DOI: 10.5592/CO/HG.2026.17

WORLDWIDE EXPERIENCES IN FLEXIBLE DEBRIS FLOW BARRIERS

CORINNA WENDELER[1], ROBERTO LUIS-FONSECA[2], MARKO BORIČEVIĆ[2], MATTHIAS DENK[2], EBERHARD GRÖNER[2], VJEKOSLAV BUDIMIR[2]

[1] *Canton Appenzell Ausserrhoden, Switzerland*

[2] *Geobrugg AG, Switzerland*

Abstract

In the last 18 years, more than 300 flexible barriers composed of ring nets have been installed for protection against debris flows and for the stabilization of channel banks, in more than 25 countries. This has made it possible to protect population centres and infrastructures, such as roads and railway lines, from great damage. These barriers have been established as a certified European product that has obtained CE marking. This contribution relates to the evolution of the first of these barriers tested on a full-scale, which led to the current systems of standardized barriers, and which have allowed the execution of multiple successful projects in full operation. Through case studies, the advantages and challenges of this technology in terms of construction technology, economic aspects and an environmentally friendly approach will be highlighted.

Keywords

debris flow, flexible barrier, ring network, CE marking, monitoring

1. Introduction

Full-scale trials conducted in Illgraben, Switzerland, between 2005 and 2008 demonstrated the feasibility of retaining solid materials carried away by debris streams. The study begins by analysing the efficiency of some of the first pilot projects, most of which were installed in Switzerland. Then, in collaboration with the Federal Institute of Forestry, Snow and Landscape (WSL), a design procedure or methodology was established that considered load combinations. Finally, its use was systematized or standardized based on the simulation of the behaviour of the high-tensile strength flexible assembly with the support of FARO software. To verify and calibrate the results of the software, data from the full-scale trials were used.

Following this development, ASM 4:1 flexible ring net barrier[1] became an efficient alternative to classic solutions against torrential debris flow phenomena in Europe, USA, Asia, Australia and South America. In large-scale projects, where the barriers were installed in a row in the same channel, the retention efficiency of large volumes and the feasibility of this type of installation in a phased manner were also tested. Designers and engineers appreciate flexible barriers, as they are an efficient, practical and economical alternative to existing classic debris flow protections[2].

Eighteen years of experience with flexible barriers means that the market has recognized its advantages as its efficiency has been demonstrated in the field. The growing knowledge of individual barriers staggered, and

[1] interlocking ring networks arranged in such a way that each inner ring is in contact with four neighboring rings
[2] gravity check dams: rigid reinforced or mass concrete, reinforced earth, or semi-rigid gabion

large barriers has made it possible to understand the advantages, but also the limits, of a barrier system of this type for the retention and control of debris flows. This acquired knowledge is presented in the following work, accompanied by case studies.

2. Full-scale testing at Illgraben, development of standard barriers and CE marking

2.1. Full-scale tests at Illgraben

Between 2005 and 2008, full-scale trials were carried out in the Illgraben canal, Wallis, Switzerland (Wendeler, 2008). In these tests it was observed that the rockfall protection barriers retained some landslides and solid materials resulting from debris flows, then the first of the approaches was energetic. The field observation caused this analogy to be discarded, as it did not effectively describe the load combination to which the barrier is subjected. A robust dimensioning concept was simply missing to demonstrate that flexible barriers composed of ring networks could retain larger debris flows in a channel without damage (Wendeler, 2008). In Illgraben, a medium- to large-sized event occurs at least a couple of times a year naturally and therefore the flexible solution could be tested very frequently (fig. 1). With the tests, two key characteristics were defined and analysed: on the one hand, a single barrier could, depending on the geometry of the channel, retain more than 1000m^3, on the other hand, it was observed that more than 10,000m^3 flowed over the barrier without causing damage. This allowed for the design and construction of a retention system composed of several stepped barriers (in a row) to successfully retain most of the material.

Figure 1. Testing of the flexible system in the Illgraben canal, Switzerland 2006. Approximate retention volume 1000m^3

About dimensioning, it was possible to determine the entity of the maximum impact pressure[3] that acts on the back of the barrier during an event, which allowed the development of the work (Wendeler, 2006), which led to the concept of final dimensioning (Wendeler, 2008).

2.2. Development of standardized barriers

The dimensioning concept and load distribution on the barrier were incorporated into the finite element software FARO (Volkwein, 2004), which was subsequently used to design the first projects—primarily located in Switzerland. After the first projects, standard barriers were designed with a certain load capacity in kN/m^2. The standardized VX type barriers are designed for channels up to 15m wide and barrier height up to 6m, supporting loads of up to 160kN/m^2. UX barriers find their application in wider channels, are installed with

[3] combination of quasi-static and dynamic stresses

posts, a barrier height of up to 6m and support loads of 180kN/m^2 (Geobrugg, 2016) (fig. 2). The state-of-the-art dimensioning concept for debris flows is available free of charge via the DEBFLOW software. This software allows a first estimate to be made for the dimensioning of a barrier or set of staggered barriers.

Figure 2. Barrier against debris flow, type UX with posts for the application of wider channels. Trachtbach, Switzerland. Along the riverbed, anti-scour protections (breakwaters and poor concrete) were also placed.

2.3. CE marking

Full-scale testing (1:1) was the basis for developing and certifying a standardized barrier system. The certification process was developed during 2017. The CE marking is based on a "European Assessment Document" (EAD 340020-00-0106) that precisely defines the suitability, type classification and annual quality controls required to meet a given standard (fig. 3). It establishes that products with CE marking comply with the European guidelines for product quality and field suitability (ETA 17/0268-17/0276 and ETA 17/0439).

Figure 3. EAD 340020-00-0106 where the maximum impact pressure p_s in kN/m^2 is established as a main dimensioning parameter

3. Dimensioning tools

The pre-dimensioning of a standard flexible barrier up to 6 m high can be easily carried out with the help of the DEBFLOW software. A more complex scenario requires the technical support of specialists who can dimension the barrier using FARO simulation software (Volkwein, 2004) and select its location within the course based on advanced 3D design tools such as RAMMS: DEBRIS FLOW (fig. 4). Section 6 presents some examples related to the construction of various typologies of this solution.

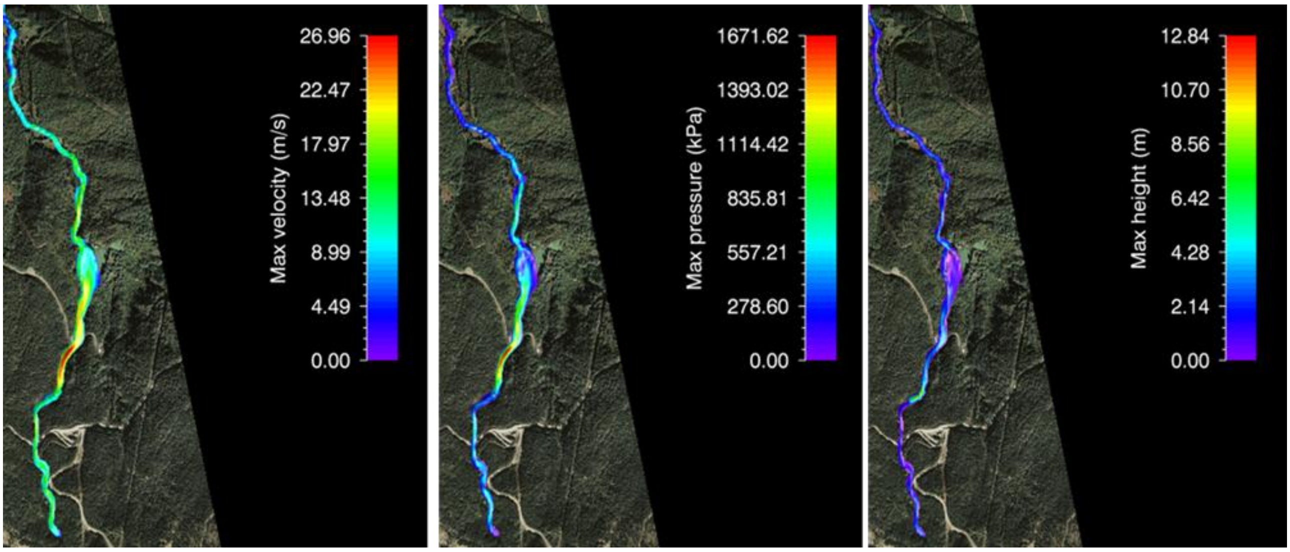

Figure 4. Example of simulation with RAMMS::DEBRIS FLOW. Retrospective analysis of the spread of a debris stream. Portainé Spain

3.1. Load combinations, such as snowslides and rockfalls

In certain cases, mostly steep terrain with steep slopes (> 35°) and at high altitudes, you will find snowslides, small avalanches/purges or rockfalls, which could or will impact the barriers. An example of this situation is the installation of multiple concatenated barriers in Hasliberg, Switzerland. Some of the barriers are located above 2000m a.s.l. Since flexible barriers are also used as avalanche and rockfall protection, a certain degree of combined load can be guaranteed. The combined load can be calculated and a barrier sized for each specific case by using the FARO (fig. 5) simulation software (Volkwein, 2004). Barrier-specific components can be rationally resized according to the simulation results (Wendeler, 2014). Figure 5 shows the simulated load case for barrier number 2 in Hasliberg (fig. 6) in a lateral avalanche impact situation, with an angle of 10° and a quasi-static load on the back of 120kN/m^2. In this special case, the retention ropes to the mountain can be loaded up to 70% of their capacity. Figure 6 shows the snow load on the barrier in winter.

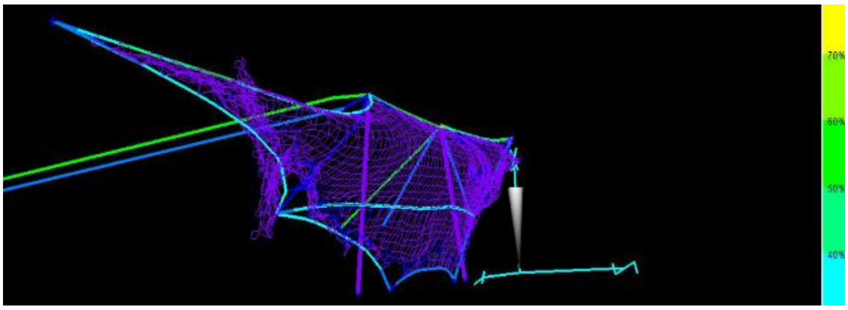

Figure 5. Graphical output of FARO simulation software, avalanche-affected barrier in Hasliberg, Switzerland

Figure 6. Barrier in Figure 5, partially covered with snow during the winter. The snow load must be considered for the final setup of the barrier. Hasliberg, Switzerland

4. Construction aspects

4.1. Ground conditions, foundation and anchoring

While the net itself is easy to model and size, secure anchoring is more complicated. Ideally, a detailed geological profile of the section to be protected is available, as well as the geotechnical parameters of the terrain. Having the possibility of carrying out tensile research tests on anchors, to evaluate the friction between the drill wall and the grout is very advantageous. Debris flow deposits are usually heterogeneous in nature and are deposited along the banks of the channel affecting the quality of the foundation soil for anchoring. The anchors calculation must be carried out by experts according to the expected loads. In case the drill parts are unstable due to the type of soil, it is recommended to use self-drilling anchors combined with a flexible anchor head. When loaded, the barrier is greatly deformed and the forces of the ropes on the anchors can change up to 30° in angle. This eccentricity without a flexible anchor head is not bearable for a normal anchor composed of threaded bar reinforcement, as its shear strength is lower than the tensile component.

4.2. Anchors after a debris flow event

Without further stabilization of the flanks, a certain degree of deterioration (washing) can be observed along the margins, especially in loose soils (fig. 7). If necessary, the net can be replaced, technically the anchor can be reused, if the upper part has been subjected to scour, it is possible to trim the excess section of bar and place a new flexible head near the surface of the ground, but not without first carrying out a load test, to find out if the remaining length is sufficient. If the initial length – drilled to accommodate the anchor the first time – had an appropriate safety factor, there is therefore a certain remaining length in reserve. In the case of frequent filling of the barrier, it is recommended to design the anchors with sufficient length and/or to avoid was undermining of the margins with structural countermeasures.

Figure 7. Washed side anchorage, barrier in the Illgraben canal, Switzerland. Partial lateral anchoring in loose material and old disused concrete breakwater

4.3. Structural countermeasures: protecting margins

Margin washing and erosion are frequent when an event occurs, especially in curves along the course. The extent of erosion depends on the volume carried away, its granulometry and the velocity of the flow. Depending on the project, reinforcement of the outer margin (breakwaters, concrete wall, gabions) or additional stabilization of the margin by flexible membrane systems, with or without erosion control geomantles (fig. 8), should be considered.

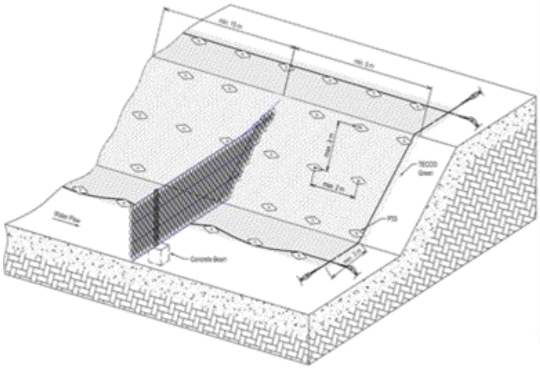

Figure 8. Slope stabilization system to control margin scour in loose material

It is important to take into consideration that the shear stresses generated in debris flow events are much greater than those that can be generated by "clean" water or a hyper-concentrated flow and this should be incorporated into the design calculation for protection measures.

4.4. Control of scour in bed and margins

Typically, scour can occur around the concrete bases that support the posts (UX) and on the margins where the side anchors are housed (VX-UX) due to sediment erosion and causes holes that directly affect the stabilization of the construction. When the barriers are full or partially full, the flow goes to its lowest level. Even hyper-concentrated flow events can occur with little solid material, but at a high speed. The optimal point of flow exit as it passes through the barrier would be in the center of the cross-section, however, this assumption is not always achieved. Experience shows that this point varies in the same barrier, from one event to another. On many occasions the current is diverted to the sides, which causes erosion of the banks with the corresponding effect on the lateral anchoring system. To avoid this undermining, breakwaters, anchored blocks or concrete walls can be placed (fig. 9 left). These solutions, although common, are often difficult to execute, due to the limited availability of local materials and difficulties in access. In this case it is much more efficient to use a flexible stabilization system as shown in figures 8 and 9 on the right.

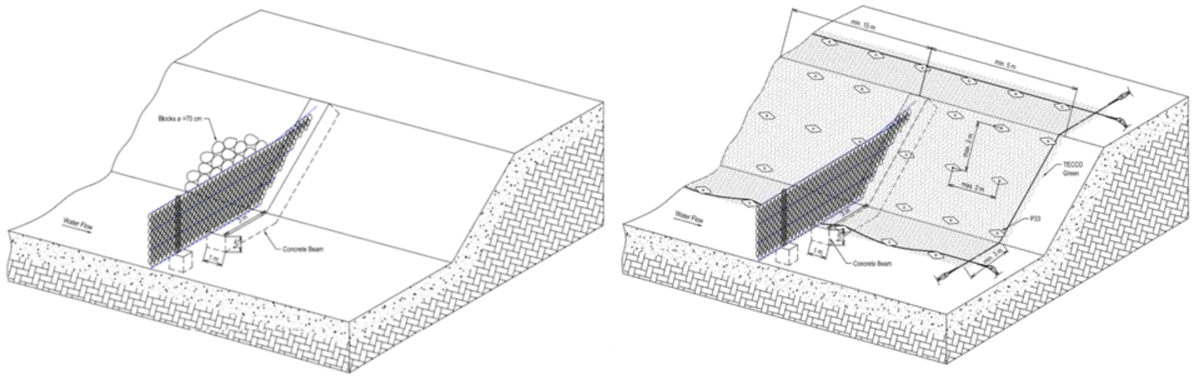

Figure 9. Stabilization of banks with rigid or semi-rigid solutions (rock armour or concrete) or with combined systems

In the case of the use of riprap blocks, when dimensioning the barriers against debris flows, the possibility of the breakwater blocks detaching must be considered. This additional load is potentially important for the barrier. If a stabilization system is to be designed, dynamic load and abrasion factors generated by the flow must be contemplated. Scouring is much more important in staggered stabilisation barrier systems, in which its function is associated with the fact that the filling and overtaking process takes place in all cases, on a recurring basis. When the expected level of scour, both on the margins and in the bed, is very high, and access to the site is adequate, combined solutions can be promoted (fig. 10) in which the flexible barrier of ring nets is inserted into a powerful reinforced concrete frame.

Figure 10. Combined solution. Barraco de la Leña. Tenerife. Spain

In this case, the foundation of the frame is executed with a powerful double row of micropiles up to 8m deep, while on the sides, the frame allows the passage of long spiral rope anchors, which are responsible for carrying the stresses inside the rock mass.

A similar case of combined application has been installed since 2016 in La Comella gully in Andorra, where a powerful reinforced concrete channel was executed, which serves as a guide or channelling of the flow, combined at several points with flexible VX-160 barriers with a capacity of up to 160kN/m^2 (fig. 11).

Figure 11. Combined solution. La Comella. Andorra

5. Basic project considerations

Generally, flexible barriers against debris flow are installed close to the area of origin of the phenomenon (upstream), while larger structural measures, such as a retention pit or diversion dike, are built further downstream. Therefore, both solutions can be perfectly combined and exploit the advantages provided by both procedures. An example of this combination is the gullies of Trachtbach in Brienz and Milibach in Hasliberg, both in Switzerland. In these projects, the combination of flexible upstream barriers with larger construction measures downstream allowed to increase the volume of retention upstream and reduce erosion in the channel. Therefore, the capacity of the protection measures, close to the object to be defended, could be reduced and more efficient structures built on a smaller scale, while the existing protection structures were easily and cost-effectively renovated.

5.1. Protective barriers as an emergency solution

The protective barriers installed in the areas of origin allow events to be slowed down (speed and energy reduction), which provides a longer alert time and possible evacuation in the danger areas. This is especially important in small catchment areas where flows are fast and travel over short distances. The protection barriers are easy to install, therefore practical for an immediate protection solution. They increase the safety of the downstream infrastructures and even allow the protection of the human team that may be carrying out work at the foot of the gully. These protective barriers can also be equipped with an alert system (more details in section 7).

5.2. Visual and landscape aspects

Flexible ring net barriers as opposed to concrete dikes are increasingly a claim when it comes to landscape protection and visual aesthetics. The design blends in and is almost invisible from afar, which is a main argument for the construction of measures in protected landscape areas. An example is the UNESCO World Cultural Heritage along the Rhine River near Koblenz (fig. 12). At the rear of the village, debris flow networks were installed and even with a partially filled barrier in 2017, the barriers are still barely visible, but they serve their purpose (fig. 13).

Figure 12. Almost invisible flexible barrier near Koblenz along the Rhine River above a UNESCO World Heritage village

In addition, environmentally friendly and sustainable construction is increasingly an important argument for construction. For example, a barrier 10m long by 4m high is 30 times lighter than its reinforced concrete equivalent, making it the "greenest solution" (fig. 13). In addition, with less material (less weight), less carbon dioxide is emitted during transport to the site (Wendeler, 2008).

Figure 13. Partially filled debris flow barrier over the German railway near Koblenz

5.3. Free access to minor fauna and natural revegetation

The relatively large openings of ring nets (300-350mm) allow the passage of small animals, when the barrier is not full, even fish when the barrier is submerged in water, in contrast to a concrete structure (Wendeler, 2008). There are several examples in which this was an express requirement of the designer. Flexible ring net barriers are also suitable for greening and integrate seamlessly into the landscape. Their open structure allows revegetation in places where it is possible, being practically incorporated into the environment.

6. Different types of barriers against debris flow

As already explained, flexible barriers against debris flows can be used in two basic functions (fig. 14), the first and most common as a protection measure (individual barriers) and the second as a measure to stabilize the banks and reduce the average slope of the channel, velocity and therefore energy (staggered).

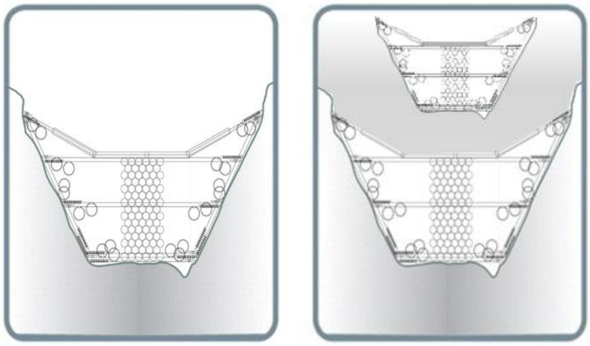

Figure 14. Different functions associated with a flexible barrier. Protection or stabilization

Protection: These are all those measures that are carried out with the aim of protecting a specific object or infrastructure, their main function is to prevent materials from reaching the area to be protected, guiding them, stopping them or mitigating their energy. This group includes rigid solutions such as concrete dikes, masonry dikes and semi-rigid dikes such as gabions, as well as the flexible barriers that are the object of this contribution. All of them are placed in the path of the debris streams, as they pass through the slopes.
Stabilization: These are all those measures that are carried out in situ that allow the movement of materials to be controlled, and their fundamental objective is to increase the safety factor. In this group are the traditional solutions of staggered, which control the transfer and deposition of materials mobilized by events, whose deposit helps to stabilize and control erosion on the margins.

6.1. Protection by single barriers

Most of the barriers installed to date are individual along roads and railways or over population settlements (fig. 15).

Figure 15. Debris flow barrier in Isenfluh, Switzerland over a population center. The outer bank channel was reinforced with a rock wall

6.2. Stabilization by multi-level barriers

Debris flow barriers can be installed in stages and thus increase the retained volume. The Swiss WSL institute promoted the installation of the first multi-level barriers in Merdenson, Switzerland, for observational purposes (Denk et al., 2008). Laboratory tests to analyze the behavior in the event of overflow and, more specifically, the evolution of the overflow velocity during a flow, confirmed the value of the load model developed for multilevel barriers (Wendeler, 2014). Examples of this configuration are the multi-level barriers at Hasliberg (Wendeler, 2014) in Switzerland (fig. 16), but also at Portainé in Spain (Luis et al., 2010) where some 26,000 cubic meters of large granular material were mobilized in a few hours, which were intercepted by a set of 11 stepped barriers (fig. 17). In Chosica, near Lima, Peru, a total of 22 stepped barriers were installed, most of the multilevel barriers have already been successfully filled during various events (fig. 18 and 19). In Chosica, it was possible to protect the road infrastructure and a huge population center downstream. Between 2018 and 2020, several barriers with a total retention capacity of 12,000m3 were installed in the Las Ceibas riverbed in Neiva, Colombia (fig. 20). Figure 20 shows a photograph from March 2022 of one of these barriers, a 56m and 6m tall UX model, which is draining and has worked very effectively.

Figure 16. Eleven debris flow protection barriers, successfully filled in Hasliberg, Switzerland

Figure 17. Two of the eleven stepped barriers located in Portainé, current state after 12 years of continuous work, Portainé Spain

Figure 18. UX barrier after 2017 events in Chosica, Peru

Figure 19. VX barrier successfully protecting a huge population center downstream, Chosica Peru

Figure 20. Large UX barrier. CAM Promoter – Autonomous Corporation of Alto Magdalena, Colombia

6.2.1. Multi-level solution in Krvavec ski resort area, Slovenia

Alpine regions are increasingly vulnerable to sediment-related natural hazards such as flash floods, debris flows, and shallow landslides, especially under the influence of climate change. This study presents a comprehensive overview of mitigation strategies implemented in the Krvavec ski resort area in northern Slovenia, a typical Alpine catchment, following a destructive debris flood event in May 2018. The event caused significant damage to infrastructure, including the valley station of the ski lift and access roads.

Figure 21. Two photos of the situation in the Brezovški and Lukenjski torrents, respectively. The channel width is between 1-2 m to several metres (Sodnik et al., 2023)

Between 2010 and 2020, the average annual precipitation at the summit of the Krvavec ski resort (approximately 1700 meters above sea level) was around 1620 mm, with no distinct seasonal distribution. Moreover, there is a clearer pattern in the monthly rainfall erosivity distribution with a clear peak in the summer period.

On 30 May 2018, a relatively extreme rainfall event occurred in this area. Around 50 mm of rainfall fell in around 30 min, corresponding to the statistically estimated return period of over 50 years. The total event duration was very short (less than 3 h), and most rainfall was concentrated in around 15–30 min. The rainfall erosivity for this specific event based on the 30-minute rainfall data can be estimated to be over 1420 MJ × mm × ha^{-1} × h^{-1} × $year^{-1}$, which is almost half of the total annual rainfall erosivity and almost twice as large as the average monthly erosivity at the Krvavec meteorological station in the period 2010–2020 (Sodnik et al., 2023).

After the May 2018 event, a geological survey was carried out to determine geological conditions for planning and executing new mitigation measures. The main objective of the field survey was to estimate the possibility and magnitude of future mass movement and debris flood events. Areas with deposited debris material and areas with high erosion potential were identified to secure input data for debris flood modelling and countermeasures design process.

In response, a multi-phase mitigation plan was developed and executed. The first phase involved restoring existing concrete structures in the downstream Reka torrent. The second phase focused on constructing a large slit check dam with a sediment retention capacity of approximately 14,000 m^3 at the confluence of two torrents—Brezovški and Lukenjski (fig. 21). The third phase introduced a series of 16 flexible ring net barriers in the steep upstream channels (12 in Brezovški gully and 4 in Lukenjski gully), to prevent side erosion (bank collapses, slumps) and thus to limit sediment supply from sediment sources, marking the first such application in Slovenia. These barriers, with a combined retention volume of approximately 8000 m^3, were designed to stabilize channel banks, reduce slope gradients, and control sediment transport.

The height of the barriers varies between 2.5 and 6.0 m, and the sediment trap capacity is between 100m^3 and 800 m^3. The top width of the barriers varies between 9 and 25 m. The total retention volume was estimated for 4 barriers in Lukenjski gully to be over 3000 m^3 and for 12 barriers in Brezovški gully (fig. 22) to be close to 5000 m^3.

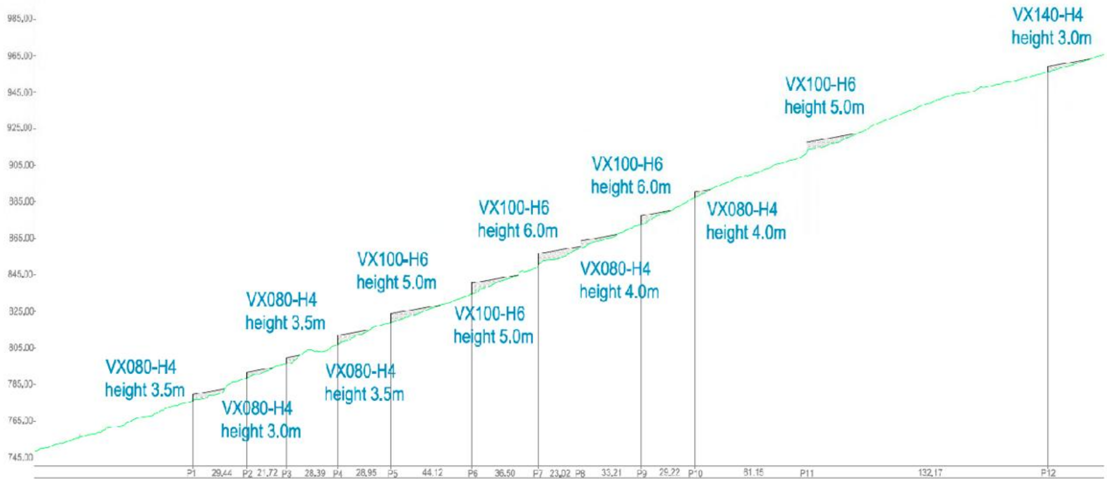

Figure 22. Longitudinal profile of the Brezovški gully with the locations of the 12 flexible barriers (Sodnik et al., 2023)

To support long-term hazard monitoring and performance evaluation, an extensive surveillance system was established. This includes UAV-based LiDAR mapping, rainfall gauges, and innovative IoT-based multisensors (Guards, see section 7) installed on selected barriers to monitor corrosion, impact forces, and environmental conditions. Additionally, a field test site was created to study concrete abrasion under real sediment transport conditions. The effectiveness of these measures was validated during the extreme flood event of August 2023 (fig. 23), which exceeded the intensity of the 2018 event. Despite higher rainfall erosivity and sediment mobilization, the installed structures successfully retained debris and prevented damage to critical infrastructure. This outcome highlights the robustness and adaptability of the hybrid mitigation approach combining flexible and rigid structures.

Figure 23. Situation in both torrents after the extreme August 2023 event.

The study concludes that such integrated and monitored mitigation systems are not only effective in reducing torrential risks but also offer valuable insights for future applications in similar Alpine environments. The approach serves as a model for sustainable sediment management and disaster risk reduction in mountainous regions.

6.3. Debris flow retention with a unique high-profile barrier

In special cases, an adapted design of more than 10 m and more than 40 m can be built. A typical example is the barrier designed and emplaced in Hüpach, next to Oberwil in the canton of Bern in Switzerland (Berger et al., 2016). This barrier has a retention capacity of more than 12,000m3. Such a construction requires powerful reinforced concrete foundations, long anchors, and special ropes like those used in suspension bridges or cable cars that need precise adjustment (fig. 24). To complete the project, special calculations were necessary for the net and ropes, adjustment of the anchors and special engineering for the design of the foundation to the ground. The decision to install a large containment structure with an annular net was based on the topography, the difficulty of access and the lack of alternatives to protect the population center located downstream. Another special construction is in Sitäbach along the Lenk stream in Switzerland. The construction is based on reinforced concrete piers, with flexible ring nets interspersed (fig. 25).

Figure 24. Special barrier solution in Hüpach, Switzerland

Figure 25. Another special solution acting as a barrier against the flow of debris in Sitäbach, Switzerland consisting of concrete piles combined with ring nets

7. Monitoring

Barriers can be monitored with sensors. A first generation of sensors (Sentinel) were associated with the braking ring system, and when a load threshold is reached, an alarm is triggered. An example is the debris flow network, installed as an immediate protection solution, at Magnacun in Switzerland. The Rhaetian railway lines in the Alps have been perfectly protected since 2009, with the surveillance system working correctly, according to the developer.

Since 2016, a new multi-sensor system[4] (Guard) with direct access to the cloud (fig. 26) has been developed capable of recording: rope loads up to 300kN, acceleration up to 200g, orientation [x, y, z axes], humidity 0-100%, temperature -50ºC to 80ºC, battery status and signal power (RSSI). As the new element, it has a sensor that allows the level of corrosive environment (corrosion current [µA]) to be known, which is essential for the planning of handling tasks. The main characteristics are summarized in Table 1.

[4] Digital interconnection of everyday objects to the internet (Internet of Things [IoT])

Table 1. Guard device properties

Feature	Description
communication	GSM/ UMTS/ LTE (2G / 3G or LTE Cat M1)
Battery life	7-10 years / no need for charging or battery change
data transmission	1 time a week, in case of a special request within a few minutes
safety	Multiple/standalone encrypted operating system
weight	2,6 kg
durability	outdoor IP67 (waterproof, UV-resistant, cold and heat-resistant), designed for accelerations up to 200g
assembly	on rope Ø16mm – Ø24mm

Figure 26. State-of-the-art Sensor Guard placed in a flexible barrier against debris flows

8. Maintenance and cleaning of the barriers

Like any structure, flexible barriers against debris flows require maintenance. It is recommended to carry out regular checks, for example annually, of the protection system if no event occurs (flow of debris, landslides, etc.) during this period. Working with a checklist and maintenance scheme, as for any other protective structure, should facilitate regular checks.

It is important to note that there are two possibilities in relation to maintenance associated with the use given to the barriers: when they are used in a staggered manner as a **stabilizing measure,** to control the erosion of the margins and to reduce the velocity of the fluid, as a general rule they are not emptied[5], even so, they should be visited with a frequency marked by the recurrence of the phenomena in the place and that at least they should be annual. Instead, barriers used as **protective measures**, usually located downstream, should be emptied and certain components replaced after an event. If possible, excavating machinery can be used at the access level. It is essential, when designing and dimensioning the system, to consider what happens to the debris stream material and to arrange a deposit area. Budget-wise, it should be noted that after a fully filled barrier, some parts need to be replaced, while anchors can frequently be reused, as explained above. A barrier can be emptied from the front when certain conditions are met: the material of the debris flow must be dry and stable; the crown of the barrier must remain stable upstream and the safety aspects for the work team must be respected.

9. Advantages of flexible ring nets for debris current protection

The main advantages of these systems are their relatively low weight and quick installation, especially in steep and hard-to-reach terrain. The material can be transported by helicopter to the high mountain areas, where construction machinery cannot reach or where it is not economically effective. Flexible barriers composed of

[5] this kind of barrier, can be filled during installation to control the margin erosion process and use available unstable material

ring nets can be used for immediate emergency protection in distressed areas and to safeguard the execution of a larger downstream structure, the latter being very common practices in Japan. Flexible barriers can be incorporated into an overall protection concept for an entire catchment area. At the same time, it has been proven over time that annular net barriers are fully equivalent to large concrete structures when designed correctly, with an erosion control concept and a maintenance plan in place. Obviously, in easily accessible areas with high frequency of debris flows, permanent reinforced concrete structures can be employed.

10. Conclusions

In recent years, many projects at a global level have become a reality and have operated very successfully, since the publication of the load combination model, developed for the dimensioning of flexible barriers composed of ring networks and the multiple suitability tests carried out in Illgraben, Switzerland. During these years of combined cabinet and field work, several construction details have been reviewed and perfected. If the hydrological processes that affect the stability of riverbanks are considered and their reinforcement is designed, flexible systems can be considered equivalent to large classic protection structures made of concrete. The lighter design of barriers makes them an unavoidable solution when easy handling, environmental requirements and landscape protection are key issues in a project. The dimensioning concept developed at WSL, in use worldwide, has been verified by several successful filled, hold, and overshoot events. Further adaptation and refinement of the dimensioning concept could be achieved with more tests, if possible, but this task is hampered by a lack of funding.

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