Channeled Landslide Protection Using Flexible Barriers - Learning from more than 10 Years of Experience

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ABSTRACT: Several flexible ring net barriers against debris flow have been installed worldwide during the last 10 years mainly for retention and a few for erosion control in the way by reducing the inclination of the river bed. The increasing number of projects showed the economic benefit of this solution. Special applications to retain big volumes with single barriers have been successfully installed in Switzerland and Japan. This paper gives examples of different special applications like one big barrier providing big 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. Furthermore, needs for maintenance and replacement works are addressed.
Keywords: landslides, debris flow, protection, barriers, experience, maintenance

1. 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, 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. The nets are appreciated, by designers and engineers, as a practical and economical addition or alternative to existing classical debris flow protections. Ten years of experience with flexible ring net barriers signify that their advantages have been recognised and their efficiency in the field have been established. The increasing knowledge of single barriers, barriers in a row and large-scale barriers have allowed 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.

2. REAL-SCALE TESTING AT ILLGRABEN, DEVELOPMENT OF STANDARD BARRIERS AND CE-MARKINGS

2.1 Real-scale testing at Illgraben

Between 2005 and 2008, real-scale testing was conducted in the Illgraben debris flow channel in Wallis, Switzerland (Wendeler, 2008). Prior testing it was observed that rockfall protection nets were retaining some slides but 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 (Figure 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, it was observed that 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 retain successfully most of the material.

Figure 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).

2.1.1 Remarks about 1:1 field tests results

Based on the described test site and recording facilities, real impact forces on flexible barrier systems could be derived and used for the development of a load model for the interaction between debris flows and flexible, permeable barriers. Herein, the measured rope forces during impact and overflow of debris flows present the most important results of the test barriers. An example is given in Figure 2. Clearly, one can follow the filling process with the increasing rope forces. Sudden load reductions show the activation of the brake elements. Even large blocks could be measured by higher weight at the balance and later by single peaks in the rope measurements. An example of a large block can be seen in Figure 3.

If a barrier stays in use fully filled e.g. for river bed stabilization one should consider that the remaining barrier height in the middle of the barrier is only ¾ of the original barrier height.

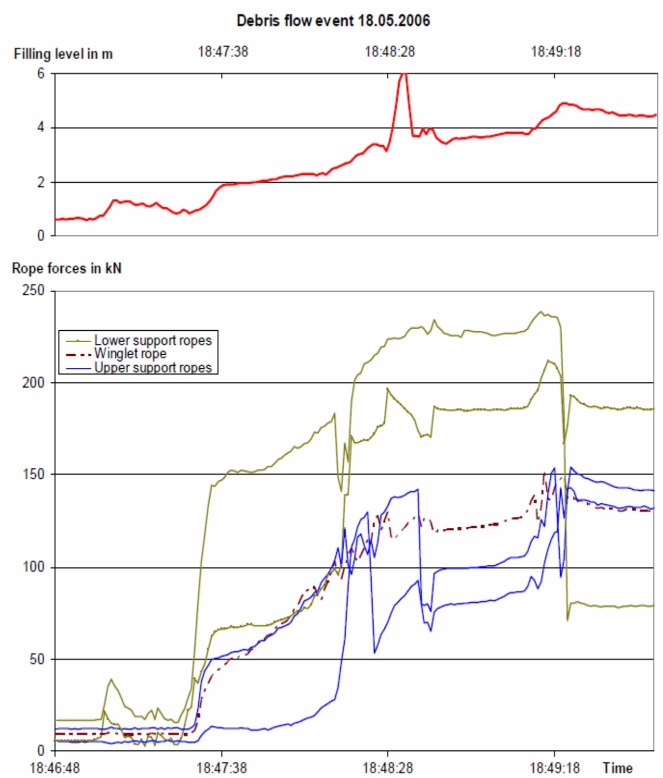

Figure 2 Rope forces and the filling height over time for the filling event in 2006

Figure 3 demonstrates also that a debris flow can overflow a filled flexible barrier. The overflow material is the remaining volume of a surge exceeding the retention capacity of a single barrier which passes the barrier without causing any damages. The barrier shown in Figure 3 was overflown by several 10'000 m^2 without any damage to the barrier.

Figure 3 Large block (left) flowing over the balance and afterwards over the barrier (right)

2.2 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 15m in width und barrier height of up to 6m, 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 6 m and taking up loads of 180 kN/m^2 (Geobrugg, 2016, Figure 4). The dimensioning concept for debris flows is now state of the art and freely accessible through the software DEBFLOW on Geobrugg website. After registration on the website, everybody can use this software and produce a first estimate for the dimensioning of a barrier.

Figure 4 UX debris flow barrier, with posts for wider stream channels application. Example of the Trachtbach in Switzerland. Additional kolk protection, rip-rap and lean concrete were placed along the stream bed

2.3 CE-marking

The real scale testing was also basis for certifying all standard barriers. Certification was achieved in 2017 (EAD document No. 340020-00-1062). 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).

3. DIMENSIONING

3.1 Results of laboratory tests

In general, it is difficult to compare such laboratory tests with field situation. Usually the physical modelling only provides an informative basis on typical tendencies. After a detailed analysis of the performed test results with a dimensional analysis the most important result is that the stopping process of the front behaves like an impulse of a pressure surge. Slow and friction dominated fronts hitting the barrier showed a reflected surge. These observations are in support of the physical behaviour of a stopping pressure surge.

The maximum dynamic force is dependent upon the velocity squared and the flow consistency. For muddy flows, the pressure surge needs a lower pressure coefficient C_w than for granular and viscous flows. Additionally, flow density influences the pressure experienced by the barrier linearly. Faster traveling fronts are deviated vertically when they interact with the barrier and result in material overtopping the barrier without filling it. The same effect also occurs for rigid barriers resulting in less retention capacity. This observation could be confirmed because the rigid barriers were greater affected by smaller impact forces than the more flexible ones. It therefore can be concluded that the flexible barriers are able to stop the debris flow whereas the rigid barriers can only deviate it. Tests comparing the retention capacity of different mesh sizes in relation to the maximum particle size were conducted (Figure 5). This enabled the determination of a good retention behaviour with a mesh size as big as the d_{90}-grain size (90% of the grains are smaller than d_{90}).

Figure 5 Influences of different mesh sizes on the retaining volume

3.2 Load model

In nature, a debris flow fills a barrier continuously. As a simplification, the developed load model for the flexible barriers uses a time discretization and considers the debris flow impact as a series of several surges which can be said to move on top of any previous surge stopped by the barrier system. The height of the single surges corresponds to the calculated flow height of the debris flow. Hence, the barrier is filled after many surges that result from the barrier height divided by the debris flow height. The drainage process of stopped material is enhanced through the added weight of additional surges. The load model and design concept given by Wendeler et al, 2006, consider usability aspects, actual valid codes and standards, debris flow intensities, annularity and fail probabilities and corresponding consequences.

3.2.1 First impact

Two components act upon the barrier during the stopping process of the first wave: a hydrostatic and a dynamic pressure. These depend on the velocity of the flow squared, the flow consistency and its density (Figure 6).

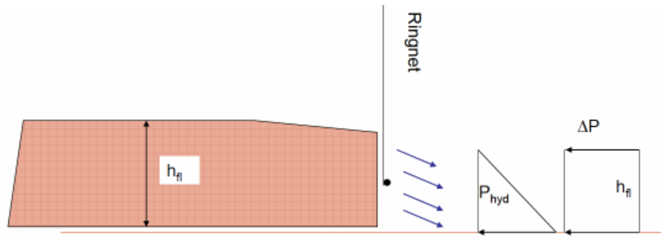

Figure 6 First impact of a debris flow and its loading components of dynamic pressure (ΔP) and hydrostatic pressure (P_{hyd})

3.2.2 Filling process

After the first impact, the assumed following surges spill over any previous now stopped material. Therefore, the dynamic component only interacts with the barrier area above the stopped material. The hydrostatic pressure, on the other hand, acts over the entire debris material caught in the net (Figure 7).

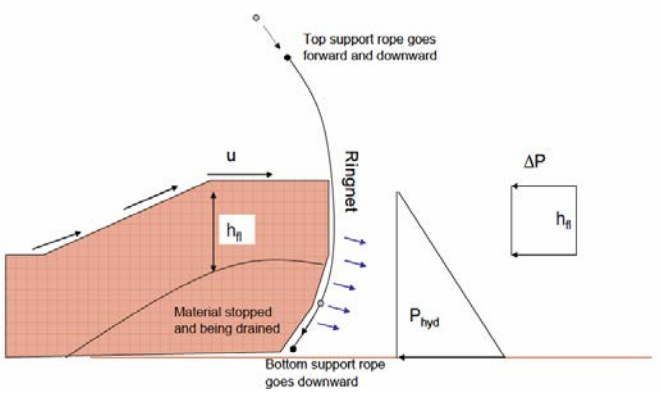

Figure 7 Second surge hiding the barrier while the filling process. The dynamic component acts one surge higher

3.2.3 Overflowing

If a barrier is filled completely, any following surges spill over the top of the barrier adding an additional load to the system by both their weight (σ) and the acting shear forces (τ). The shear force is usually ten times smaller than the normal force and is neglected in this loading approach for flexible barrier design. The retained material behind the barrier changes now from the hydrostatic state to an active earth pressure for wet material. The time it takes to drain the material depends on the debris flow composition and the water content. Figure 8 illustrates the loads that must be applied.

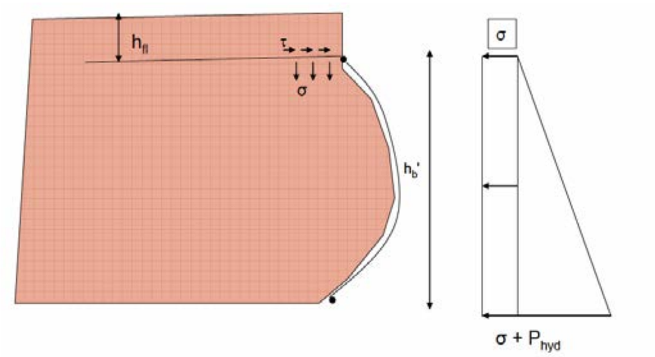

Figure 8 Overflowing process of an overtopping surge after the filling of the barrier

3.2.4 Rope and anchor loads

The loads acting in the ropes and transmitted to the anchorage finally result from the theory of the rope equation. For that the acting pressures should be divided over the single support rope bundles. The parameters that can be used to solve the rope equation iteratively with Newton iteration are for each rope bundle the rope length and its section area times the rope modulus, the decisive rope load in kN/m and the assumed sag of the rope alone together with the elongation of the integrated brake rings. After a rope force has been obtained the according elongation of the brake elements must be re-checked with the brake ring characteristics. If the difference to the initially assumed elongation is too large the rope equation must be solved again using an adjusted elongation.

3.3 Special load case scenario such as snowslide and rockfall

In certain cases, mostly very steep slopes (>35°) and at high altitude, snow slides, small avalanches or rockfall will be encountered which additionally impact the debris flow nets. An example of this situation 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 as a protection against avalanches and rockfall, a certain degree of combined loading can be guaranteed. The combined loading can be calculated and a barrier 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). Figure 9 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.

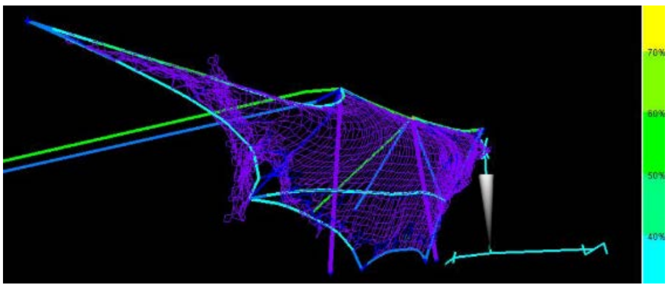

Figure 9 FARO simulation software output when barrier number 2 is impacted by an avalanche in Hasliberg, Switzerland

In this special case, the upslope guy wires are loaded up to 70% of their capacity. Figure 10 shows the snow load on the barrier in winter.

An easy predetermination of the dimensioning of a standard barrier up to 6 m in height can easily be performed with DEBFLOW software. A more complicated scenario can still be dimensioned by Geobrugg or WSL with FARO simulation software. A few special cases regarding construction are described in section 6.

Figure 10 Barrier partially snowed in during winter. The snow load must be considered for designing

4. CONSTRUCTION ASPECTS

4.1 Subsurface and anchoring

While the netting itself is easy to model and to dimension, safe anchoring is more complicated (figure 11). Ideally, a detailed geological profile of the section to be protected is available as well as the geotechnical parameters of the subsurface. Having the possibility to perform pulling tests on the soil nails to assess the friction between the subsurface and the grout is another advantage. 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.

Figure 11 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

4.2 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 (figure 12).

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. If 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 recommend designing the anchors with sufficient length or to prevent the washing out of the banks with structural counter-measures.

4.3 Structural countermeasures: protection of the banks in stream beds

Especially in bends along the stream, the washing out of the outer bank and its erosion are prevalent when a debris flow occurs. The amount of erosion is dictated by the volume and the velocity of the flow. Depending on the project a reinforcement of the outer bank should be considered (rock blocks, wall, gabions or additional flank stabilization by netting with or without erosion control mats. It is important to consider that the shearing forces of a debris flow are much higher than of water and this must be incorporated in the design calculation for the protection measures.

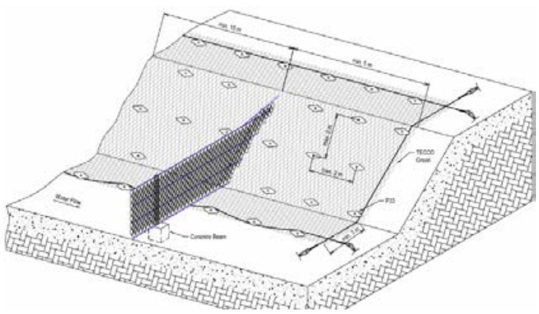

Figure 12 Slope stabilisation with TECCO® for flank stabilisation when installing a debris flow barrier in loose material

4.4 Kolk protection

When barriers are filled or partially filled, the material downstream 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 itself. When planning, it must be considered whether a field needs an artificial channel back to the stream. The necessity for a protection against kolk must 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.

5. PLANING ASPECTS

Often debris flow barriers are installed close to the source zone of the debris flows while 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. Examples of this combination are the streams Trachtbach in Brienz and Milibach in Hasliberg, both in Switzerland. In both projects, the combination of the nets upstream and the larger construction measures downstream allowed to increase the retained mass upstream and diminish the erosion in the stream bed. Therefore, the capacity of the concrete protection measures could be lowered and constructed at smaller scale and existing protection structures were easily and cost effectively renovated and added to the protection measures series.

5.1 Protection nets as an immediate solution

Protection nets installed in the source zones of debris flows, slow these down, which allows for longer warning and evacuation time in the endangered areas. This is especially of importance in small catchment zones where debris flows are rapid and travel along short distances only. The easily installed protection nets are therefore 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 be equipped as well with a warning system (more details are given in section 7).

5.2 Visual and landscape protection aspects

Debris flow protection nets instead of concrete dams are more and more an alternative regarding landscape protection and visual aesthetics. The filigree design is almost invisible from far away and a primary argument for protection measure construction in landscape protection zones. An example is the UNESCO World Cultural Heritage along the Rhine close to Koblenz (Figure 13). 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 (Figure 14).

Figure 13 Almost invisible debris flow barrier close to Koblenz along the Rhine above an UNESCO World Culture Heritage protected village

Additionally, environment friendly building and sustainability is more and more an important argument 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’. On top of that with less weight, less carbon dioxide is emitted during transport to site (Wendeler, 2008).

Figure 14 partially filled debris flow barrier above the German Railway close to Koblenz

5.3 Passages for small animals and greening

The relatively large openings of the ring nets allow for passage of small animals, when the barrier is not filled, even fishes when the barrier is immersed in water, in contrast to a concrete structure (Wendeler, 2008). There are examples where this was an expressed wish of the developer. Ring nets are as well appropriate for greening and blend perfectly into the landscape.

6. DIFFERENT TYPES OF DEBRIS FLOW BARRIERS

6.1 Single barriers

Most barriers installed are single barriers along roads and railway tracks or above settlements (Figure 15).

Figure 15 Debris flow barrier in Isenflue above a settlement. The outer bank of the stream was reinforced with a rock wall

6.2 Barriers in a row (multi-level barriers)

Debris flow nets can be installed in a row, to increase the retained volume. The first multi-level barriers were installed in Merdenson in Switzerland for observational purposes by the WSL (Denk et al., 2008). Subsequent laboratory tests to analyse the overflow behaviour, and more specifically the overflow velocity evolution during a flow, confirmed the developed load design for multi-level barriers (Wendeler et al., 2010). Examples for this setup are the multi-level barriers in Hasliberg and Menderson (Wendeler et al., 2014) in Switzerland but also in Portainé in Spain (Luis et al., 2010) as well as Chosica in Peru. Most of the multi-level barriers have already been successfully filled during events (Figure 16). Chosica is the most recent example in 2017, protecting efficiently several cities built downstream (Figure 17).

Figure 16 11 debris flow protection barriers, successfully filled in Hasliberg in 2011

Figure 17 Filled debris flow barrier in 2017 in Chosica Peru, protecting successfully a large city downstream

6.3 Large debris flow retention with single barrier (special construction)

In special cases, an adapted design higher than 10m and larger than 40m can be constructed. A typical example is the debris flow barrier in Hüpach, next to Oberwil in the canton 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, long anchors and needs special ropes used for cable cars which need precise adjustment (Figure 18). Special calculations for the netting and the ropes, adjustment to the anchoring and special foundation engineering in exposed terrain was necessary to complete the project.

Figure 18 Special construction of a debris flow barrier in Hüpach, in Switzerland, with a width of 40 m and a netting height of 10 m

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 along the stream Lenk, in Switzerland. The construction is based on concrete slices and netting in between (Figure 19).

7. SURVEILLANCE

Protection nets can be monitored with sensors (Sentinel System). In larger systems, some components can be monitored such as the ring brakes and when a loading threshold is reached, an alarm is triggered. An example is the debris flow net, installed as an immediate protection solution, in Magnacun in Switzerland. The railway tracks of the Rhaetian Railway are perfectly protected since 2009, with the surveillance system working faultlessly, according to the developer.

Figure 19 Another special construction acting as a debris flow barrier in Sitäbach consisting of concrete slices piled up and netting mounted in between

8. MAINTENANCE AND CLEANING OF BARRIERS

As any protection structure, debris flow barriers require maintenance from time to time. It is recommended to undertake regular, for example yearly, checks of the protection system if no event (debris flow, slides, …) occurred during that time span. Working with a checklist and a maintenance scheme, such as for any other protection structures, should facilitate regular controls. After an event, the barrier needs emptying and replacement of certain components. A filled barrier can for example be cleaned from behind with an excavator. It is essential, when planning for the system, to consider what happens to the material of the debris flow and to organise a deposit area. Budget wise, it should be considered that after a fully filled barrier, parts should be replaced, whereas the anchoring can often be reused, as explained earlier. A net can be emptied from the front when certain conditions are fulfilled. The material of the debris flow should be dry and stable and the netting must be stabilized upslope and safety aspects for the working crew should be respected.

9. ADVANTAGES AND LIMITS OF FLEXIBLE NETTING FOR DEBRIS FLOW PROTECTION

The main advantages of these systems are their relative low weight and rapid installation. Especially in steep and in terrain difficult of access. The materials can be transported by hand or with helicopters wherever construction machines cannot reach the site or where it would not be 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 in an overall protection concept for an entire catchment area. At the same time, it has been proven over time that ring net barriers are fully equivalent to large concrete structures when properly planned, with an erosion control concept and an established maintenance plan.

10. CONCLUSION

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 10 years. Several construction details have been revised and improved. When considering the hydrological processes affecting the stability of the stream banks and planning for reinforcement, the flexible ring net systems can be considered as equivalent to classical large concrete protection structures. The lighter conception of the barriers makes it an unavoidable solution when easy handling, environmental requirements and landscape protection are key issues of a project. The dimensioning concept developed at the WSL, in use worldwide, has been verified by several fillings and successfully retaining events. A further adaptation and refining of the dimensioning concept could be achieved with more testing, but is hampered by lack of funding.

REFERENCES

Berger C., C. Wendeler, L. Stieglitz and G. Lauber (2016): Examples of debris retention basins combining concrete and net structures, Interpraevent Luzern, Switzerland.

Denk M., A. Roth, C. Wendeler und A. Volkwein (2008): 1:1 Feldversuche für flexible Schutznetze gegen Murgang – Versuche, Bemessung, Anwendung, Publikation für die Technische Akademie Esslingen, Deutschland.

Geobrugg (2016): Ringnetzbarrieren aus hochfestem Stahldraht: Die ökonomische Lösung gegen Murgänge, Schweiz.

Luis-Fonseca R.., C. Raimat, J. Albalate and J. Fernandez (2010): Proteción contra Corrientes de derrubios en areas del Pirineo. Obras Urbanas, Julio/Agosto 2010 número 22, Spain.

Speerli J., R. Hersperger, A. Roth and C. Wendeler (2010): Physical modeling of debris flow over flexible ring net barriers, Conference on Physical Modeling in Geotechnics ETHZ, Switzerland.

Volkwein A. (2004): Numerische Simulation von flexiblen Steinschlagschutzsystemen, Dissertation ETHZ, Schweiz.

Wendeler C., B.W. McArdell, D. Rickenmann, A. Volkwein, A. Roth and M. Denk (2006): Testing and numerical modeling of flexible debris flow barriers. In Zhang, M. and H. Wang (eds.): Proc. Of the sixth International Conference on Physical Modeling in Geotechnics, pp. 1573-1578. Balkema.

Wendeler C. (2008): Murgangrückhalt in Wildbächen – Grundlagen zu Planung und Berechnung von flexiblen Barrieren, Dissertation ETHZ, Schweiz.

Wendeler C., J. Glover (2014): Multiple load case on flexible shallow landslide barriers – mudslide and rockfall, IAEG Conference Turin, Italy.

Wendeler C., A. Volkwein, A. Roth and N. Nishimura (2014): Successful hazard prevention using flexible multi-level barriers, Interpraevent in Nara, Japan.