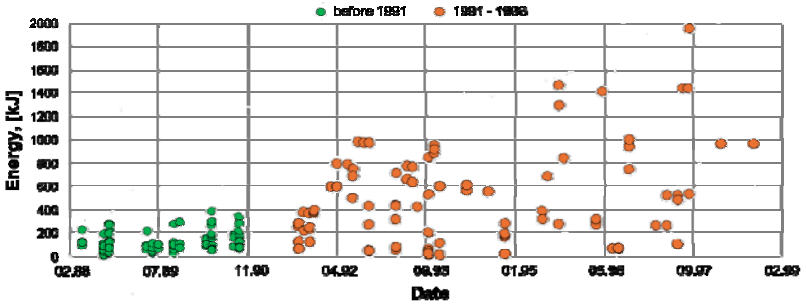


Fig. 6 Rockfall barrier testing in Switzerland from 1988 to 1998 (Gerber, 2025).

Field testing methods also evolved as their limitations became evident. First method (fig. 7.1): rocks were rolled down a natural hard rock slope. However, substantial energy was lost during ground contact, some rocks stopped before reaching the barrier, and impact velocities varied widely (6–24 m/s), resulting in poor repeatability. Second method (fig. 7.2): at Beckenried, a gantry crane with an inclined cable track allowed more controlled rock release. Typical impact velocities ranged from 10 to 22 m/s with realistic translational and rotational components. Nonetheless, impact height and angle still varied, and blocks consistently struck only the middle portion of the barrier. Improved method (fig. 7.3): introduced in 1991, using an inclined cable car system with a guillotine release mechanism. At a predefined point, a secondary rope was cut, allowing the block to travel directly toward the barrier without ground contact. This method achieved velocities of 25–27 m/s in Beckenried and 29–31 m/s in Giswil. In 1998, a similar facility was constructed in Italy (Peila, 1998). Blocks were guided by a cable car system, and an explosive charge severed the lifting rope at the release point to produce a direct impact. The monitoring system was comparable to the one supplied by the University of Cantabria for the Beckenried site (Luis Fonseca, 1995; Ballester et al. 1996). Although this method improved test control, results from some European facilities such as Trento in Italy, were later questioned due to unintended ground contact or unplanned rock braking during impact.Muraishi and Sano (1999) presented a Japanese certification method combining static laboratory tests with full scale slope tests, where a boulder is dropped from a crane onto a barrier on a 35° slope, producing a 55° impact angle. The method uses four test types -basic, cumulative, maximum load, and special component tests- captured with high-speed cameras. They concluded that this free fall approach is the most reliable because it consistently reproduces impact location, angle, and energy, ensuring repeatable performance evaluation. In 2000 the FOEN (Swiss Federal Office for the Environment) initiated the development of a certification procedure for rockfall barriers and introduced a fourth testing method (figs. 7.4 and 8) to overcome the limitations of previous approaches.

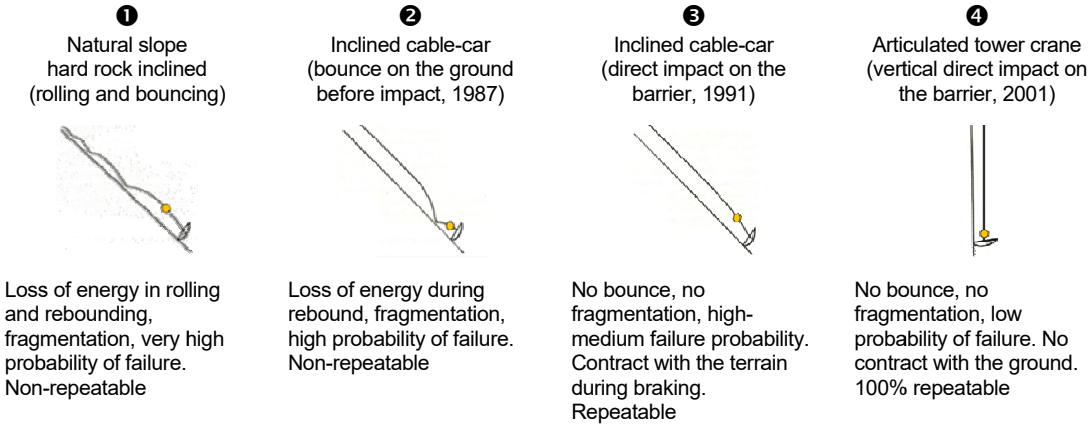


Fig. 7 Classification according to the test method generations (modified from Baumann, 2002).

A permanent test facility in Lochezen (fig. 8) uses a tower crane to drop a controlled concrete block onto a barrier fixed to a vertical rock wall, allowing precise control of impact conditions. The setup

ensures constant impact positions, avoids ground energy losses, and includes video and detailed measurements, improving test reliability and repeatability. The introduction of this evaluation method significantly improved test quality, repeatability, and overall reliability. Between 2001 and 2007, FOEN certified 24 barriers (Gerber, 2025), each tested at both the Maximum Energy Level (MEL) and Service Energy Level (SEL= 50% MEL) and with MEL values ranging from 100 to 5000 kJ.

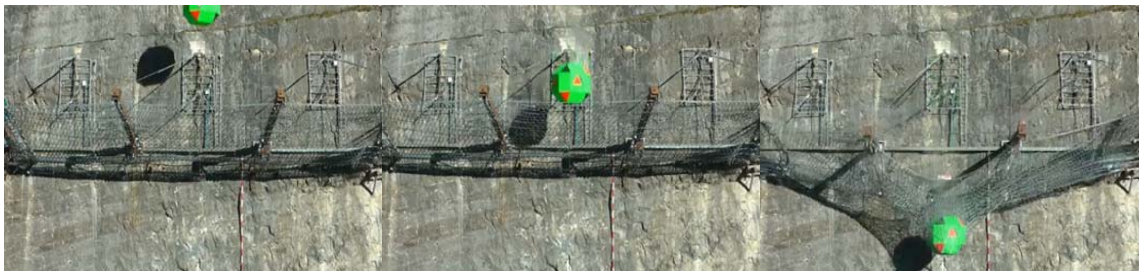


Fig. 8 Vertical test at Walenstadt during April 2025. 12.5MJ barrier (block 25t, v = 32m/s).

In 2018, based on the results of previous experiments, FOEN proposed a more detailed analysis of the braking process and load transmission for both energy levels (SEL and MEL). Figure 9, shows a vertical test on a 2000 kJ barrier (using a 6400 kg boulder impacting at 25 m/s) showed a braking time of 0.4 s, traveling 5 to 7 m within the net elongation path, and a total contact time of 0.56 s. This detailed evaluation highlights the importance of understanding the full braking phase to improve the accuracy of system performance assessments.The variation in braking forces and block deceleration can be measured throughout the contact time with the net, during both the inbound and outbound phases (fig. 10). The measurements show that if maximum deceleration occurs early in the braking phase, the braking distance is short; if it occurs later, braking distance becomes longer.

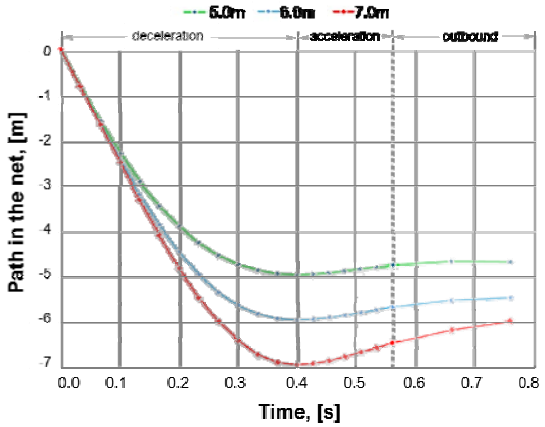


Fig. 9 Braking process in a vertical test 2000kJ of energy (modified from Gerber, 2025).

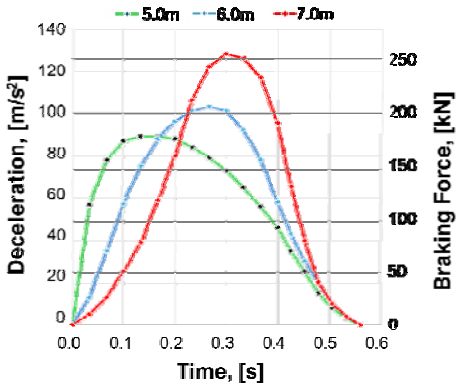


Fig. 10 Deceleration and braking forces at contact time (modified form Gerber, 2025).

3.2 Contrast needed

Natural-slope testing is essential because vertical drop tests (fig 11b), while useful for measuring basic parameters such as impact energy and component performance, many times do not replicate real rockfall behaviour. On a slope, blocks accelerate, bounce, rotate, strike at oblique angles, and often undergo multiple impacts before reaching the barrier, altering their velocity, direction, and impact energy. Natural-slope tests capture ground-barrier interactions and complex dynamics that vertical tests cannot reproduce. They verify the proper activation of energy dissipators and ensure that vertical-test results remain valid under real operating conditions. Between 2019 and 2020, full-scale (1:1) natural-slope tests were conducted at Chant Sura, Flüela Pass, Switzerland (fig. 11a), revealing the real-world effects of eccentric and critical areas impacts.



Fig. 11 Tests on natural slope and vertical drop, equant shaped boulders.

These experiments also demonstrated how block rotation, shape, and size significantly influence random impact energy and load distribution on the system. Thirty experiments were conducted using boulders of different shapes and weights from 320 to 840 kg. After several initial ground contacts, the boulder's behaviour changed significantly once it interacted with the barrier, as the catch membrane's distinct mechanical properties altered the impact angle and rendered ground-based interaction models no longer applicable. The tests showed that oblique impacts increased stresses at the post heads due to added tangential forces, while the blocks' kinetic energy was reduced by up to 67% along their trajectory because of friction, bouncing, and ongoing contact with the ground. Additionally, off-centre impacts led to a more asymmetric load distribution, causing forces in the upslope retaining ropes of the border fields to rise by about 33%. Overall, these findings emphasize the strong influence of impact angle, rotation, and block–terrain interaction on the loading experienced by the barrier (fig. 12).

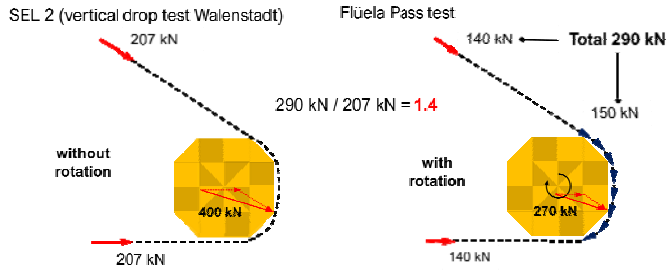


Fig. 12 Comparison vertical drop test (left) with Flüela pass natural slope field test (right). Lower energy in the field testleads to higher forces compared to the vertical test.

3.3 Latest trends at full-scale tests

A series of complementary vertical impact tests were carried out in Walenstadt, Switzerland, following lessons learned from the slope tests at Flüela Pass (Caviezel et al. 2022). These tests aimed to reproduce the barrier loads and deformation observed and to assess how well standardized test setups can simulate real impact conditions. Using the European-prescribed boulder mass and minimum impact velocities, different configurations were examined to determine whether equivalent or substitute loading conditions could reliably represent actual barrier performance and meet user safety expectations. **MEL-E** is a three-field test, with a boulder impacting in a top corner of the centre field (Eccentric), the impact energy also aligns with the 100% MEL value (fig. 13).

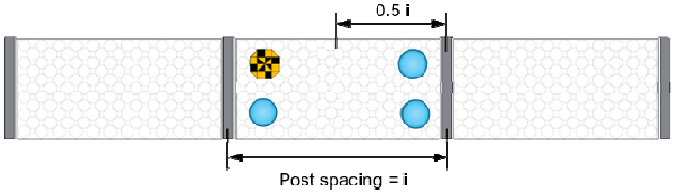


Fig. 13 Eccentric impact at MEL, in the top corner, near the midfield post head of a three-field system.

Tests conducted near the post head, showed increased loads on both the net and the retaining ropes. Because impacts in the upper corner apply greater stress to these components, an asymmetric test configuration is required. The MEL-E test demonstrated 20–30% higher forces in the upslope ropes and a 49% higher braking force compared to the standard MEL test. These results indicate that MEL-E is the most appropriate test to replicate the field-observed behaviour of rotating blocks, which generate asymmetric and high loads. **MEL-S** is a Single field test, where a test boulder impacts centrally within a single field barrier (made up of two posts only). The impact energy aligns with the 100% MEL value (fig. 14).



Fig. 14 Single field impact at MEL, corresponding to an extreme field impact.

Because the MEL-S setup uses a smaller net area and fewer energy-dissipation devices, the barrier must withstand the same impact energy with less components. Tests showed that upslope-rope forces in MEL-S were 26% higher than in the standard MEL, and the remaining U-brakes absorbed 46% more energy. Comparing MEL-S with MEL impacts in the border field revealed similar upslope-rope

forces and no asymmetric energy absorption in the brakes. Overall, MEL-S is the more demanding load case, effectively confirming the proper functionality and robustness of the barrier's border field (fig. 14 right). In addition, internal tests have been conducted per Geobrugg considering two other critical points of the barrier, trying to replicate the impacts seen in the field over the years and the experiences at Flüela, two types of tests are shown in: **rope separation** inside barriers and **direct impacton a post** (Roduner et al. 2023 and TSÜS, 2020).Internal tests on barriers confirm that rope separation area, including brake elements, exhibit high strength, good energy absorption capacity, and controlled deformability. The brake function as main elements in the redistribution and dissipation of impact loads before arriving to the ground anchors or protect the entire length of the barrier by dividing it in sections. The observed deformation modes match with design models. After certifying a 3000 kJ barrier with a MEL and two consecutive SEL impacts, further SEL hits were launched in various locations, trying to replicate impacts observed in the field over the years (Roduner et al. 2023).The **direct impact on post** (free fall test on profile HEA 120) it was done on a 500kJ barrier type GBE that successfully stopped the boulder fell at SEL (m = 580kg, v = 25m/s). Tests results and numerical simulations (Pimpinella, 2025) show that when a post is struck directly, a plastic hinge forms in the steel profile (figure 15). Although this may not compromise the barrier's performance during that specific impact, it weakens the post for any subsequent impacts because the flattened section has reduced bending resistance. Additionally, the permanent deformation of the post lowers the barrier's effective residual height.



(a) (b) (c)

Fig. 15 Steps of the numerical simulation: (a) t = 0.085s (b) t = 0.125s (c) t = 0.450s

Further vertical tests -particularly those examining **rope separation**- are crucial for understanding how flexible components behave under extreme loading and how energy is redistributed when a rope fails. These tests confirm the system's redundancy and ensure that containment performance remains intact. Likewise, direct impact tests on posts are essential to evaluate their structural strength, controlled deformation, and interaction with anchors and ropes. Together, these complementary tests provide key insights for improving barrier design and guaranteeing reliable performance under high-energy rockfall conditions. The **MEL–M** is a three-field test, with two test boulders impacting simultaneously (Multiple Simultaneous Impact) into the centre, and border field (Geobrugg, 2025). The total impact energy of the two impacts shall correspond to 100 % of the MEL energy, with each block carrying 50 % of that energy. Both impacts shall occur simultaneously, within a time difference not exceeding 0.1 s between first and second contact (fig. 16).

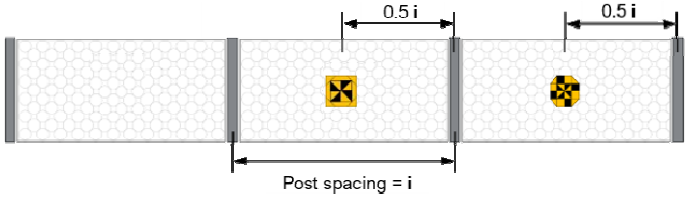


Fig. 16 Two boulders release simultaneously.

A 3000kJ barrier test was performed to validate its behaviour in the multiple impact test, simultaneous fall, and impact (fig. 17) of two boulders of 4800kg mass at 25m/s (using Swiss and European standardised equant shape boulders each with 1500kJ service energy).

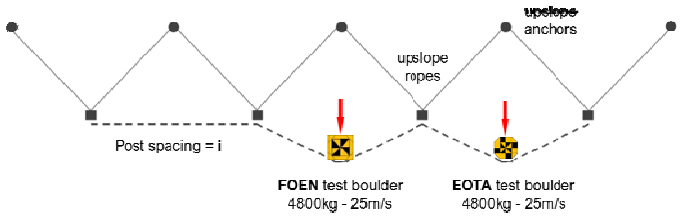


Fig. 17 Scheme of the two boulders released at service level.

Due to the multiple asymmetrical loading of the system of the fields 2 and 3 the post number 3 is subjected to high stress as the support rope is deflected on both sides of the post (like MEL-S test). Further the tension of the ring net on both sides of the post 3 causes the support head and the upslope ropes to experience high loads and no openings of the net occur ad post head (fig. 18). To address fragmentation-related issues, some guidelines recommend reducing a barrier's rated capacity by one-third (MBIE, 2016). However, this simplification is insufficient, as empirical evidence shows barriers can still fail under eccentric impacts at service-energy level.



Fig. 18 Simultaneous impact on two barrier fields (mid-field and extreme field).

Summarising: **MEL-S** as reference for maximum energy absorption for border fields, post stability, and overall structural performance under a symmetric load. In contrast, the **MEL-E** test simulates an eccentric impact in the upper area of the middle field, close to the post head and upper support ropes. This eccentric test simulates the effects of rotating blocks and off-centre impacts, which introduce tangential forces and increase stress at the post head. Using both MEL-S and MEL-E configurations allows assessment of the barrier's energy absorption performance across its full width, covering both symmetric and asymmetric loading conditions. **MEL–M** consider fragmentation and multiple impacts.

4 Regulations. Timeline and status

In the early 2000s, the absence of unified international standards for evaluating rockfall barriers led different countries to establish their own testing approaches. Switzerland introduced a national certification procedure in 2001(Gerber, 2001), later revised in 2006, which became widely adopted internationally, while Italy developed a non-mandatory guideline. Building on the Swiss methodology, European Organisation for Technical Assessment (EOTA) published ETAG 027 in 2008 (ETAG, 2008)to harmonize testing across Europe, later allowing inclined test setups and defining SEL as 33% of MEL before being transformed into European Assessment Document (EAD) 340059-00-0106 in 2018, though its implementation varies among EU countries. Despite these developments, the Swiss approach remains the most stringent and reliable. A key limitation across all standards is that foundation design has never been included in certification, leaving it to contractors based on manufacturer test data. The 2003 AASHTO recommendations emphasized the necessity of full-scale testing due to the limitations of numerical models and compared impact methods, highlighting vertical free-fall tests as the most accurate (Higgins, 2003). Finally, Austria's ONR 24810 (2021) introduced strict requirements to ensure barrier integrity since 2013, including preventing openings, controlling deformation, and enforcing maintenance and inspection to guarantee continuous protection.

4.1 Swiss complementary guidelines 2018 & 2022

Until January 31, 2018, the Swiss "Guideline for the Approval of Rockfall Protection Kits" governed certification, with public funding limited to compliant systems. In 2018, FOEN introduced a complementary guideline to help assess whether commercially available barriers meet project-specific requirements, particularly regarding foundation design, which is not addressed in current European standards. Although ETAG 027 (2008), later converted into an EAD in 2018, established the framework for testing and CE marking-placing responsibility on manufacturers-some regions still require higher safety levels than those defined in EAD 340059-00-0106. Research and full-scale tests by Geobrugg and WSL, supervised by TÜS, demonstrated the need for more realistic testing conditions, including zone-specific impacts and block rotation, presented in Caviezel et al. (2022), significantly improving the evaluation - design of rockfall protection barriers.

4.2 Requirements, according to the complementary guideline of the FOEN 2018

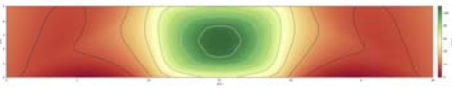
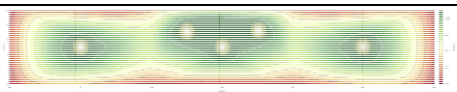
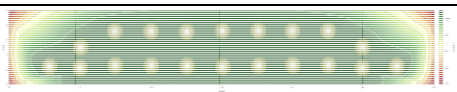
The FOEN (2018) complementary guideline sets stringent criteria to ensure that rockfall protection barriers and their foundations deliver reliable performance in real projects. Only systems meeting all requirements -without weak components such as undersized anchors- are considered sufficiently safe. The evaluation uses the manufacturer's European Technical Assessment (ETA) and technical

documentation to assess key factors including block trajectory, impact energy, deflection, braking distance, anchorage performance, residual height, slope angle, and any intermediate supports. A central requirement is the residual height (h_R), which must remain at least 50% of the nominal height after the MEL test, and 65% for oblique-impact tests. The maximum braking distance (w) is linked to MEL energy and defined through FOEN's logarithmic expression: $w = 1.534 \cdot ln(MEL\ [kJ]\ ) - 3.06$ [m]. Barriers without intermediate brakes must be limited to 60 m in length, and any system failing to meet FOEN requirements should not be used. The FOEN (2018) guideline expands on the ETA and provides a more comprehensive framework to ensure the quality, safety, durability, and real-world suitability of rockfall barriers, with particular focus on anchoring systems and foundation design.

4.3 Additional requirements, according to 2022 supplementary guidance

Since 2020, Geobrugg and WSL have developed extended full-scale test programs to address new market demands and increase the safety factor of rockfall barriers, as emphasized by Caviezel et al. (2022). These programs include specific impact field tests that go beyond FOEN (2018) requirements. Current standards validate impacts only at the centre of the barrier, creating a 'safe zone' of guaranteed performance. However, safety decreases as real impacts deviate from this area. Table 1 highlights the safety levels of existing certified systems and the additional FOEN requirements.

Table 1. Perception versus reality of the current level of security of the barriers.

Outline	Perception versus reality
	barrier resolves 100% of the impacts in its entire catchment area (**perception**)
	current regulations only guarantee the absorption of energy in the centre of the central field, according to all current directives (**reality**)
	the eccentric (MEL-E) and critical areas (MEL-S) trials proposed by Switzerland in 2022, increase the safe zone (**reality**)
	multiple impact tests (MEL-M) and additional tests at critical points, enlarge interception area (**reality close to perception**)

The regulatory process -while essential- evolves more slowly than scientific and technological developments. For this reason, the standard EAD 340059-00-0106 currently in force in all EU member countries, including Norway, Iceland, Liechtenstein and Switzerland it also recognized worldwide as main technical reference. Table 2 provides a summary of the recommended rules, which shall be applied (the last two recommendations could be optional).

Table 2. Design criteria for a safer application of rockfall protection kits.

Criteria	Entity leader
EAD 340059-00-0106. Class A h_R control	EOTA
vertical free-fall testing at both energy levels: SEL and MEL	FOEN, EOTA
maximum elongation control	FOEN
post-impact openings control	ONR
MEL-E eccentric impact test	FOEN
MEL-S single-field or border-field impact test	FOEN
MEL-M multiple-impact	Geobrugg
direct impact on post-test (optional)	Geobrugg
impact on rope separation test (optional)	Geobrugg

5 Conclusions

Current rockfall barrier certification does not reflect real-world rockfall behaviour, as it only evaluates centred, single-block impacts and ignores eccentric loading, block rotation, multiple impacts, and terrain interaction—all of which generate significantly higher forces, especially in posts and border fields. Full-scale slope tests such as those at Flüela Pass reveal critical behaviours missed by standard procedures, including 20–30% higher forces in upslope ropes and increased loads in edge zones. New complementary tests (MEL-E, MEL-S, MEL-M) better reproduce real loading scenarios by assessing eccentric impacts, multiple simultaneous impacts, and stresses on key components like rope partitions and posts. Because the current EAD standard omits foundations, anchoring, eccentric impacts, angular velocity, and multi-block effects, additional requirements from FOEN (2018); Caviezel et al. (2022)

and Geobrugg (2025) are crucial. Combining vertical, eccentric, extreme, multiple, and zone-specific tests greatly expand the barrier's verified safe area, resulting in higher reliability, better-designed components, and improved real-world safety. It is probably time to think about a new EAD release.

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