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Twenty years' experience in flexible debris flow protection

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Abstract. Flexible ring net barriers against debris flow have been installed worldwide during the last twenty years mainly for the purpose of retention and a few for erosion control in the way by reducing the inclination of the riverbed. An increasing number of projects (40 barriers within Switzerland, more than 100 worldwide by 2017) showed the economic and environmental benefit of this solution. Special applications to retain larger volumes with single barriers have been successfully installed in several countries across the globe. This contribution gives examples of different special applications like one big barrier providing large retention capacity, several barriers in line or filled-up barriers for erosion control. Advantages and challenges for the use of flexible ring net barriers are discussed on a technical and economic level and needs for maintenance and replacement works are addressed.

Key words: *debris flow, flexible protection, maintenance*

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Обзор двадцатилетнего опыта защиты от селевых потоков гибкими противоселевыми барьерами

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Аннотация. Гибкие барьеры для защиты от селевых потоков устанавливались в последние двадцать лет по всему миру для удержания селевой массы и иногда для контроля эрозии и уменьшения уклона русел. Растущее число проектов (40 барьеров в Швейцарии и более 100 по всему миру в 2017 г.) показало экономические и экологические преимущества этого решения. В некоторых странах были установлены специальные решения для удержания селей большого объёма. В публикации описаны несколько особенно примечательных решений, таких как один барьер с особо высокой удерживающей способностью, решение из нескольких барьеров и система заполненных барьеров для контроля эрозии. Обсуждаются преимущества и сложности использования барьеров с технической и экономической позиций, а также затронуты вопросы обслуживания и ремонта.

Ключевые слова: *селевой поток, гибкий противоселевой барьер, обслуживание*

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Introduction

Since 2005, over 250 flexible debris flow barriers have been installed, in more than 25 countries. Between 2005 and 2008, full scale experiments at the test site Illgraben, in Switzerland, proved the feasibility of retaining debris flows.

The efficiency of some of the first reference projects, mostly installed in Switzerland, was analysed and a load design was then established together with the Forest, Snow and Landscape Federal Institute (WSL). Standard systems were then developed with the simulation software FARO. Data from real-scale testing were used to verify and calibrate the software outputs.

Following this development, the flexible ring nets became increasingly an alternative to classical debris flow protections in Europe, Asia, USA and South America. In large scale projects, where nets were installed in a row in the same channel, the efficiency of retaining large volumes and the feasibility of this type of installation in a row were proven as well.

Designers and engineers appreciate the nets as a practical and economical addition or alternative to existing classical debris flow protections.

Twenty years of experience with flexible ring net barriers signifies that their advantages have been recognized and their efficiency in the field has been established. The increasing knowledge of single barriers, barriers in a row and large-scale barriers has allowed us to understand the advantages but also the limits of such a netting system for debris flow retention. This acquired knowledge is presented in the following paper, accompanied by case studies.

Real-scale testing in Illgraben, development of standard barriers and CE marking

Real-scale testing in Illgraben

Between 2005 and 2008, real-scale testing was conducted in the Illgraben debris flow channel, in Wallis, Switzerland [*Wendeler, 2008*]. Prior testing, rockfall protection nets revealed that they were retaining some slides. Still, the dimensioning concept was missing to prove that flexible ring nets could retain larger debris flows in a channel without sustaining damage. In Illgraben, a middle to large debris flow is occurring at least once a year naturally and therefore, a flexible ring net could be tested yearly (see Fig. 1).

Two key characteristics were defined and analysed with testing. On one hand, a single barrier could, depending on the channel geometry, retain over 1000 m^3. On the other hand, over 10,000 m^3 were flowing over the barrier without damage. This led to planning and constructing a debris flow retention system with several nets in a row to successfully retain most of the material.

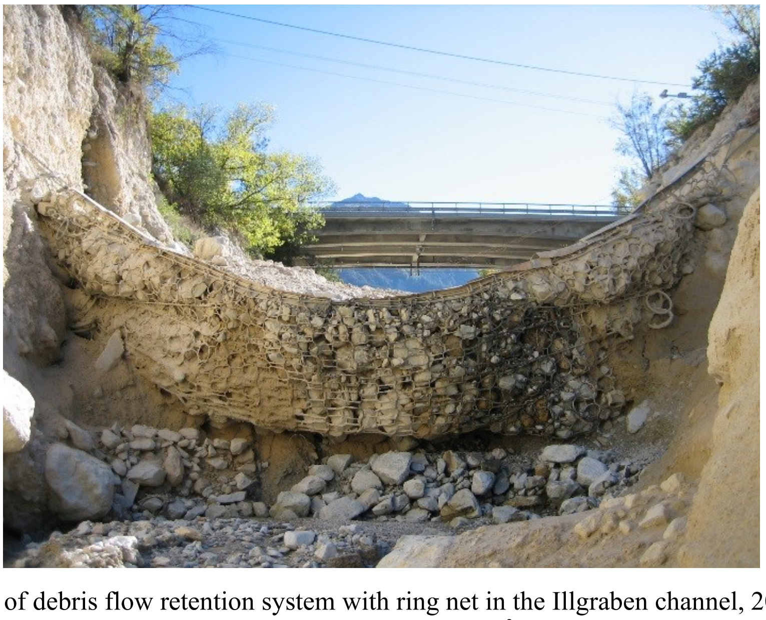

Fig. 1. Testing of debris flow retention system with ring net in the Illgraben channel, 2006. Retention volume approx. 1000 m^3

On the dimensioning side, the weight acting on a debris flow net during an event were better understood, thanks to an extensive measuring concept on and around the system [*Wendeler, 2006*], which lead to the final dimensioning concept [*Wendeler, 2008*].

Development of standardized barriers

The dimensioning concept as well as the distribution of the loading on the net were integrated in the finite element software FARO [*Volkwein, 2004*] and first projects, mostly in Switzerland, were dimensioned with it.

Following the first projects, standard barriers were designed with a given load capacity in kN/m^2. VX barriers are conceived for channels up to 15 m in width and a barrier height of up to 6 m, taking loads up to 160 kN/m^2. UX barriers find their application in larger channels, are installed with additional posts, a barrier height up to 6m and take up loads of 180 kN/m^2 [*Geobrugg, 2016*] (see Fig. 2).

The dimensioning concept for debris flows is now state of the art and freely accessible through the software DEBFLOW. After registration on the website, everybody can use this software and produce a first estimate for the dimensioning of a barrier.

Fig. 2. UX debris flow barrier, with posts for wider stream channels application. Example of the Trachtbach in Switzerland. Additional kolk protection, riprap and lean concrete were placed along the stream bed

CE marking

The real scale testing was also basis for certifying all standard barriers. Certification was achieved in 2017 (EAD document Nr. 340020-00-106[2]). The CE marking is based on a “European Assessment Document” which defines precisely the suitability, the type classification and yearly quality controls necessary to correspond to a certain standard. This states that the products with CE marking fulfil the European guidelines for product quality and field appropriateness (ETA 17/0268-17/0276 and ETA 17/0439).

Dimensioning

DEBFLOW makes it easy to predetermine the dimensioning of a standard barrier up to 6 m in height. Geobrugg or WSL with FARO simulation software can still dimension a more complicated scenario. Section 6 describes a few special cases regarding construction.

Special load case scenario such as snowslides and rockfall

In some instances, mostly very steep slopes (>35°) and at high altitude, snow slides, small avalanches or rockfall will be encountered, which could or will impact the debris flow nets.

An example is the multiple-barrier setup in Hasliberg in Switzerland. Some of the barriers are situated above 2000 m in elevation. Since flexible net barriers are also used to protect against avalanches and rockfall, a certain degree of combined loading can be guaranteed. The combined loading can be calculated, and a barrier can be dimensioned for every special case with the use of FARO simulation software [*Volkwein, 2004*]. Specific components of the debris flow barrier can be individually reinforced depending on the simulation results [*Wendeler, 2014*].

Fig. 3 illustrates the simulated load case for barrier number 2 in Hasliberg in a situation of a lateral avalanche impact, with an angle of 10° and a load of 120 kN/m^2. In this special case, the upslope guy wires are loaded up to 70% of their capacity. Fig. 4 shows the snow load on the barrier in winter.

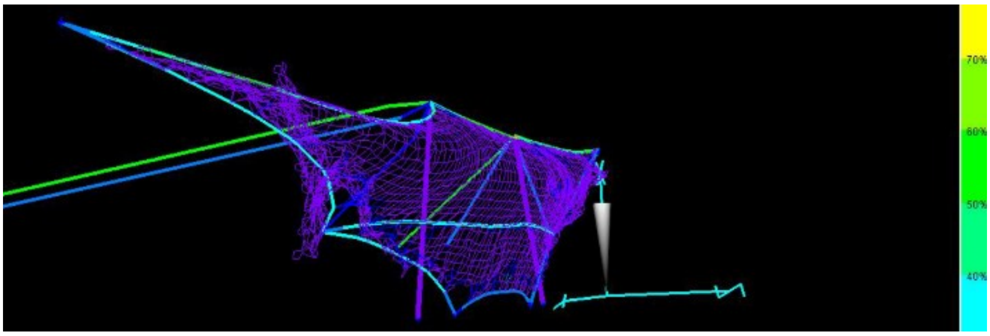

Fig. 3. FARO simulation software output when an avalanche in Hasliberg, Switzerland impacts barrier number 2

Fig. 4. same net than in Fig. 3, partially snowed in during winter. The snow load has to be taken into account when designing the barrier

Construction aspects

Subsurface and anchoring

While the netting itself is easy to model and to dimension, safe 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 subsurface. Another advantage is the possibility to perform pulling tests on the soil nails to assess the friction between the subsurface and the grout.

Debris flow deposits are heterogeneous in nature and deposited along the sides of the channel affecting the subsurface quality for anchoring. The dimensioning of anchor forces need to be determined by experts in those cases. It is as well recommended to use self-drilling anchors with a flexible anchor head. The barrier when loaded is largely deformed and the forces of the ropes on the anchors can change up to 30° in angle. This eccentricity without flexible anchor head is often not bearable for a normal threaded anchor since the pushing resistance is much smaller than the pulling component.

Reuse of the anchoring after a debris flow event

Without additional flank stabilisation, a certain degree of washing out can be observed along these stream banks, especially in loose soil (see Fig. 5).

When exchanging the net, the anchoring can technically be reused when the top of the anchor is cut off, a loading test is performed, and a new flexible anchor head is mounted. Assuming that the anchor length was drilled the first time with a safety factor and possesses a certain length in reserve. In the case of frequent filling of the net, it is recommended to design the anchors with sufficient length or to prevent the washing out of the banks with structural countermeasures.

Fig. 5. Washed out anchoring of the debris flow barrier number 25 in the Illgraben channel. Anchoring partially in loose material and partially in disused concrete debris flow barrier

Structural countermeasures: protection of the banks in stream bends

Especially in bends along the stream, the washing out of the outer bank and its erosion are prevalent when a debris flow occurs. The volume and the velocity of the flow dictate the amount of erosion. Depending on the project, a reinforcement of the outer bank should be considered (for example, additional flank stabilisation by netting with or without erosion control mats (see Fig. 6)).

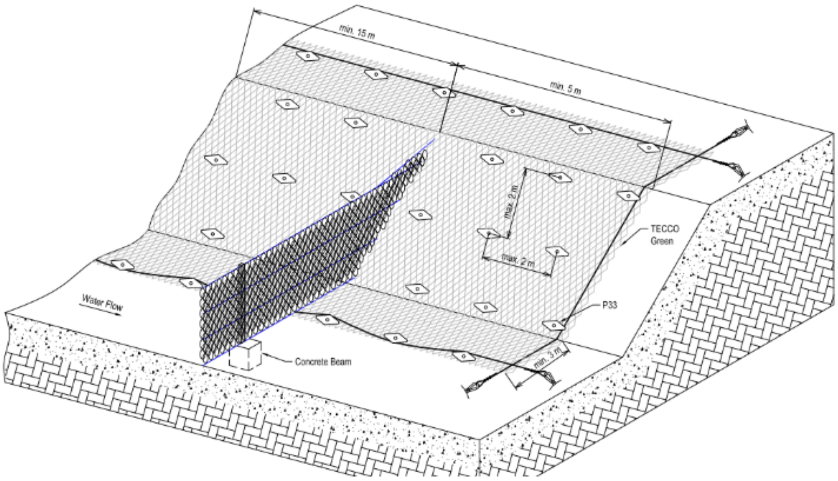

Fig. 6. Slope stabilisation with TECCO for flank stabilisation when installing a debris flow barrier in loose material

It is important to consider that the shearing forces of a debris flow are much higher than of water and this has to be incorporated in the design calculation for the protection measures.

Kolk protection

When barriers are filled or partially filled, the downstream material must be directed back into the original stream bed. This is especially important for barriers retaining a debris flow in an open field rather than in the stream bed.

When planning, it must be considered whether a field needs an artificial channel back to the stream. The necessity for a protection against kolk has to be established, for example with anchored rock blocks. When choosing this solution, the dimensioning of the lower nets should consider the possibility of these rock blocks getting torn away. The additional load being potentially fatal to the barrier.

Planning aspects

Often, debris flow barriers are installed close to the debris flow's source zone. At the same time, greater structural measures, such as a retaining basin or deviation measures, are constructed further down.

Net barriers and large steel and concrete construction can therefore be perfectly combined. The advantages of both methods can be specifically used together. An example of this combination is the streams Trachtbach in Brienz and Milibach in Hasliberg, both in Switzerland. In both projects, combining the nets upstream and the larger construction measures downstream allowed for increased retained mass upstream and diminished the erosion in the stream bed.

Therefore, the capacity of the concrete protection measures could be lowered and constructed at a smaller scale, and existing protection structures could be easily and cost-effectively renovated and added to the protection measures series.

Protection nets as an immediate solution

Protection nets installed in the source zones of debris flows slow them down, allowing for longer warning and evacuation times in endangered areas. This is especially important in small catchment zones where debris flows are rapid and travel along short distances only.

Therefore, easily installed protection nets are practical for an immediate protection solution. They increase the safety of the infrastructure downstream and even allow for the protection of the construction crew building a retaining basin, for example. These protection nets can also be equipped with a warning system (more details are given in section 7).

Visual and landscape protection aspects

Debris flow protection nets instead of concrete dams are increasingly being considered an alternative for landscape protection and visual aesthetics. The filigree design is almost invisible from far away, and this is a primary argument for construction of protection measures in landscape protection zones.

An example is the UNESCO World Cultural Heritage along the Rhine close to Koblenz (Fig. 7). At the back of the village, debris flow nets are installed, and even with one barrier partially filled in 2017, the nets are still barely visible but fulfilling their purpose (Fig. 8).

Fig. 7. Almost invisible debris flow barrier close to Koblenz along the Rhine above an UNESCO World Cultural Heritage protected village

Fig. 8. partially filled debris flow barrier above the German Railway close to Koblenz

Additionally, environmentally friendly buildings and sustainability are increasingly important arguments for construction. For example, a debris flow barrier (ten by 4 meters) is 30 times lighter than a concrete barrier of the same dimensions, making it the 'greener solution'. With less weight, less carbon dioxide is emitted during transport to the site [*Wendeler, 2008*].

Passage for small animals and greening

The relatively large openings of ring nets allow small animals, even fish, to pass when the barrier is not filled or immersed in water, in contrast to a concrete structure [*Wendeler, 2008*]. Ring nets are also appropriate for greening and blend perfectly into the landscape.

Different types of debris flow barriers

Single barriers

Most barriers installed are single barriers along roads, railway tracks, or above settlements (see Fig. 9).

Fig. 9. Debris flow barrier in Isenflue above a settlement. The outer bank of the stream was reinforced with a rock wall

Barriers in a row (multi-level barriers)

Debris flow nets can be installed in a row to increase the retained volume. The WSL installed the first multi-barriers in Merdenson, Switzerland, for observational purposes [*Denk et al., 2008*].

Subsequent laboratory tests to analyse the overflow behaviour, specifically the overflow velocity evolution during a flow, confirmed the developed load design for multi-level barriers [*Wendeler et al., 2010*].

Examples of this setup are the multi-level barriers in Hasliberg [*Wendeler et al., 2014*] in Switzerland, Portainé in Spain [*Luis et al., 2010*], and Ana Chosica in Peru.

Most multi-level barriers have already been successfully filled during events (see Fig. 10). Ana Chosica is the most recent example, from 2017, protecting several cities built downstream efficiently (see Fig. 11).

Fig. 10. Debris flow protection barriers, successfully filled in Hasliberg in 2011

Fig. 11. Filled debris flow barrier in 2017 in Peru, protecting successfully a large city downstream

Large debris flow retention with single barrier (special construction)

An adapted design higher than 10m and larger than 40 m can be constructed in special cases. A typical example is the debris flow barrier in Hüpach, next to Oberwil in the canton of Berne in Switzerland [*Berger et al., 2016*].

This barrier has a retaining capacity of more than 12’000 m^3. Such a construction necessitates strong abutments of steel-reinforced concrete and long anchors, and special ropes are needed for cable cars, which need precise adjustment (see Fig. 12). Special calculations for the netting and the ropes, adjustments to the anchoring and special foundation engineering in exposed terrain were necessary to complete the project. The decision to install a large retaining structure with netting was based on the topography, the difficulty of access and lack of alternatives to protect the village below. The debris flow barrier has not been filled yet.

Another special construction is situated in Sitäbach, Switzerland, along the stream Lenk. It is based on concrete slices with netting in between (see Fig. 13).

Fig. 12. Special construction of a debris flow barrier in Hüpach, in Switzerland, with a width of 40m and a netting height of 10 m

Fig. 13. Another special construction acting as a debris flow barrier in Sitäbach, consisting of concrete slices piled up and netting mounted in between

Maintenance and cleaning of barriers

As with any protection structure, debris flow barriers require maintenance from time to time. If no event (debris flow, slides, etc.) occurred during that time span, it is recommended to undertake regular, for example yearly, checks of the protection system. Working with a checklist and a maintenance scheme, as with any other protection structures, should facilitate regular controls.

After an event, the barrier needs emptying and the replacement of specific components. A filled barrier can, for example, be cleaned from behind with an excavator. When planning for the system, it is essential to consider what happens to the material of the debris flow and to organise a deposit area. Budget-wise, it has to be considered that parts have to be replaced after a filled barrier, whereas the anchoring can often be reused, as explained earlier.

A net can be emptied from the front when certain conditions are fulfilled. The debris flow material has to be dry and stable, the netting has to be stabilised upslope, and safety aspects for the working crew have to be respected.

Advantages and limits of flexible netting for debris flow protection

These systems' main advantages are their relatively low weight and rapid installation. Especially in steep and rugged terrain. The material can be transported with helicopters wherever construction machines cannot reach the site or are not economical.

Ring nets can be used for immediate protection in endangered zones to safeguard the construction of a permanent structure below. These practices are common, for example, in Japan. Ring nets can, therefore, be incorporated into an overall protection concept for an entire catchment area.

At the same time, it has been proven that ring net barriers are fully equivalent to large concrete structures when properly planned, with an erosion control concept and an established maintenance plan.

Obviously, in easy-access areas with a high frequency of debris flows, permanent concrete structures are to be favoured as they are more economical.

Conclusions

Since the publication of the load design of flexible protection nets and their appropriateness tests in the Illgraben in Switzerland, many projects have been successfully installed in the last 20 years.

Several construction details have been revised and improved. Considering the hydrological processes affecting the stability of the stream banks and planning for reinforcement, the flexible ring net systems can be considered equivalent to classical large concrete protection structures. The barriers' lighter conception makes them an unavoidable solution when easy handling, environmental requirements and landscape protection are key issues of a project.

The dimensioning concept developed at the WSL, which is in use worldwide, has been verified by several filling and successfully retaining events. More testing could further adapt and refine the concept.

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