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DESIGN OF FLEXIBLE DEBRIS FLOW BARRIERS

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ABSTRACT

A new type of flexible net barrier system designed to protect against debris flows with volumes of up to 1000 m^3 has been developed. A detailed study and testing programme, conducted for the first time, has demonstrated their highly cost effective and efficient design in comparison to massive concrete barriers. A multi-step impact model was developed describing the filling process and the acting forces to the barrier simultaneously. During debris flow events, the total pressure distribution on the net can be approximated by time-discretizing the continued filling and by tracking following surges over the original deposits. In case of a completely filled barrier, overflowing debris material loads the net with a normal and shear force component. The hydrostatic pressure and the additional weight of overflowing material are reduced through compaction and drainage over time. The observed overflow of a filled barrier without any damages led to the idea of multilevel barrier application to gain higher retention volumes.

The theoretical model has been validated and verified using a full-scale and instrumented field installation of a net barrier at the Illgraben torrent in Switzerland. This enabled (a) to investigate its performance, (b) to measure the impact forces and (c) to provide information on the expected maintenance. Impact and shear forces were measured at a shear wall and a force plate which delivered useful information for the model like pressure profile over flow height, density, normal and shear forces.

The developed load model guides design of debris flow retention, and provide impact forces for correct barrier design.

Key words: Debris Flows, Barrier, Mitigation, Dimensioning, Design

INTRODUCTION

Debris flows can be mitigated by (a) dewatering the debris, which removes one necessary component for a debris flow, and (b) providing a retention system. These two principles apply to flexible barriers that are commonly used for rockfall protection. To apply flexible barriers to debris flow, several questions require answers: What are the debris flow loads? How does the barrier perform during the filling process? What are the physical limits for the investigated barriers? Focussing on these questions a load model is presented that allows the design of flexible barriers for debris flows.

Experiences from North America, Japan and Europe (Duffy 1998 & De Natale *et alii,* 1996) have proven that flexible protection systems have an ideal bearing behaviour to stop dynamic loads such as debris flows due to their large deformation capacity and their water permeability.

A flexible debris flows barrier (see Fig. 1) is typically placed in the river channel between the river banks, with a potential to span up to 15 m (25 m

Fig. 1 - Debris flow barriers 1998 in Aobandani, Japan (left, 750 m³ retained, deflection 2 - 3 m, remaining barrier height reduced from original 5 m down to 3.5 m) and 2008 in Villar Sautoreglia, Italy (right, 1500 m³ retained). Post-event material (water and sediments) goes over the barriers

Fig. 2 - Development of a load model for flexible debris flow barriers: Field tests in the Illgraben (left), physical modelling with small scaled tests in the laboratory (centre) and numerical modelling with the finite element software (right) (Wendeler, 2008; Volkwein, 2004)

with additional posts) with heights ranging 2 to 6 m. A steel net is spanned by support and lateral ropes. The ropes are anchored in the banks with anchor lengths depending on the load capacity of the ground. Plastically deforming and hence energy absorbing elements in the ropes allow large plastic deformations in the barrier system and reduce the peak loads during impact.

The goal for a design model for such barriers is to obtain the forces within the single components (ropes, net, posts, anchorage, foundation). Furthermore, the adjustable lengthening of the energy absorbers allows optimizing the load distribution within the system.

Like rock fall loads the main force acts dynamically on a protection barrier during debris flow. In contrast to falling rocks, debris flows produce a distributed load and debris flows occur in surges.

In the following; a load model is presented that allows a design of a flexible barrier against debris flows. This model has been developed and validated based on laboratory test, full scale field tests and numerical simulations (Wendeler, 2008; Wendeler *et alii*, in prep., Fig. 2).

DESIGN PRINCIPLES

Due to the net's permeability an impacting granular debris flow is drained as a result of the retention of rougher material. The stopped certain length of the debris flow and the amount of debris material gives the so called relevant length / mass-ratio. The continuous filling of the barrier can now be modelled step by step: After the first impact the additional material overrides the first arrested surge (see Fig. 3) providing additional weight and

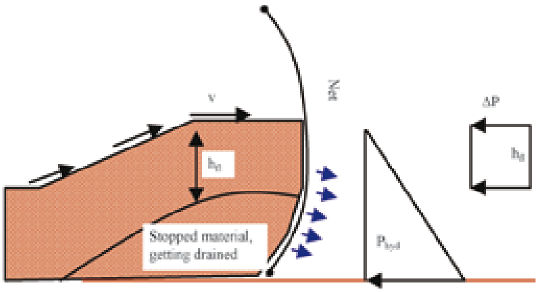

Fig. 3 - Modelled second filling wave of a debris flow with flow height h_0 and its loading components of dynamic pressure (ΔP) and hydrostatic pressure (P_{hyd}) (Wendeler et alii, in prep.)

compressing the underlying sediment thereby releasing most of it's pore water over the time (Wendeler, 2008).

Should a barrier fill completely following surges will spill over the barrier adding additional loads by weight and shear forces. The time to drain fine granular material depends on grain size composition and the water content at impact. The static loads transform from hydrostatic to earth pressures.

Different aspects have to be considered to avoid barrier failure:

- strong anchorage
- strong support ropes
- energy absorption
- protection of the top support ropes against abrasion
- retention volume commensurate with the design volume.

The maximum retention capacity of a barrier is dependent on the channel slope, deposition angle and the height of the barrier (Lien, 2003). Empirical studies suggest that the deposition angle corresponds to 2/3 of the original torrent gradient (Rickenmann, 1999, Fig. 4).

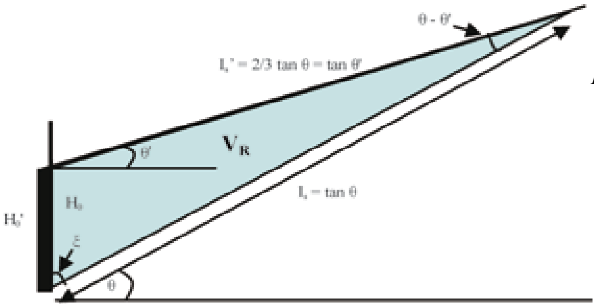

Fig. 4 - Deposit in the flow direction behind the barrier (Wendeler, 2008)

Kinetic energy is mainly dissipated in the energy absorbing brake elements. To activate the brake elements, the net must transfer the load to the support ropes in which they are installed. During a debris flow both single impact loads from individual boulders and fully distributed loads of the flow's front occur. The links between the single net meshes have to be strong enough to withstand the high forces that must be transmitted to the margins and supporting structure.

SAFETY CONCEPT

Ideally, intensity and return period lead to a probabilistic density function to describe the debris flow pressure. However, this safety concept was not based on a probabilistic analysis because of limited field investigation data. But the given safety parameter were deduced from existing Swiss guidelines dealing with natural hazard impacts on buildings (Egli, 2005) and snow fences (Buwal, 2007).

Resistance: The resistance safety factor can be set to γ_R= 1.35 according to Buwal (2007).

Load: The safety factor on the loading is first influenced by the risk potential (Tab. 1). Three risk classes were defined in Table 2 summarizing proposed safety load factors. A preliminary guideline for a safety concept of debris flow protection measures is in review in Austria (ONR 24802, 2009).

Risk class	Potential consequences
1	• Low risk potential in loss of human life • Low economic consequences
2	• Medium risk potential in loss of human life • Significant economic consequences
3	• High risk potential in loss of human life • Serious economic consequences

Tab. 1 - Classes according to risk potential

Risk class \ Return period	1 - 30 years	30 – 100 years	More than 100 years
1	1.0	1.0	1.0
2	1.3	1.3	1.2
3	1.5	1.3	1.2

Tab. 2 - Safety factor γ_F on the loading site for different time periods and risk classes

DIMENSIONING

DEBRIS FLOW CHARACTERISATION

From a mechanical point of view debris flows can be divided in two main types:

- Mud flows that consist of water and fine material; and.
- Granular debris flows that consist of water and a coarser grain size distribution, typically lacking the clay fraction.

STEP BY STEP APPROACH

Figure 5 shows a step by step approach to design net barriers. The first step is to estimate a possible debris flow volume VDF. Numerous different formulas are proposed in the literature, although each has limited reliability. Therefore, observations and experiences at the location of the project should be used in conjunction with the respective formulas. A further method is to execute a geomorphologic assessment of the sediment potential (Rickenmann, 1999). It is therefore recommended that debris flow volumes must be determined in detailed site-specific studies and that a frequency-magnitude relationship needs to be established using extreme value statistics in order to obtain a reliable design basis. Examples on relationships between debris flow Volume V_{DF}, catchment area A_c and mean slope inclination I_s can be found in Bergmeister *et alii* (2008), Rickenmann & Zimmernann (1993), Hampel (1980) or D'Agostino *et alii* (1996). The volume capacity for one flexible net barrier system lies in a range of

$$V_R = 100\ m^3 - 2{,}000\ m^3$$

depending on channel topography.

Several studies have proven that the peak discharge of a debris flow is correlated to its volume. There are

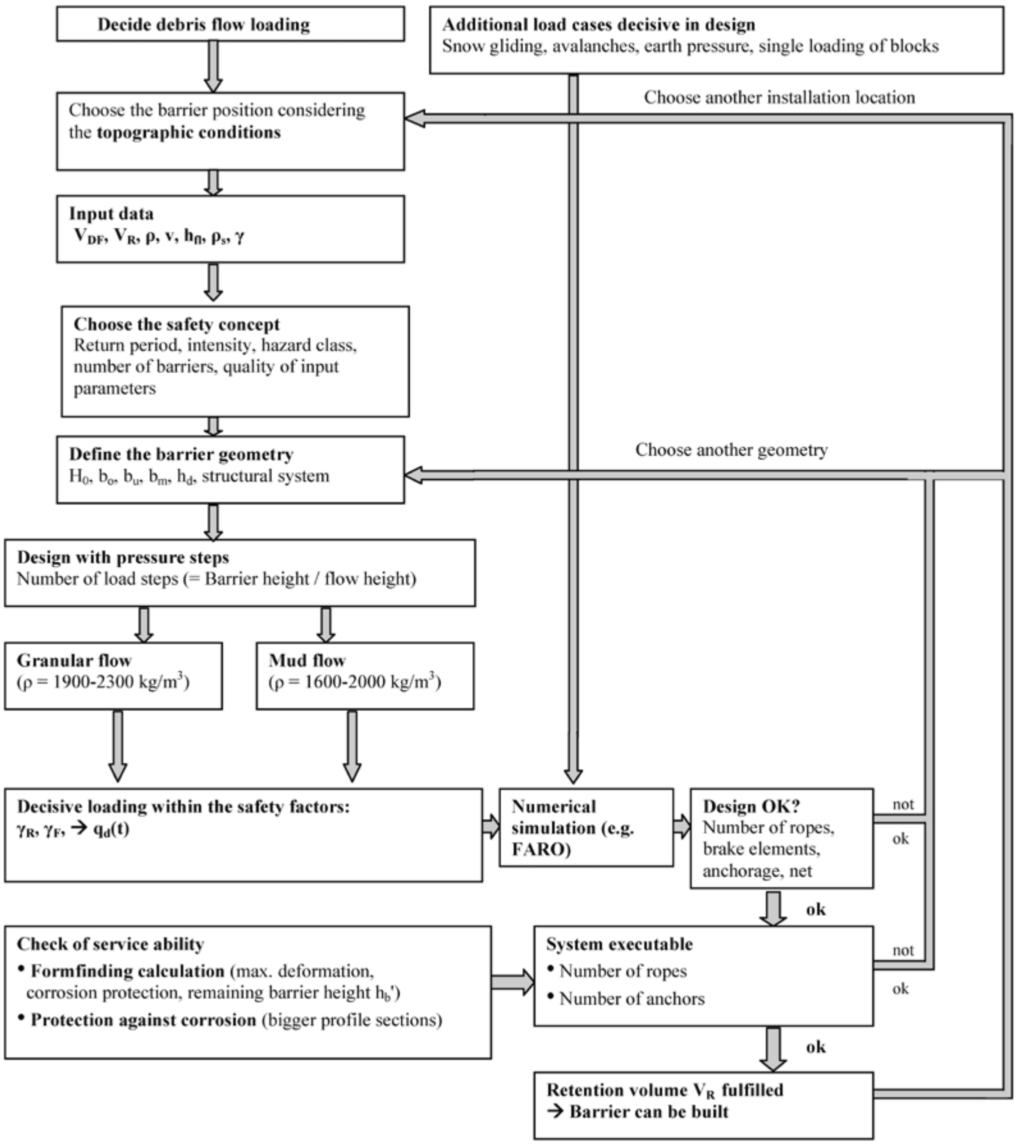

Fig. 5 - Diagram for step wise dimensioning procedure for flexible debris flow barriers. A symbol list can be found at the end of the document

different relations for granular debris flows and mud flows. Mizuyama *et alii* (1992) propose for a granular debris flow (debris avalanche) the empirical relationship between peak discharge and debris flow volume:

$$Q_P = 0.135 \cdot V_{DF}^{0.78} \quad (Q_{P,d} = 5\ m^3/s - 30\ m^3/s) \qquad (1)$$

Using the peak discharge Q_{Pd}, allows estimating the average flow velocity v at the front of the flow. Rickenmann (1999) proposes a regime condition for the relation between velocity, peak discharge and slope inclination (friction considered). I_s refers to the gradient of the torrent (tangent of the slope inclination in degrees). Typical values for Is are $I_s = 0.18$ (10°), $I_s = 0.36$ (20°) or $I_s = 0.58$ (30°).

$$v = 2.1 \cdot Q_P^{0.34} \cdot I_S^{0.2} \quad (v_d = 2\ m/s - 8\ m/s). \qquad (2)$$

Japanese guidelines (PWRI, 1988) suggest a Manning-Strickler equation to determine the average flow velocity (see also Gregoretti, 2000). Here, n_d refers to a pseudo-manning value which typically lies between 0.05 s/m$^{1/3}$ and 0.18 s/m$^{1/3}$, while the values for granular debris flows lay between 0.1 s/m$^{1/3}$ and 0.18 s/m$^{1/3}$.

$$v = \frac{1}{n_d} \cdot h_{fl}^{0.67} \cdot I_s^{0.5} \quad (v_d = 1 \text{ m/s} - 8 \text{ m/s}) \tag{3}$$

However, it is recommended to use super elevation and to back calculate the velocities in combination with a sensitivity analysis instead of using eqn. 3.

It is recommended to use both equations and compare the results.

The flow depth h is calculated as a function of the cross section and the peak discharge.

$$h_{fl} = \frac{Q_p}{v \cdot b_u} \quad (h_{fl,d} = 0.1 \text{ m} - 3 \text{ m}) \tag{4}$$

However, the typical flow depth is better measured in the field based on levees or scour marks.

The density of the material is about ρ ≈ 1,600-2,000 kg/m³ for a mud flow and about ρ ≈ 1,900-2,300 kg/m³ for a granular debris flow RICKENMANN (1999).

The post-event barrier height is about 3/4 of its pre-event height. Thus the minimum barrier height is determined as follows:

$$h_b = \sqrt{V_R \cdot \frac{32}{9} \cdot \frac{1}{b_m} \cdot \frac{1}{\sin\varepsilon\left(\frac{\sin\varepsilon}{\tan(\theta - \theta')} + \cos\varepsilon\right)}} \leq 6m \tag{5}$$

with V_R retention volume, ε barrier inclination and θ and θ′ the gradient of the material before and after a debris flow event.

MULTI-LEVEL CONSIDERATIONS

The distance between two barriers is important for the construction of a multi-level barrier in series. The distance should be long enough that a hydraulic jump and a backwater curve next to the check dam can achieve the greatest loss of energy (see Figure 6, the blue-line is the water level). The inclination of the river bed behind a filled barrier I_s' should achieve a subcritical flow regime in order to have more stable river bed conditions.

The distance between the barriers should not be smaller than the influenced backpressure length.

The behavior of multi-level net barriers was studied in the Merdenson torrent in the Canton of Valais, Switzerland. Three barriers were installed in series in 2006. During the following winter in January 2007, debris flows filled the barrier systems. The total retained volume was 800 m³ as determined by 3D topographic measurements before and after the filling event (Fig. 7).

The field tests showed the potential for several barriers in series to increase the retention volume and their ability to stabilize river bed method. Finally, the long-time behavior of steel barriers (abrasion, corrosion) was studied at the test site over a three year period.

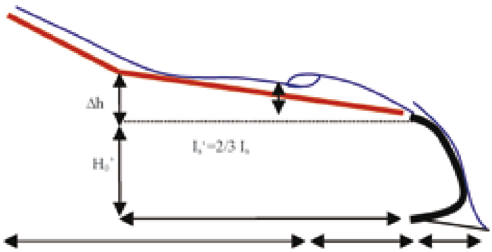

Fig. 6 - Filled barrier as a check dam and its flow regime with the change from subcritical flow by a hydraulic jump to supercritical flow regime (WENDELER, 2008)

Fig. 7 - 3-D Model of the Merdenson torrent with empty barriers (left) and filled barriers (right)

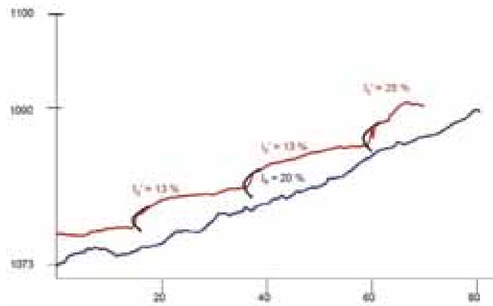

Fig. 8 - Cross sectional line of the Merdenson torrent without (blue) and with filled barriers (red)

RANGE OF APPLICATION OF FLEXIBLE BARRIERS AGAINST DEBRIS FLOWS

Barrier systems should be located in a relatively straight torrent section. The torrent's gradient should be as low as possible to reduce the impact velocity and to maximise the retention capacity. The location should be easily accessible to ensure inspection and debris removal upstream of the barrier. The bed at the barrier location should be stable enough to withstand the expected erosion; otherwise the channel bed and the barrier will require stabilization measures. The banks on both side of the torrent need to support the anchor loads. After a debris flow, plastically deformed components must be replaced; most commonly these are the brake elements.

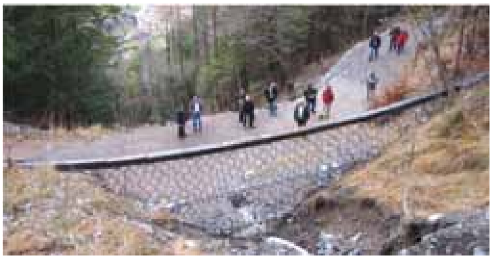

Fig. 9 - Debris flow barrier in the Engler torrent, Berner Oberland, Switzerland

A gap between the net and the riverbed avoids unwanted filling through normal bedload or sediment transport.

PROTECTION WITH A SINGLE BARRIER

Figure 9 shows a single barrier system installed in the Engler torrent of Meiringen, Switzerland. A hospital is situated beneath a small road. An active landslide supplies material for small debris flows every period of heavy rainfall. The function of the barrier is to catch the material and to slow down and stop the debris flow. The barrier must be cleaned out after an event.

INCREASED RETENTION USING A MULTILEVEL SYSTEM

With several barriers in a row, the retention capacity can be increased. Figure 10 shows a multilevel system in the Hasliberg region in the Bernese Alps at the Milibach torrent. Thirteen barriers were installed in a row and have a collected retention capacity of approximately 10,000 m^3 of debris. The multilevel system works by successively filling each barrier in the torrent, should the first barrier fill to maximum capacity any further material overflows into the following barrier until the entire system is filled. The barriers must be cleaned out after an event.

ENHANCEMENT OF A RETENTION BASIN

Figure 11 shows the application of a barrier as a supplementary structure of a retention basin to increase the retention volume. The barrier is situated at the Schlucher Ruefe torrent in Liechtenstein.

RIVER BED STABILIZATION

The barriers in the Merdenson torrent, Canton of Valais, Switzerland (Fig. 12), are intended to stabilize the river bed. Remaining filled, the step-wise arrangement of the filled barriers leads to an energy loss of the debris flow regime. The barriers remain filled after an event. Static loads and corrosion have to be considered.

Fig. 10 - Multi-level debris flow barriers in Hasliberg region, Switzerland

Fig. 11 - Debris flow barrier at the Schlucher Ruefe torrent, Liechtenstein

Fig. 12 - Filled multi-level barriers in the Merdenson torrent, Switzerland

Fig. 13 - Net barriers as a repair and deviation construction in the Illgraben, Switzerland

DEVIATION STRUCTURE, REPAIR OF EXISTING STRUCTURES

At check dam 25 in the Illgraben in Switzerland (Fig. 14), the debris flows increasingly eroded the slopes on the right side of the dam. Two barriers installed in

Fig. 14 - Scoured check dam base (left) and protected check dam base by a naturally filled net barrier

Fig. 15 - Net barrier against culvert blockage installed directly in front of a culvert, The Narrows, CA

Fig. 16 - Net barrier against driftwood

two stages remain filled with debris. The retention of material redirects subsequent debris flows back over the repaired concrete check dam. Both barriers were filled with a natural debris flow and will remain filled.

PROTECTION AGAINST SCOUR

Figure 14 illustrates the consequences of debris flow scour to the base of a check dam in the Merdenson torrent. A net barrier was directly installed in front of the dam. It now acts as protection for the dam toe.

CULVERT BLOCKAGE

In front of culverts where debris and drift wood is expected, a net can be installed to protect culverts from blockage (Fig. 15).

DRIFTWOOD RETENTION

The barriers can be applied in torrents to catch driftwood. The load distribution is similar to debris flow loading. For the driftwood load case, a different dimensioning concept has to be applied (Fig. 16; Rimböck, 2003).

SUMMARY AND CONCLUDING REMARKS

A design concept has been proposed that allows the dimensioning of flexible barriers to mitigate debris flows. The design load is a debris flow with a certain flow depth and represents a worst case scenario including smaller loads from sediment filling (if there is no gap between the net and riverbed) or flood events.

Since no useable design concepts are available so far we propose the presented design concept as a basis for a design guide. We welcome further discussion and suggestions for its optimization. The proposed design concept is of course limited to debris flow that can be covered by the proposed barriers. Huge events in very wide channels or with enormous flow heights are not considered yet and a design concept has first to be validated for such dimensions. But we hope that the future international developments in this area will improve the knowledge and the capabilities of such barriers.

LIST OF SYMBOLS

d_{90}	90 % of the grains are smaller than this size	[mm]
I_s	Torrent inclination	[-]
I_s'	Inclination of retained material behind a barrier	[-]
V_R	Retained volume behind a barrier	[m^3]
V_{DF}	Total debris flow volume	[m^3]
A_c	Catchment area	[km^2]
H_0	Height of an unfilled barrier system	[m]
H_0'	Height of a filled barrier	[m]
h_d	Height of the basal opening	[m]
h_{fl}	Flow height of the debris flow	[m]
n_d	Pseudo-manning value	[s/m$^{1/3}$]
b_u	Bottom width of the barrier section	[m]
b_o	Width of the barrier at the top ropes	[m]
b_m	Middle barrier width	[m]
ρ	Density of the debris flow	[kg/m^3]
Q_p	Design debris flow discharge	[m^3/s]
v_d	Design flow velocity	[m/s]
$v_{d,max}$	Maximal design flow velocity	[m/s]
γ_F	Safety factor for the loading side	[-]
γ_R	Safety factor for the resisting side	[-]
ΔP	Dynamic component of debris flow pressure	[N/m^2]
P_{hyd}	Hydrostatic pressure of debris flow	[N/m^2]

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