Practical guide for debris flow and hillslope debris flow protection nets and its application in case studies

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Abstract. Debris flows and hillslope debris flows endanger people and infrastructures. Technical protection measures are important elements in addition to spatial planning (adapted use of space like hazard maps) and organizational measures (warning systems, emergency plan, evacuation). Additional to other rigid protection measures flexible debris flow nets and hillslope debris flow nets were developed in 2008, and 2010 respectively. Such flexible barriers consist of an interception surface of netting spanned between horizontal support ropes including energy devices and posts for large span width. Since then, they are available on the market worldwide. Many projects were successfully installed and already filled by debris flow events. After more than ten years of experience and demonstrating that these measures work against debris flow and hillslope debris flow, they are fully accepted as possible measures for integral protection against debris flow. To provide planners and engineers the experience and know-how of these flexible protection nets, a practical guide was initiated by the Swiss Federal Roads Office (FEDRO) and Swiss Federal Office for the Environment (FOEN). Two case studies with planned and installed flexible nets, in one case for a debris flow and in the other case for a hillslope debris flow, are presented.

1 Introduction

Debris flows are flowing mixtures of solids and water in steep torrent channels and are characterized by a surge-like flow behaviour [1]. Hillslope debris flows occur on open steep slopes and are smaller in volume [2].

Flexible debris flow barriers were first tested by small scale tests in Oregon at the USGS flume in 1998 by Natale et all [3]. Around 10 m^3 of material were released and caught by a so-called flexible barrier. Initial design approaches given by WSL (Swiss Federal Institute for Forest, Snow and Landscape Research) were published in 2001 by Dieter Rickenmann in an internal report [4]. This approach was based on the energy method in which the impact time of the stopped material by the flexible barrier is the most decisive parameter like the design of rockfall barriers. This impact time is hard to estimate and not clearly defined in the report [4]. The findings of [4] were based only on physical modelling and the question remained whether the impact time of the debris flow would last only the first rope load peak or the complete time of filling up the barrier. For muddy or watery debris flow this impact time can be rather long because a lot of material is passing through the barrier before clogging and increases the rope forces. In this case, forces are overestimated by this approach.

Initial knowledge of large-scale tested flexible barriers was collected by chance when impacted rockfall barriers were loaded by a debris flow or an open hill slide.

Between 2005 and 2008 real scale field tests with a flexible barrier in a real torrent called Illgraben (Switzerland) were performed [5]. A three-year funded CTI (Commission of Technology and Innovation) project produced a large series of lab tests resulted in new knowledge about the clogging effect of grain size versus ring net size and basal opening versus flow height [6]. The basal opening is the distance between the lower support ropes and the riverbed and is used to pass normal runoff without large amounts of bedload and wood. These results end up being used in several flexible barrier designs in Switzerland like the Hasliberg project [7] or the Hüpach project [8].

Between 2009 and 2012 another CTI funded project took place with many series of large-scale open hill flow tests to measure impact pressure in mudflows to improve the knowledge of the pressure surge model suggested in [5]. Results of this project can be found in [9] and [10]. Alternative approaches on design of flexible debris flow barriers were determined later in [11].

Up to now, more than 600 flexible debris flow barriers and 400 hillslope debris flow barriers have been installed worldwide by the manufacturer Geobrugg AG. Several of these barriers have already been impacted.

Until 2020, no general guideline for flexible nets against debris flow and hillslope debris flow were available for planner and engineers to help and make them more familiar with this kind of structures. There is a need to summarize and standardize the design approach of these structures for planners and engineers.

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2 Practical guide

In December 2020 a FOEN (Swiss Federal Office for the Environment) and FEDRO (Swiss Federal Roads Office) financed project resulted in a practical design guide for flexible nets against debris flows and hillslope debris flows [12]. A team of experts collected all former design approaches and summarized them in this document. The document is subdivided into a practical part and a technical part. Additionally, reference projects were collected and described, and a case study calculation provided.

The basic principle published design approach from WSL [5], is still determined as most practical valid approach, and was therefore used to calculate a case study in the practical guide. Most of the so far existing flexible barriers mainly the later explained CE-marked barriers were designed on that common approach which is based on real scaled field tests. The most important service ability aspects were mainly summarized in [13], [14] and help to improve long-term maintenance of these flexible systems.

Although most of the debris flow and hillslope debris flow nets are already CE marked this marking is only valid for special barrier dimensions or specific pressure values. If these values do not fit the requirement of the torrent or the slope parameters this practical guide will help experts in designing. The most important input parameters for debris flow impact pressure are the volume, the flow velocity and height, the density of the flow as well as the flow consistency (mud or granular). To estimate these values either field investigations and/or numerical simulations or empirical calculations are essential according to [15]. The same values are needed for the hillslope debris flow barrier design but obtaining the data is more difficult as only breakout heights and deposition heights are currently indicated on Swiss hazard maps. Numerical simulations for example with RAMMS (rapid mass movement simulations, developed by WSL) can be helpful to estimate the dynamic parameters.

To determine the most suitable design for a torrent with certain input parameter all three load cases must be taken into account: pressure surge, filling up the barrier and overflow [5], [12]. These load cases are illustrated in Figure 1. Impact pressure (Eq. 1) [5], [12] is composed of hydrodynamic and hydrostatic pressure during the pressure surge. The hydrodynamic component is calculated by the pressure coefficient (c_d), mean velocity (v) and material density (ρ). The hydrostatic component is based on the flow height (h_{fl}), gravitational force (g) and material density (ρ). Overflow condition is calculated by the hydrostatic pressure with the residual height (h'_{b}) and the additional weight of the overflow over the flow height (h_{fl}). Further the retention volume (V_R) of the barrier has to be obtained. To determine the potential retention capacity and to define the number of barriers for large release volumes. The retention volume is calculated with the following parameters: residual height (h'_{b}), mean width of protection net (b_m), angle between protection structure and riverbed (ε), riverbed angle (θ) and angle of material deposition (θ') (Eq. 3).

$$F_{surge} = c_d \cdot v^2 \cdot \rho + 0.5 \cdot h_{fl} \cdot \mathrm{\rho} \cdot \mathrm{g} \quad (1)$$

$$F_{overflow} = \rho \cdot g \cdot h'_{\mathrm{b}} + h_{fl} \cdot \mathrm{\rho} \cdot \mathrm{g} \quad (2)$$

$$V_R = 0.5 \cdot (h'_{\mathrm{b}})^2 \cdot \mathrm{b}_m \cdot \sin\varepsilon \cdot \left(\frac{\sin\varepsilon}{\tan\theta - \theta'} + \cos\varepsilon\right) \quad (3)$$

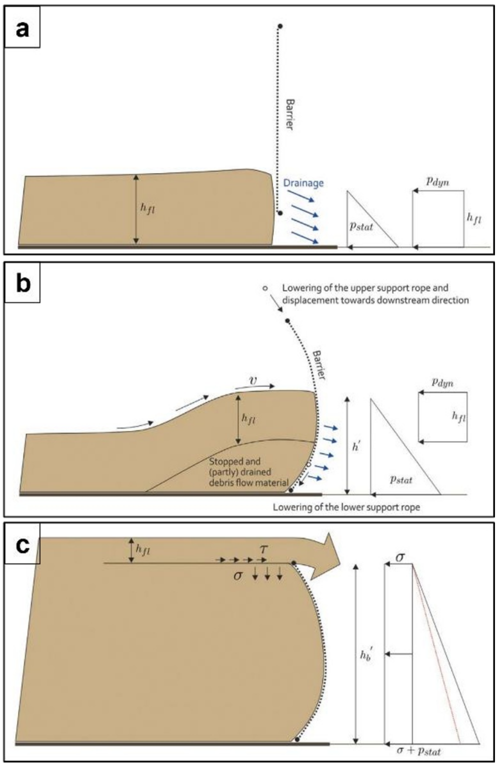

Fig. 1. a) Pressure surge consisting of hydrostatic and dynamic pressure; b) Filling process; c) Overflow condition with acting additional weight on the hydrostatic pressure [12].

3 Case study debris flow event Southern California

In the following section, a case study from Southern California is presented. Here, post-wildfire conditions created a potential debris flow hazard for infrastructure.

In 2020, the 5th September El Dorado Fire burned around 90 km^2 of forest, part of the north flank of San Bernadino Mountains. Based on the debris flow analysis, a moderate debris flow hazard was identified to occur during rainfall intensities of 24 mm/hr (USGS debris flow modelling). The debris material consisted of ash, wooden and boulder debris. The highway was protected by ditches and retention basins. Additionally, two flexible debris flow barriers were installed in two different canyons for further protection of the highway.

In an additional step, exhaustive structural dimensioning for the barrier design was done due to the request that no post would be installed in the riverbed. Based on the canyon geometry, a standard so-called UX-barrier, from the manufacturer Geobrugg AG, would have worked. An UX-barrier system includes posts to accommodate greater span width. The request to avoid posts resulted in a so called VX-barrier being installed. This barrier increased the sag of the net leading to less residual height and hence less retention volume.

The volume to dimension the barrier was set to 5000 m^3. Based on a 5 m system height, with a residual height of 3.9 m and cross-section geometry a total retention volume [Eq. 3] of approximately 3490 m^3 could be achieved. Material exceeding this volume would overtop the barrier. Table 1 summarises the data that were used for dimensioning.

Table 1. Dimensioning data debris flow barrier.

Parameter	**Unit**	**Symbol**	**Value**
Density	[kg/m^3]	ρ	2200
Velocity	[m/s]	v	5.5
Pressure coefficient	[-]	c_d	2.0
Flow height	[m]	h_{fl}	0.8

Since overflow condition were defined based on the retention capacity and release volume all three load cases (Fig. 1) were analysed. The resulting impact force (F_{surge}) was calculated as 145 kN/m^2 [Eq. 1]. The load case for the overflow resulted as $F_{overflow}$ in 94 kN/m^2 [Eq. 2].

A strong thunderstorm impacted the El Dorado burned area on July 30, 2021. Estimated rainfall of 25 mm/hr exceeds the thresholds of 15-24 mm/hr used for the debris flow model.

Overall, several debris flows occurred in different canyons along the intersect SR 38. The installed flexible debris flow barrier was overtopped and did not fail. However, at one location there was a backfilling effect of the retention basin. Due to the road over height and a clogged inlet underneath the road, the overtopped debris material was retained and filled up the basin then reached upstream to the barrier. The second barrier was impacted with less volume and therefore, retained most of the material and got only slightly overtopped. In Figure 2, the filled barrier consists of ash, debris, and wooden material with the inlet further downstream of the barrier.

The barriers were cleaned by an excavator, the energy absorption elements were replaced, and the barriers were reinstalled to their original system height.

Since the calculated retention volume is smaller than the design volume, an overtopping would be expected. Installing a second barrier in the same canyon would help to retain more material further upstream to avoid the filling of the debris retention basin close to the road.

The practical guide was not published at the initial planning stage of the project to help engineers and planners. However, after the event back analysis, the practical guide supported for further adjustments of the barrier concept helped with the maintenance concept. It also helped to understand and verify the dimensioning of the net superstructure.

Fig. 2. Filled debris flow barrier with inlet downstream.

4 Case study hillslope debris flow event Sicily

Heavy rainfall occurred on October 1st, 2009, in the North-eastern part of Sicily (Italy). According to [16] many debris slides, debris flows, and mud flows occurred. In Giampilieri and Scaletta Zanclea the event caused victims and 1652 people lost their houses due to the damage.

Based on the slope stabilization analysis in [16], mitigation measures were planned, and a flexible high tensile mesh nailed into the soil was installed. In the terrain of debris flow and hillslope debris flow occurrence, flexible barriers were planned. A standard SL-Barrier (shallow landslide barrier) of the manufacturer Geobrugg AG was installed with a system height of 3.5 m and a total length of 25 m to protect an access road to the village.

After a rain event in 2011, a hillslope debris flow hit the SL-Barrier and filled it with approx. 50 m^3 (Fig. 3). The maximum deposited material height was 2.5 m. The width of material deposition was around 12 m, corresponding to approximately half of the barrier length.

Back calculation of the dynamic impact (F_{dyn}) (Eq. 4) was used to estimate a range of impact pressure. Density and pressure coefficient can be estimated based on the field observation after the event. For the velocity a lower and faster values was chosen to establish a maximum and minimum impact pressure. Based on dimensioning values in Table 2 a dynamic impact force of 55 - 152 kN/m^2 results.

$$F_{dyn} = c_d \cdot v^2 \cdot \rho \tag{4}$$

Table 2. Dimensioning data hillslope debris flow barrier.

Parameter	**Unit**	**Symbol**	**Value**
Density	[kg/m^3]	ρ	1900
Velocity maximum	[m/s]	v	10
Velocity minimum	[m/s]	v	6
Pressure coefficient	[-]	c_d	0.8

Fig. 3. Partially filled shallow landslide / hillslope debris flow barrier SL-150 (red rectangle) with the starting zone above the structure.

5 Conclusions

Experience, knowledge, and projects of involving flexible protection barriers against debris flow and hillslope debris flow have grown over the past 15 years. The practical guide was created to present a comprehensive overview of the state of the art.

The case study in southern California showed a potential debris flow hazard due to a post-fire storm event. Based on the debris flow modelling, flexible debris flow protection measures were planned and dimensioned. The storm event of 30th of July 2021 showed the need for such structures. Further, it pointed out that the retention volume calculation versus release volume must be considered carefully. The released volume during the event was about the size estimated based on the debris flow modelling and was used for the dimensioning of the debris flow barrier. Nevertheless, only one single barrier with the given geometry is not capable of capturing 5000 m^3. A second barrier further upstream could have helped to capture more volume before it reached the highway.

The case study in Sicily contained a heavy rainfall event in 2009. Afterwards mitigation measures were planned and installed. This barrier was directly tested after a rain event and proved its functionality.

Both case studies showed the success of flexible barriers for debris flow as well as for hillslope debris flow. The determination of the design parameter and location of the barriers were not trivial. The practical guide helps and supports an improved procedure for such complex projects and enables the selection of the most suitable measure for a certain hazard situation.

The authors would like to thank the Swiss Federal Roads Office and Swiss Federal Office for the Environment, especially Philippe Arnold, Eva Gertsch, and Reto Baumann, to initiate the Practical guide for debris flow and hillslope debris flow protection nets. Likewise, the authors thank Catherine Berger, Matthias Denk, Christoph Graf, and Lisa Stieglitz for their effort and the Swiss Federal Institute for Forest, Snow and Landscape Research for the support.

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