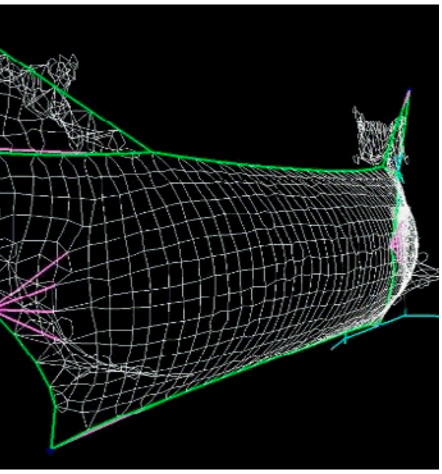

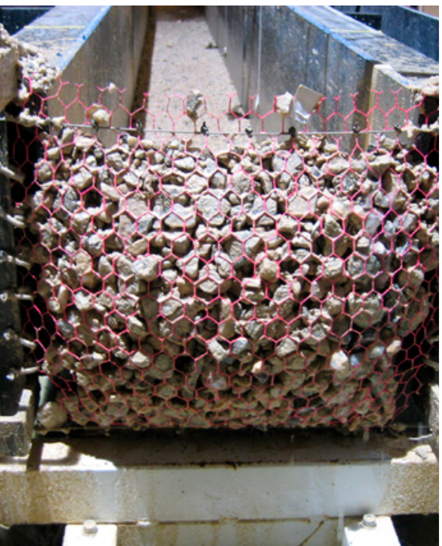

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Design and application

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Side view of a filled debris flow barrier in Illgraben VS, May 2006
Numerical simulation of debris flow barrier
Debris flow front
Physical modelling of debris flow barriers in laboratory

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Preface

The somewhat impressive performance of today's flexible rockfall protection net installations has motivated research in the last few years into exploring the potential of net installations with regard to their use with distributed loads. While this has been common practice in the area of active avalanche protection, their use in debris flow channels was also examined at the WSL from 2005 to 2008. This involved general suitability, a draft of a load model for the assessment and the development of suitable verification procedures. Initially, the structure of the barriers was specified just as little as the combination of different components typical in the area of net installations. For example, cables, supports, so-called brake elements and suitable nets. This research project was partially financed by the Commission for Technology and Innovation (KTI) of the Swiss Federal government.

The project dealt with different aspects of the barriers. On the one hand, this involved theoretical approaches and numerical simulations. However, it became apparent that small-scale laboratory - experiments are not suitable for developing physical models. The rheology of debris flows and their interaction with a barrier, particularly a flexible one, is too complex. The most important findings were obtained from the (partially multiple) installation of barriers in two active debris flow channels. Only in this way could the suitability of a barrier type be clearly verified. The practical elements such as installation, maintenance, emptying or clearing could also be optimised as also the supporting structure. Long-term observations with regard to service life and corrosion behaviour are still underway at the WSL.

This report summarises the findings of the Swiss Federal Research Institute WSL with regard to the functionality of flexible debris flow barriers. It is based to a large extent on the dissertation of Corinna Wendeler, which was a by-product of the above project. I am confident that engineering practice provides a useful basis for the assessment of flexible debris flow barriers and the verification of the necessary elements.

Birmensdorf, March 2014

Manfred Stähli, Head of Mountain Hydrology and Mass Movement Research Unit

Summary

Experience gained in North America, Japan and Europe has proven that flexible protection systems provide an ideal method of resisting dynamic loads such as those resulting from debris flows, due to their large deformation capacity and permeability to water. Similar to rockfall loads, the action of debris flows on a protection barrier is mainly dynamic. However, in contrast to falling rocks, debris flows do not impose a concentrated impact but a distributed load on the protection system. Therefore, structural adaptations of a typical rockfall protection system are unavoidable in order to achieve a reliable protection system against debris flows such as special rope guiding details, abrasion protection, etc. This report summarizes the results of a research project aimed at developing a dimensioning concept for flexible debris flow protection systems. The concept involves specially focused research combining laboratory tests, fully instrumented field installations and the corresponding numerical simulations. The report is intended to provide a basis for engineers or other specialists in the field of natural hazards to calculate and understand the design of flexible barriers against debris flows within channelized river beds.

1 Introduction

The progress over the last few years in the area of protection nets to restrain high-energy rockfall, with the relevant experience gained, allows the basic advantages of flexible protective structures to extend their range of application to channelized debris flows. This report provides information on the boundary conditions for this area of application when using flexible barriers. Based on the procedure described here, it is possible to correctly assess flexible debris flow barriers.

On the one hand, this report is intended for planning departments that put out tenders as well as manufacturers and providers of flexible debris flow barriers. The background for the assessment is the assumption of a "design" debris flow, whereby a distinction must be made between a granular event and a mudflow. The characteristic debris flow dimensions necessary for this, such as flow height h_{Fl} and front speed v_{Fr} are therefore not calculated here but have to be determined separately in advance. This also requires appropriate expert opinions or simulations. Further basic information on debris loads for object protection can be found in Egli (2003).

The doctoral thesis of Corinna Wendeler (Wendeler, 2008) is authoritative in the area of protection nets for preventing debris flows. This report is based to a large extent on the findings there that are based on extensive field and laboratory experiments as well as numerical simulations. In the meantime the results have been adopted by other institutions and included in assessment proposals (Kwan & Cheung, 2012) or publications (Canelli et al., 2012; Brighenti et al., 2013).

The application area of the protection barriers examined here is limited to channels with clear channel mounts. A protection barrier spans one embankment to another. Between the river bed and the lower net edge, a free space (passage) can discharge the normal outflow and low-level high water does not cause damage. It also provides an escape for animals.

The protection net is spanned using supporting cables and is also fixed along the area of the embankment (e.g. with edge cables). The cables are anchored in the embankments. If the span width becomes too wide (typically >15–20m), intermediate supports can be installed for the supporting cables. In addition so-called brake elements in the supporting cables stretch them when loaded so that the cables can optimally align with regard to the respective load action. In the case of a barrier overflow, the top supporting cable must be provided with abrasion protection. Fig. 1 shows an example of a barrier designed in this way.

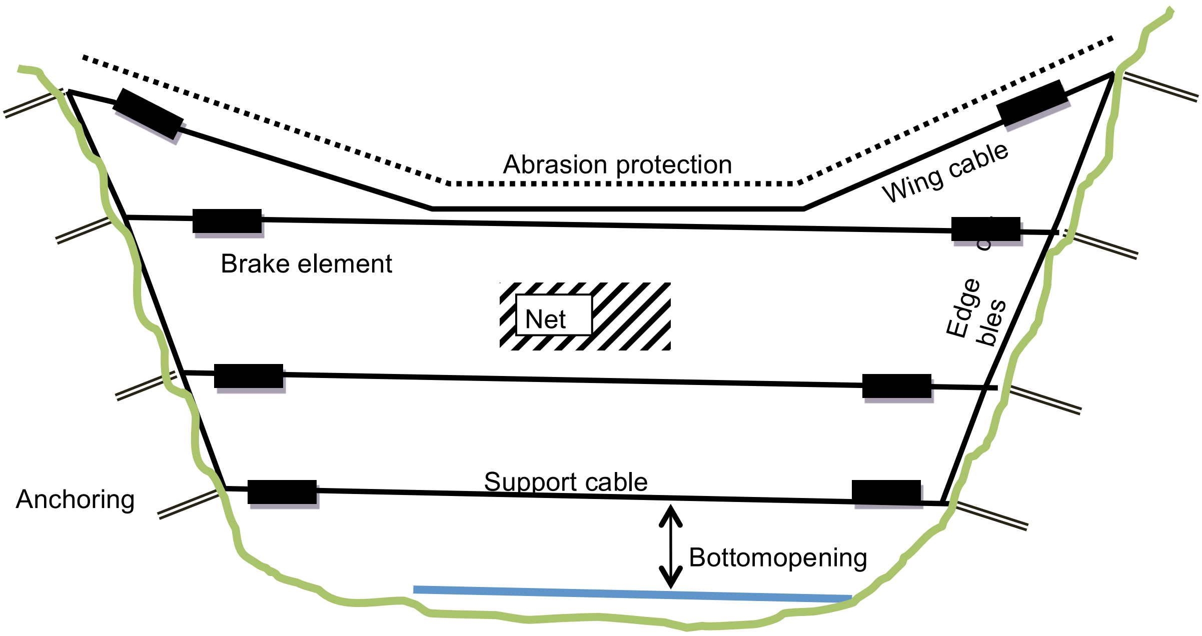

Fig. 1: Basic arrangement of a typical flexible debris flow barrier.

The barriers dealt with here are designed to slow down and collect the incoming debris flow material as a result of their large deformation capability. The net structure enables drainage of the debris mixture, which quickly comes to a standstill and is stabilised due to the increasing friction of the solid particles. Additional debris material is stopped or decelerated via the upwards backlog channel (silting up) until the net barrier is completely backfilled.

The major advantage of net barriers is their comparatively simple and quick installation. The largest device necessary is a drill truck to install the lateral anchors. The remaining material can be delivered by truck or helicopter and installed without the use of heavy machinery. The finished construction looks very transparent and is thus well integrated in the landscape. As a rule the corrosion protection of the barrier components guarantees a minimum event-free service life of between 30 and 50 years. If an event occurs, the barriers can be emptied and repaired in an efficient and coordinated manner. For the latter, as a rule the brake elements in particular must be replaced.

Flexible debris flow barriers can be used in many different ways. Examples are shown in Annex C. For example, if several barriers are installed in succession in a channel, the maximum retained volume increases accordingly (so-called multi-level barriers). Multiple barriers are particularly useful near the triggering area. Here the barriers can completely stop a small debris flow and thus prevent channel and bank erosion as well as the increasing mud-flows that arise. In comparison to conventional debris-flow barriers, flexible barriers are advantageous especially in the triggering area as they can easily be flown in with a helicopter.

The assessment is based on calculated impact pressures, which are converted into forces acting on the barrier. This procedure showed the best efficiency, Wendeler (2008), and is thus preferable to other approaches such as an energy approach, which is also described in Kwan & Cheung (2012) but is not recommended in this report. An assessment developed on a solely theoretical basis is not recommended. For this reason, this guideline proposes the basic verification of the functionality of a barrier concept used by means of 1:1 field data. Based on this, numerical models can be calibrated and/or validated and in turn variations of the tested barrier type are developed with the aid of numerical or analytical methods.

The debris flow events dealt with here are described using the following parameters (see also Fig. 2) which must be determined separately* in advance:

- Density
- Front/flow speed v_{Fl}
- Flow height h_{Fl}
- Total volume V
- Diameter of single blocks d
- Channel slope
- Sedimentation angle

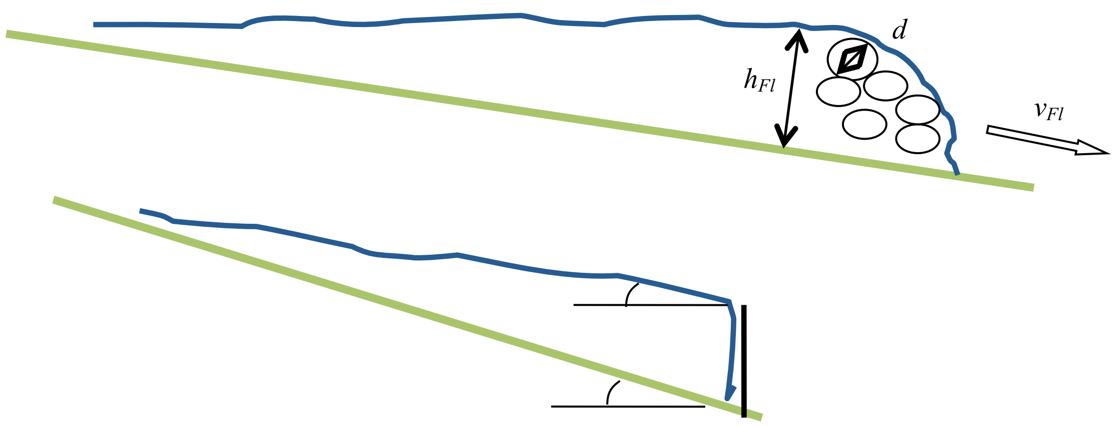

Fig. 2: Relevant characteristics of a debris flow front (above) and the deposited debris flow material (below) determined according to specific procedure, e.g. Egli (2003) or Hürlimann et al. (2008).

The front density is decisive for the type of debris flow depending on the geological conditions in the drainage area, the grain size distribution and the water content in the mixture. Depending on this, a granular or fluid event may be assumed. The flow height and speed significantly influence the expected impact pressures The total volume in combination with the channel slope and the sedimentation angle is relevant with regard to the total retention capacity of each barrier.

For the maximum load of a debris flow barrier it is assumed that the debris flow occurs suddenly and that the barrier is thus loaded by an impacting front. Chapter 3 shows the load model used for this.

2 Components of a flexible debris flow barrier

As Fig. 1 shows, a typical flexible debris flow barrier consists of various components that are briefly described in the following. All components must possess adequate corrosion protection.

2.1 Net

The net is initially loaded by the debris flow and must transfer the acting impact forces and compressive forces to the supporting structure. Its spatial distribution must be matched to the load-bearing capacity of the nets, i.e. weaker nets require more supporting cables. The mesh size should approximately correspond to the d_{90} grain size, i.e. 90% of the incoming particles have a diameter smaller than d_{90}. In this way, water and smaller particles can be well drained.

2.2 Supporting cables

The supporting cables transfer the loads acting on the net to the anchors. Depending on the expected load, a supporting cable can consist of several individual strands. As a rule several supporting cables are uniformly distributed over the barrier height. The supporting cable position should also be optimised with regard to the expected deformations of the barrier. An optimal alignment of the cables is enabled by means of integrated elements that allow for large deformations (so-called brake elements, see section 2.4).

2.3 Wing cables and edge cables

The wing cable runs, e.g., across the middle half of the barrier parallel to the upper supporting cable and is guided upwards at the sides. This cable arrangement causes the debris flow to be concentrated towards the barrier centre and reduces embankment erosion. The wing cable also reduces the lowering of the upper side of the net.

The edge cables run parallel to the embankment and are anchored to it at regular intervals. As a result, the net is laterally supported and lateral openings in the barrier are prevented.

2.4 Brake elements

The debris loads are transferred via the net, supporting cables and the wing cable to the anchors. Elements installed here with a large plastic deformation capacity reduce load peaks that can arise for the individual impact of large blocks and - due to their large elongations – optimise the barrier shape to better sustain the acting loads. The brake elements and connected cables must be matched to each other here. As the loads increase with the level of filling, brake elements with continuously increasing load deformation characteristics are recommended.

2.5 Anchoring

The lateral anchors of the cables are normally installed using cable anchors or self-drilling anchors with flexible anchor heads. The orientation of the anchors should be adjusted to the geometry of the barrier. The flexible anchor head enables optimum loading by the cables even when the barrier is deformed. Anchor head foundations are recommended.

2.6 Supports

In the case of larger span widths (> 15–20 m) for wide channel beds that result in useful heights that are too low in the case of an event or when filled, additional supports can hold them up. The support foundation must be designed for tension, compression and shear.

2.7 Abrasion protection

If a barrier overflow is expected due to the long service life of a barrier that is already filled or for a serial installation of several individual barriers, the upper supporting cable and wing cable must be provided with protection against abrasion and the individual impact of large blocks. The deformations of the upper barrier edge must be able to adjust to abrasion protection and shear force peaks in the longitudinal cables should be prevented.

3 Force-based loading approach for debris flow barriers

Substantial fluid structure simulations are required in order to completely describe the impact of debris flow at a barrier in a physically correct manner. Despite the general availability of suitable software, such simulations involve a great deal of time and effort. In particular, the flow properties of a debris flow must be correctly recorded and this requires extensive calibration. For the simulation of the flexible barriers, their deformation capacity must also be included in the simulation and the loads acting within the barrier and at the anchors must also be correctly represented. Boetticher et al. (2011a & b) describe this kind of simulation in detail. In practice however - at least for now - they cannot be suitably applied. In this respect, the use of a suitable load model such as the one described in the following can be used instead.

3.1 Model basis

Wendeler (2008) presents an approach that determines the pressures acting on the barrier and thus the acting forces, which attempts to represent the real situation very well. This approach is also used in the following. Wendeler (2008) showed that with an energy approach according to Kwan & Cheung (2012) a conversion of debris flow kinetic energy into suitable rockfall energy initially appears simple but does not provide satisfactory results. The loads on the barriers differ too much compared to the field data. In addition, the acting debris energies still have to be transformed into forces in the components and the anchors.

As mentioned in section 1, a debris flow event with a distinct front is assumed for the barrier as the maximum load (Fig. 3). The barrier encounters this with the so-called "initial impact". Afterwards the barrier is filled with the rest of the material. This continuous process is discretised in this load model so that the barrier is filled in individual steps with a uniform step height (e.g. equal to the flow height) (Fig. 4). If additional debris flow material or subsequent events are expected after complete filling of the barrier, the overflow loading condition must also be considered for the assessment (Wendeler, 2008; Kwan & Cheung, 2012, Fig. 5).

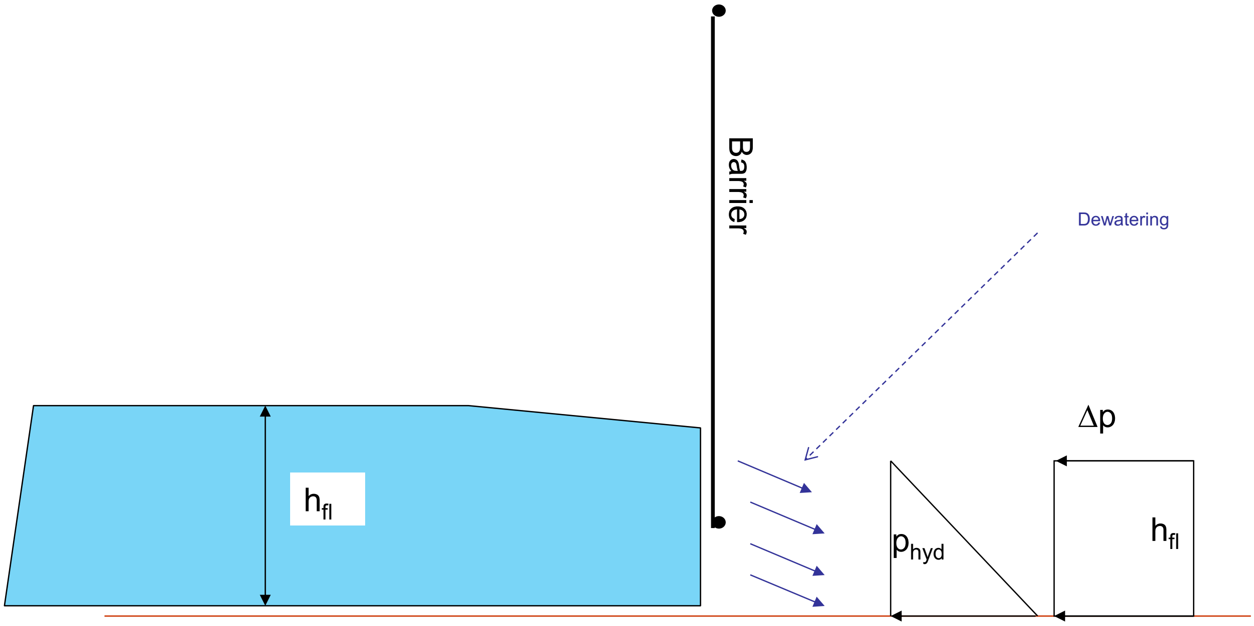

Fig. 3: Initial impact of the debris flow on the barrier with applied pressure impulse model consisting of the hydrostatic pressure p_{hyd} and the hydrodynamic pressure Δp.

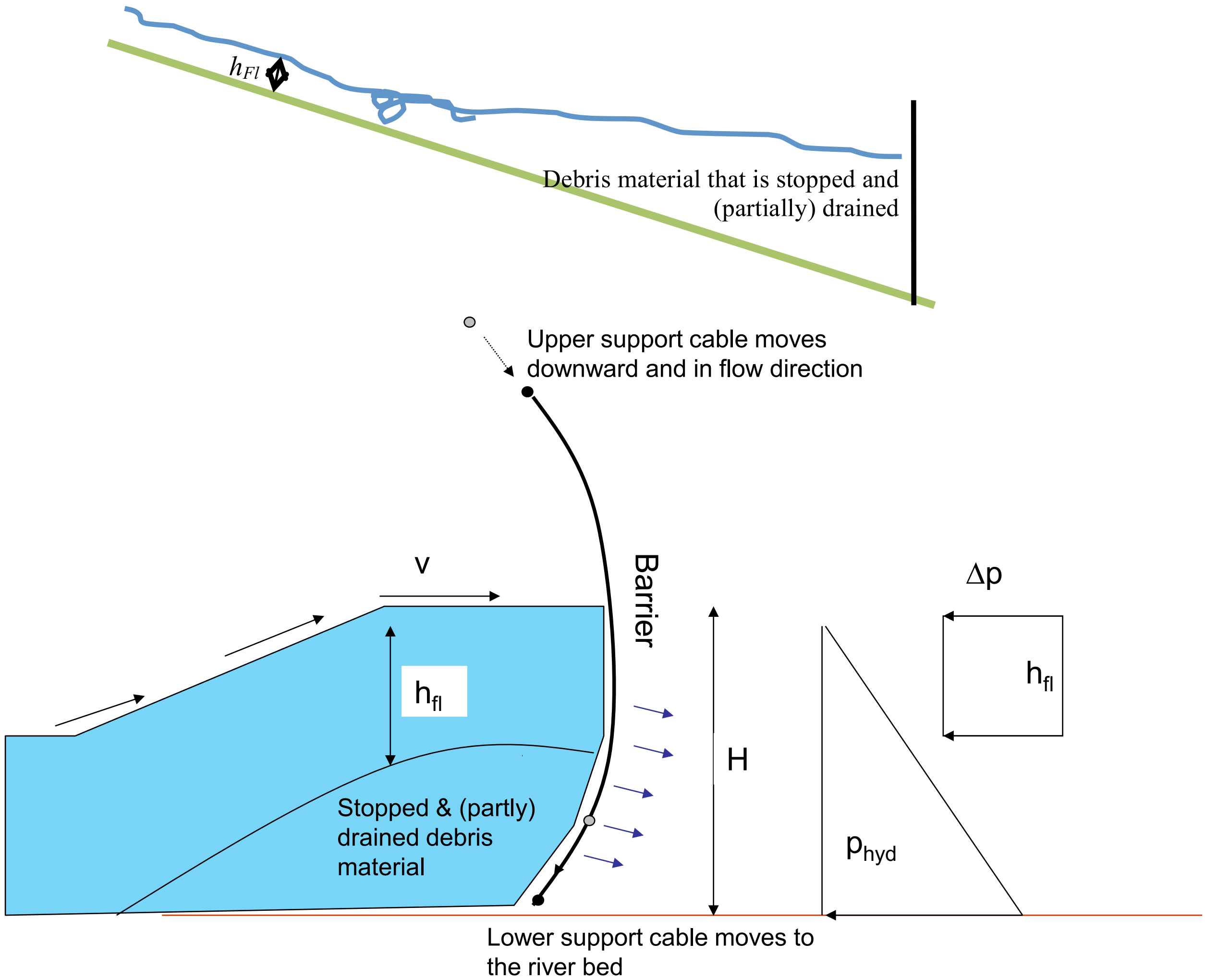

Fig. 4: Actual filling process (top) and discretised filling process in the model incl. expected deformations of the barrier (bottom).

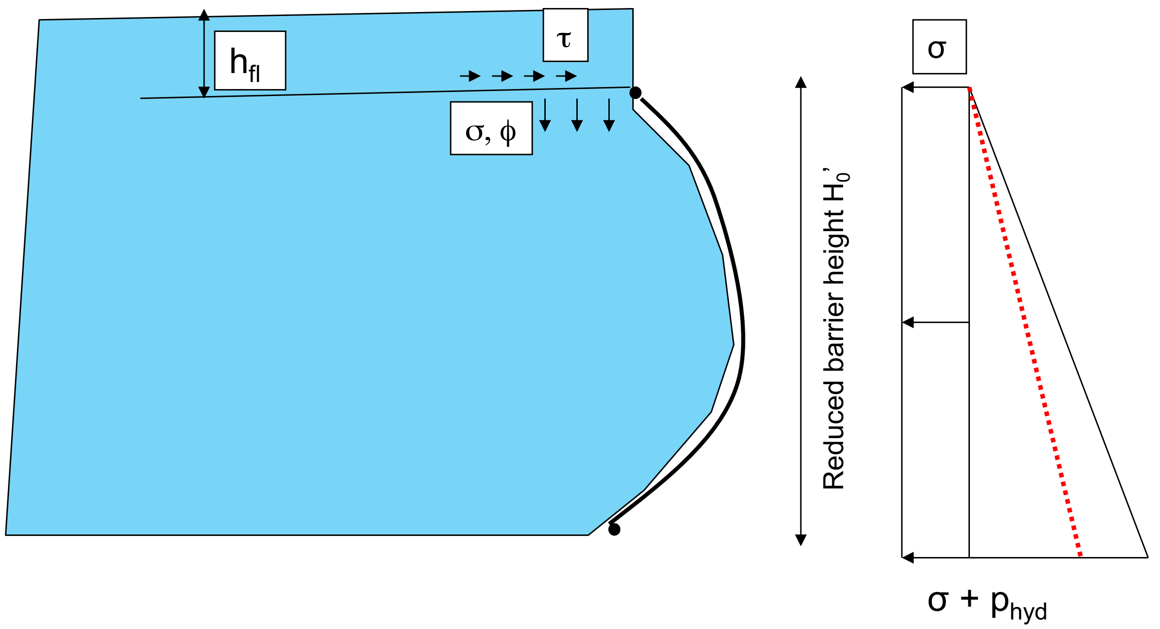

Fig. 5: Load situation during barrier overflow that only exhibits a reduced useful height due to filling compared with the initial height.

3.2 Determination of relevant loads

The acting hydrostatic ($\Delta p = p_{stat}$) and hydrodynamic (p_{dyn}) pressures [N/m^2] are assumed to be uniformly distributed over the channel width (the suitability of this model in Wendeler (2008) is verified for typical channels but still has to be checked for the channel geometry in individual cases) and calculated according to

$$p_{dyn} = \alpha \rho v^2 \text{ and } p_{stat} = KH\rho g \quad (1)$$

with	v	=	Impact speed		
	H	=	Current filling height		
		=	Debris density	=	1600 – 2200 kg/m^3
		=	Pressure coefficient	=	2.0 (0.7 – 1.0 for 1900 kg/m^3)
	K	=	Earth pressure coefficient	=	1.0
	g	=	Gravitational constant	=	9.81 m/s^2

In the case of overflow, an additional tractive/shearing stress acts on the upper side of the filled barrier which must also be dissipated by the barrier:

$$\tau = h_{Fl} \rho g \tan \varphi \quad (2)$$

with	h_{Fl}	=	Flow height
	φ	=	Friction angle of the debris material

In this case, the selection of the pressure coefficients is decisive for the calculation of the impact pressures. As shown in Egli (2003), for example, this can be assumed to be 2.0 for the impact of granular debris flow front. At the same time this value also takes into account the corresponding higher pressures which can arise during the impact of individual blocks. However if the debris flow involves a fluid event (debris density 1900 kg/m^3), the pressure coefficient can be reduced down to 0.7 according to Wendeler (2008). However, the impact of impacting blocks that may be carried along with the flow must then be considered separately. The size of the individual blocks can be estimated using the expected flow height.

The following apply:

- The maximum value for watery/faster and granular/slower debris flows must be determined for the hydrodynamic pressure. An example of "granular" can be found in Table 4.
- The dynamic pressure affects the flow height h_{Fl} which is assumed to be constant during the filling process; a possible reduction due to a channel width increasing with increasing storage depth is therefore not considered in order to be on the safe side (for examples, see Annex A).
- As a result of the deformation behaviour of a flexible barrier, it must be assumed that the initial height of the barrier is reduced due to the elongation of the supporting cable brakes. The acting hydrostatic pressures therefore can be reduced accordingly. The channel cross-section also reduces the pressure area.
- The acting pressures are applied depending on the valid safety concept with corresponding safety factors as proposed in Fig. 7 and/or Wendeler (2008) or Egli (2003).
- The stability of the barrier must also be proven for the impact of large individual blocks (determine diameter from channel analysis). If the dynamic pressure coefficient was set at 2.0, verification for the impact of large individual blocks can be omitted.

If the discretised filling process is visualised according to Fig. 6a–d, the relevant basic data for the acting pressures shown in Fig. 6e can be found. A tabular representation of the influence of pressure could thereby appear as represented in Annex A.

Alternatively, if a constant relevant flow volume if assumed, the flow height for a trapezoidal channel, e.g., can vary during the filling process (for examples see Annex A).

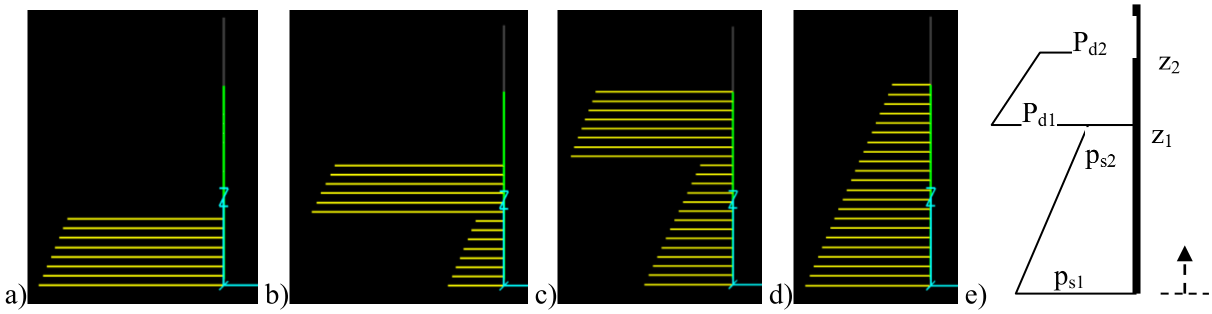

Fig. 6: a) Pressure distribution in the flow direction for the initial impact, b) and c) incremental filling process, d) overflow load case, e) abstraction of the relevant pressure values $p_{s/d\ 1/2}$ and heights of influence $z_{1/2}$.

4 Verification of the load bearing capacity

Sufficient stability that is essential for the application of a flexible debris flow barrier as well as its usability. However, up to now there are only assessment guidelines for debris flow barriers for rigid structures in Switzerland. This chapter therefore provides an adequate basis for the verification of flexible barriers that prevent debris flows. This will ensure reliable operation in the future.

The load-carrying capacity of a flexible debris flow barrier is verified using a combination of field experiments, simulations and analytical calculations. The reason for a combined approach is that it is currently almost impossible to load a barrier exactly to its design loads using a natural debris flow event. The verification of the load-carrying capacity of a debris flow barrier therefore consists of the following elements 4.1 to 4.3:

- A prototype of a debris flow barrier model is assessed according to 4.2 or 4.3.
- The corresponding function is then verified in a test according 4.1. Here all components must correspond to the types that are subsequently used.
- The results of the experimental load are compared in detail with those expected according to the design. For this purpose, relevant measurement data (anchor loads, fill level) and video recordings must be available.
- Additional barriers with a similar structural design can then be assessed in future according to the methods 4.2 or 4.3. All applied models must have been calibrated and validated in field tests.

4.1 Verification of the basic functionality using a 1:1 filling /load

In a 1:1 field test using either an artificial or natural triggering of a debris flow, a barrier with a basically similar structural design as the barrier to be verified is loaded. The filling process must be documented with video recordings. The following elements must be verified.

4.1.1 Structure of the barrier

All components of the barrier are clearly identified and documented. The components are manufactured according to the underlying plans and are documented and verified after installation. The expected behaviour of the barrier and all individual components under a load action must be described in advance with regard to the expected anchor loads, deformations in height and flow direction as well as brake element elongations.

4.1.2 Influence

It must be possible to describe the artificial or natural debris flow event that the barrier encounters with regard to its rheological properties. It must feature rheological properties similar to a debris flow. The description is to be verified by appropriate measurements. Relevant properties include the flow height, front speed and channel cross-section (alternatively channel cross-section and discharge volume) as well as the density of the debris flow material.

4.1.3 Debris flow barrier interaction

The debris flow impact must be large enough for the barrier to be completely filled. The loads on the anchors should be measured directly or it must be possible to clearly derive them using any connected brake elements. The deformations of the barrier in height and flow direction as well as any braking lengths must be recorded and compared with the original assessment methods. Observed damage must be documented. Furthermore, the effective degree of filling or overflow situation, useful height, degree of loading with regard to dimensioning or existing structural reserves must be specified.

4.2 Assessment/verification by means of simulations

The simulation program used must be capable of dynamically calculating all barrier components and the completely assembled barrier. The load for this can either be introduced using forces that vary over time and act on the net area or a fluid structure interaction that enables the direct calculation of the impact of debris flow material on the barrier. A complete calibration or validation with 1:1 field/test data with regard to the structural and debris flow simulations must be available for the software used. The results of the simulation provide the expected anchor forces, the deformations of the barrier in the height and flow directions, the deformations of any brake elements as well as information on the utilisation of the individual barrier components.

4.3 Analytical verification

The barrier components can also be analytically assessed using suitable approaches. Converting the debris flow energies into rockfall energies or similar is not permitted. The pressures acting on the net are the starting point for the analytical verification required here. The latter transfers the load onto the supporting cables. For example, the load-carrying capacity of the net and the maximum forces acting in the cables are then to be verified for this. The maximum load in the net is determined here by the maximum distance between the two supporting cables. The load on the cables can be assumed to be uniformly distributed. The governing differential equation of a cable is then solved iteratively for this loading state until the calculated cable forces match the cable and braking elongations expected for these forces.

5 Further requirements

The requirements presented in this section must also be provided for the barrier together with the structural evidence (see section 4).

5.1 Ease of installation of the construction

The technical documentation for the barrier must include all information necessary for the successful and correct installation/assembly of the barrier. This includes:

- Identification/designation of the barrier components
- Placement of the barrier in the channel according to position, alignment, bottom opening (see 5.6), etc.
- Placement and alignment of the anchoring
- Expected anchor loads (necessary for the design of the anchors)
- Assembly sequence/installation instructions
- Maintenance plan (see 5.7)

5.2 Retention capability

The mesh sizes of the protection net should not exceed the grain fraction d_{90} (90% of the debris flow material is smaller). Otherwise a suitable small-meshed secondary netting must be mounted on the primary netting.

5.3 Retained volume

The maximum retained volume achieved with the (single) barrier must be calculated and specified. The appropriate calculation considers the current channel topography, the expected settlement of the barrier in a filled state as well as the sedimentation angle of the accumulated debris flow material.

5.4 Abrasion protection

As a rule, the durability of abrasion protection cannot be assessed for a single debris flow event. For this reason, other results from durability tests must be available for the service life of the barrier. Alternatively, a barrier kit can also contain an appropriate number of spare abrasion protection units and an appropriate inspection plan for the barrier.

5.5 Corrosion protection

Corrosion protection of the barrier components must be adequately assessed and verified for the service life of the barrier (for example, see EOTA, 2012). In the case of abrasion protection, it must be assumed that the corrosion protection coating would be lost in the event of overflow. For this reason an adequate material thickness must be foreseen.

5.6 Behaviour in the event of flooding, wood debris or sediment transport

In the event of flooding or sediment transport that should not fill the barrier, an adequate size of the bottom opening in relation to the expected event parameters and compositions (e.g. driftwood) must be verified.

5.7 Maintenance/servicing

The barrier must be regularly inspected according to the event frequency in the channel of the installed barrier. The technical documentation for this provides an appropriate checklist as well as limit values that can be used to decide whether repair work is necessary. This also applies for partially activated brake elements or a reduced basic outlet cross-section due to sedimentation. The maintenance plan also includes information about a notification and action plan in the case of an incident.

6 Safety factors / risk concept

The loads to be applied must be multiplied by an appropriate safety factor according to applicable standards (e.g. according to Fig. 7 / Wendler (2008) or Egli (2003)). This can take place during the calculation of the decisive debris flow pressures.

Wiederkehr-periode / Gefahren-klasse	1 - 30 Jahre	30 - 100 Jahre	Über 100 Jahre
1	1.0	1.0	1.0
2	1.3	1.3	1.2
3	1.5	1.3	1.2

Fig. 7: Proposal for safety coefficients for debris flow loads according to Wendeler (2008).

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Annex A Examples for load determination

The following figure shows a possible schematic for the assessment of debris flow barriers according to (Wendeler, 2008). The acting pressures for two different situations are determined as typical examples in the two tables below.

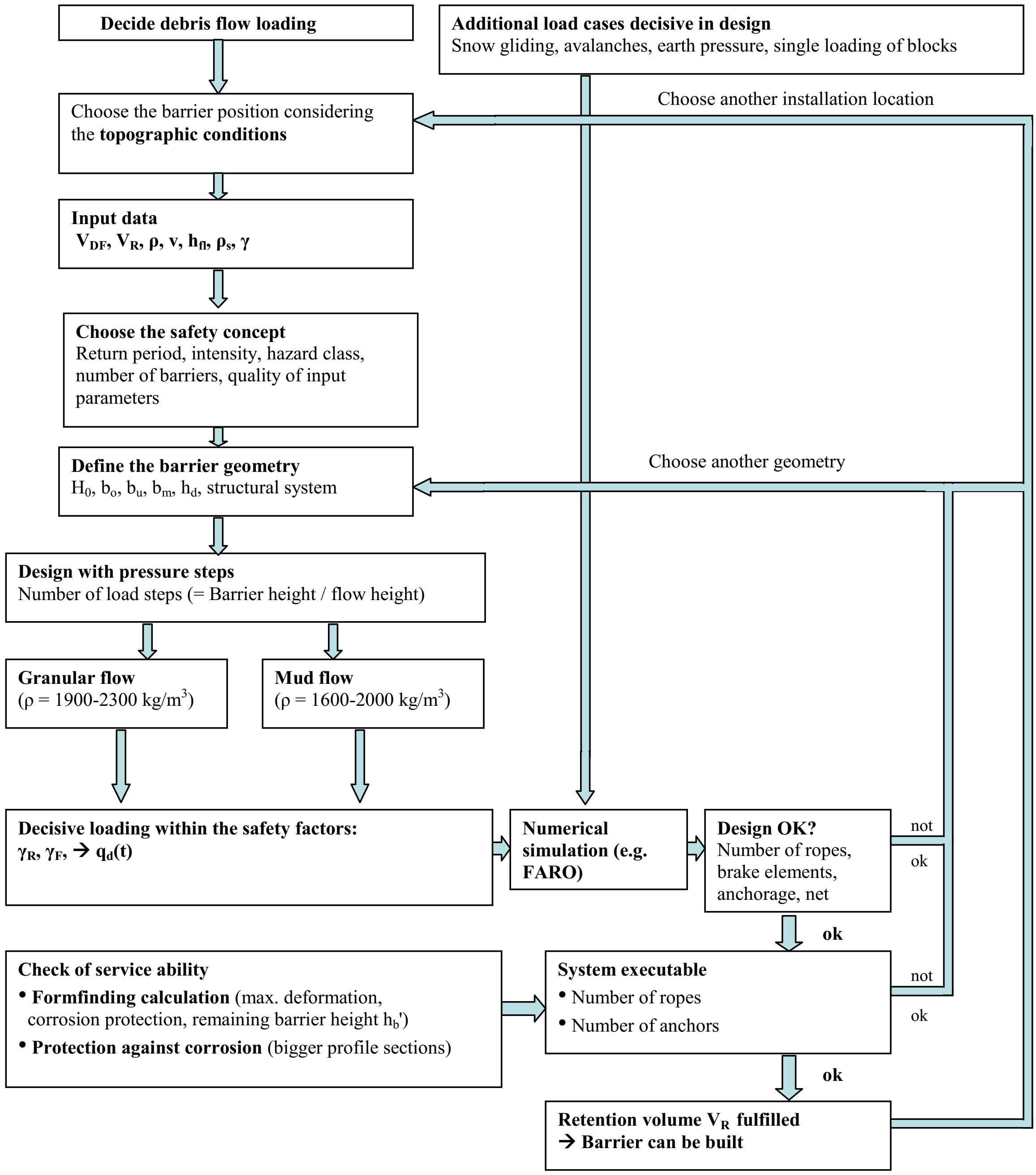
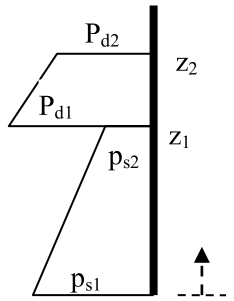


Fig. 8: Flow chart for the assessment and verification of a flexible debris flow barrier.

Table 1: Example for the tabular determination of the acting pressure loads at a constant flow height. As a result of the assumption that the barrier drops to 75% of the original barrier height, the load area reduces accordingly (direct consideration with "0.75*0.75" for pressure value calculation).

Flow speed	V = 5.8 m/s
Debris flow density	= 2200 kg/m^3
Flow height	h_{Fl} = 1.0 m
Average impact pressure of the debris flow height	p = 160 kN/m^2
Barrier height	H = 6 m

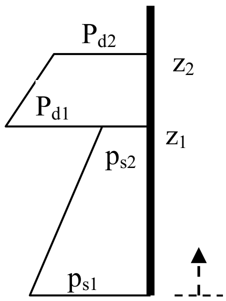


Load stage Press. value	1	2	3	4	5	6	Over-flow	
P_{d2}	149	149	149	149	149	149	22	kN/m^2
P_{d1}	171	171	171	171	171	171	151	kN/m^2
P_{s2}	--	22	22	22	22	22	--	kN/m^2
P_{s1}	--	43	65	86	108	130	--	kN/m^2
z_2	1.0	2.0	3.0	4.0	5.0	6.0	6.0	m
z_1	0.0	1.0	2.0	3.0	4.0	5.0	0.0	m

Table 2: Example for the tabular determination of the acting pressure loads for a constant flow volume.

Key data

Flow rate	200	m^3/s
Lower width	5.6	M
Upper width	36.7	M
Upper height	13.5	M
Debris flow density	2.2	to/m^3
Flow speed	7	m/s
Flow cross-sectional area	29	m^2
Pressure coefficient	2	(Density < 1900 kg/m^3 → 0.7, otherwise 2.0)
Dynamic pressure	216	kN/m^2
Safety coefficient	1.3	



Load level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**= Over-flow**
z_1	0	1.4	2.7	4.1	5.4	6.8	8.1	9.5	10.8	12.2	13.5	m
Relevant width z1	5.6	8.7	11.8	14.9	18.0	21.2	24.3	27.4	30.5	33.6	36.7	m
Flow height	3.1	2.5	2.0	1.7	1.4	1.3	1.1	1.0	0.9	0.8	0.8	m
z_2 = z1 + h_fl	3.1	3.8	4.7	5.7	6.8	8.0	9.2	10.5	11.7	13.0	14.3	m
Relevant width z2	12.8	14.4	16.5	18.8	21.4	24.1	26.8	29.7	32.6	35.5	36.7	m
P_{d2}		280	280	280	280	280	280	280	280	280		kN/m^2
p_{d1}		350	337	328	321	316	312	308	306	303		kN/m^2
p_{s2}	280	69	57	47	41	35	31	28	25	23	21	kN/m^2
p_{s1}	452	107	132	161	192	225	259	293	328	364	400	kN/m^2

Annex B Examples for analytical evidence

The loads on the supporting cables and the net can also be determined analytically (Wendeler, 2008). The acting pressures must be transferred accordingly. Fig. 9 shows an example in the case of four supporting cables uniformly distributed over the barrier height. In Table 3, we can see an example for the solution of the differential equation governing the mechanical behaviour of a cable loaded with a uniformly distributed load q. The cable force is determined iteratively here based on the cable/braking elongation. Table 4 shows a possible determination of the load that acts on a net strip (2D simulation) within the barrier. The strength of the net can then be verified.

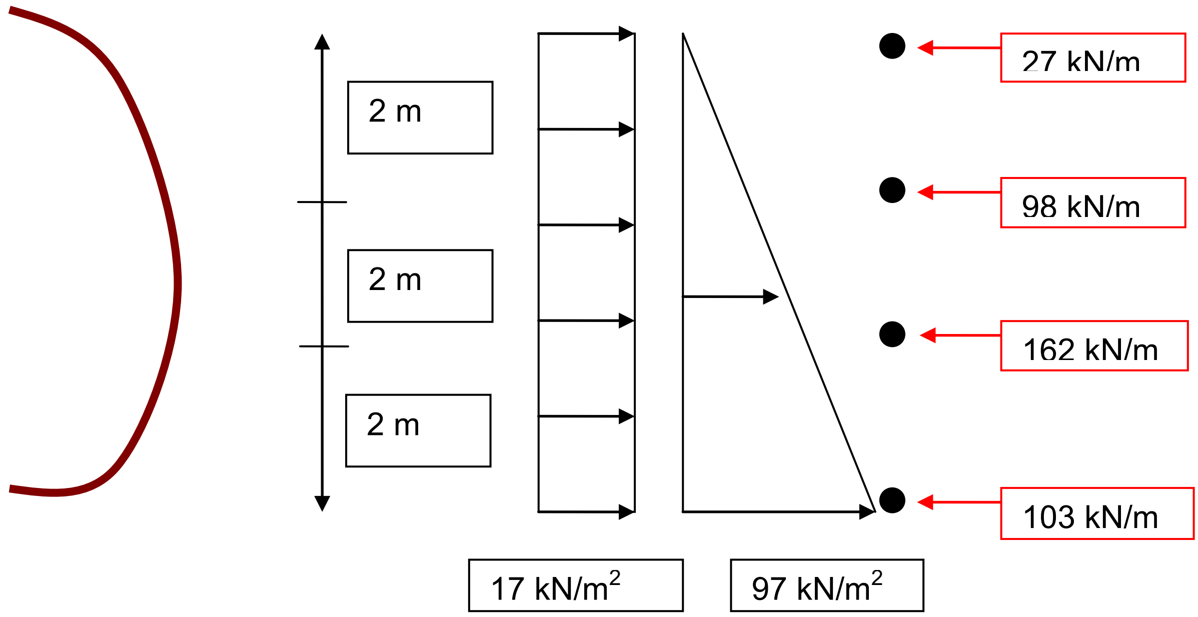


Fig. 9: Determination of the uniformly distributed load for the supporting cables: Distribution of the hydrodynamic and hydrostatic pressure of the completely filled barrier on 4 uniformly distributed supporting cables.

Table 3: Iterative determination of the cable force with the aid of differential calculus for uniformly loaded cables. The elongation of the brake elements (yellow) is adjusted until the calculated extension of the brake/cable combination (red, bold) results in a comparable value. Afterwards a check must be made to determine whether the resulting braking elongation matches the value calculated according to the braking elongation characteristics.

Uniformly distribution load q	27000	[N/m]
Length l	10	[m]
Passage f	0.5	[m] = 1/30-1/50 L
Initial length of cable So	10.07	[m]
Brake elongation brtot	3.70	[m]
s1	13.77	
H_1	89800	
H_new	89650	
H^3+b*H^2-c		

$$H^3 + H^2 \cdot EA \cdot \left[1 - \frac{1}{s_0} \cdot l\right] = \frac{EA \cdot q^2 \cdot l^3}{24 \cdot s_0}$$

E_Modulus	1.28E+11	[N/m^2]
Cross-section area A of cable	7.68E-04	[m^2]

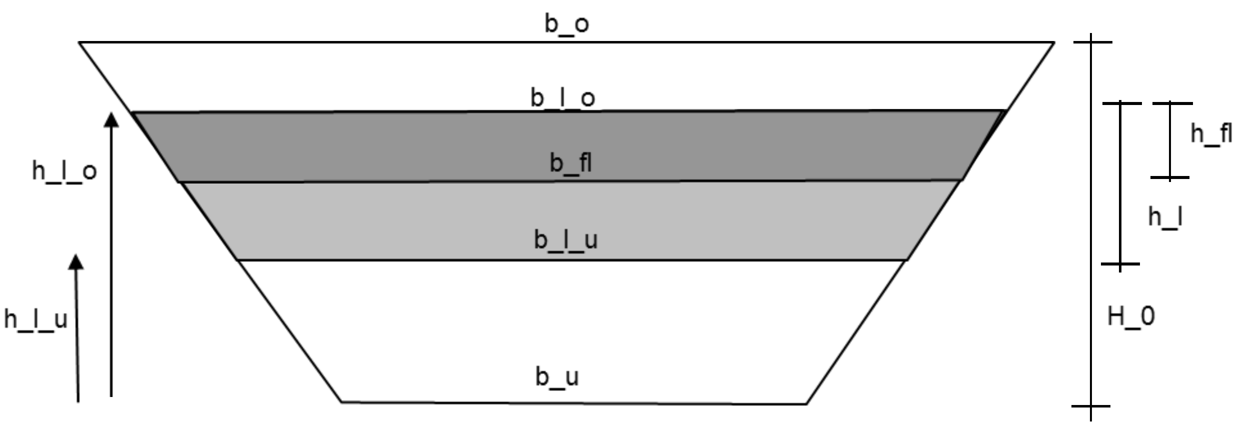
SF	9.83E+07	[N]
Factor b	26897168	
Factor c	2.16898E+17	
Hnew+1	89650	[N]
	89650	
F_cable	**162056**	[N]
Extension	**3.76**	

Table 4: Example for the determination of the maximum load on a net strip.

Analytical net verification for debris flow barriers - Calculation of the maximum influence

System		Granular	
Debris flow density	rho	2.2	to/m^3
Flow speed	v	7	m/s
Flow height	h_fl	0.7	m
Barrier height	H_0	13.5	m
Top barrier width	b_o	36.7	m
Bottom barrier width	b_u	5.6	m
Height above load action*	h_l_o	13.5	m
Height below load action	h_l_u	0.0	m
Relevant top barrier width**	b_l_o	36.7	m
Relevant barrier width at start of flow height	b_fl	36.7	m
Relevant bottom barrier width	b_l_u	5.6	m
Load strip height	h_l	13.5	m
Static pressure of lower load strip edge	p_u	291	kN/m^2
Dynamic pressure	p_dyn	216	kN/m^2
Static influence	P_stat	11033	kN
Dynamic influence	P_dyn	5609	kN
Sum of influences	**P_stop**	**16642**	**kN**

*No subsidence of the barrier expected as suspension mounted without brakes & supporting cables.



Annex C Application examples of flexible debris flow barriers

Example in Grönbach / Merligen

During the course of planned flood protective measures, Grönbach bei Merligen (BE) was also equipped with a debris flow protection system to prevent damage to the residential area and log jams. There is a retention space for debris and driftwood with a total volume of approx. 12,000 m^3 above the planned protective system. This is completed at its lower end with a debris flow barrier described in the following and shown in Fig. 10 that holds back solids carried along but lets normal (flood) water runoff and smaller particles pass through.

The planned measure foresees that several guide walls made of concrete are arranged parallel to the flow direction at the lower end of the retention space and their spaces in between are connected with protection nets. A part of the planned debris flow barrier must remain passable as a street and is therefore closed with a gate and not a net.

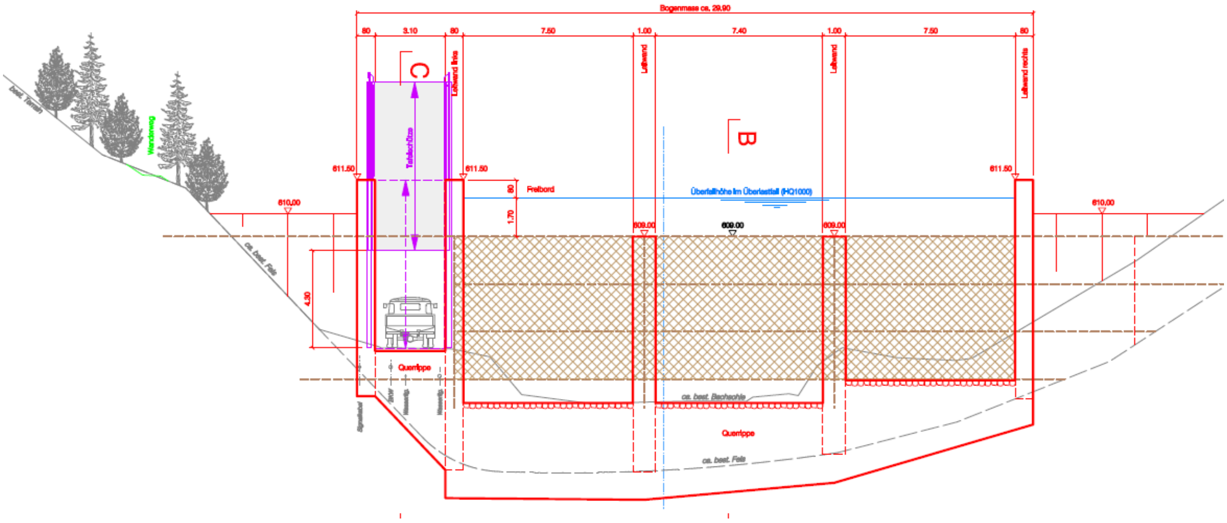


Fig. 10: Installed debris flow barrier in Grönbach / Merligen.

The debris flow front may not be assumed to be uniformly distributed over all barrier segments. As individual channels with lateral deposition can form in the river bed, a debris flow front that the barrier encounters would be concentrated at a minimal width and would not be uniformly distributed over the entire installation. This primarily gives rise to a higher flow height and speed. The calculation for the minimum width of the initial impact is taken from the general assessment of the debris flow situation. In extreme cases, it would mean that the entire debris flow front is only assumed to strike a single barrier section.

It is only possible to reduce the flow height in the subsequent filling process when the filling height exceeds the original channel depth and the debris flow uniformly fills the full width of the barrier. However, if the general debris flow analysis reveals a non-uniform filling over the barrier width, the assumed width of influence could be smaller than the full barrier width and have a single barrier section as a reserve.

The guide walls must be designed such that they can also dissipate the loads when they are only loaded on one side.

Example in Hüpbach

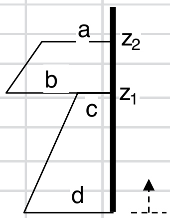
The barrier shown here is an example of the realisation of the dimensioning concept for very large dimensions presented in this report. The system is almost 40 m wide at the top edge. The height is a maximum of 19.2 m at the edges and 13.5 m in the middle (relevant for filling). Table 5 shows the loads determined for granular and liquid debris flows. The barrier was designed such that the supporting cables feature "ideal" parabolic sagging from the outset (see Fig. 11).

Fig. 11: Installed debris flow barrier in Hüpbach.

Table 5: Influences (top) of granular debris flow (=decisive) and (bottom) mudflow in Hüpbach

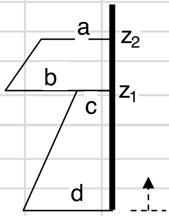
Granular debris flow

Discharge	200	m^3/s										
Lower width	5.6	m										
Upper width	36.7	m										
Top level	13.5	m										
Density	2.2	to/m^3										
Flow velocity	7	m/s										
Section area	29	m^2										
Pressure coefficient c_d	2	(Dichte<1900 --> 0.7, sonst 2.0)										
Dynamic pressure p_dyn = c_d*rho*v^2	216	kN/m^2										
Safety factor	1.3											
Load level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**= Overflov**
z_1	0	1.4	2.7	4.1	5.4	6.8	8.1	9.5	10.8	12.2	13.5	m
Relevant width z1	5.6	8.7	11.8	14.9	18.0	21.2	24.3	27.4	30.5	33.6	36.7	m
Flow height	3.1	2.5	2.0	1.7	1.4	1.3	1.1	1.0	0.9	0.8	0.8	m
z_2 = z1 + h_fl	3.1	3.8	4.7	5.7	6.8	8.0	9.2	10.5	11.7	13.0	14.3	m
Relevant width z2	12.8	14.4	16.5	18.8	21.4	24.1	26.8	29.7	32.6	35.5	36.7	m
a		280	280	280	280	280	280	280	280	280		kN/m^2
b		350	337	328	321	316	312	308	306	303		kN/m^2
c	280	69	57	47	41	35	31	28	25	23	21	kN/m^2
d	452	107	132	161	192	225	259	293	328	364	400	kN/m^2



Mudflow

Discharge	200	m^3/s
Lower width	5.6	m
Upper width	36.7	m
Top level	13.5	m
Density	1.8	to/m^3
Flow velocity	10	m/s
Section area	20	m^2
Pressure coefficient c_d	0.7	(Dichte<1900 --> 0.7, sonst 2.0)
Dynamic pressure p_dyn = c_d*rho*v^2	126	kN/m^2
Safety factor	1.3	



Load level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**= Overflov**
z_1	0	1.4	2.7	4.1	5.4	6.8	8.1	9.5	10.8	12.2	13.5	m
Relevant width z1	5.6	8.7	11.8	14.9	18.0	21.2	24.3	27.4	30.5	33.6	36.7	m
Flow height	2.4	1.8	1.5	1.2	1.0	0.9	0.8	0.7	0.6	0.6	0.5	m
z_2 = z1 + h_fl	2.4	3.2	4.2	5.3	6.4	7.7	8.9	10.2	11.4	12.7	14.0	m
Relevant width z2	11.1	13.0	15.2	17.7	20.4	23.2	26.1	29.0	32.0	34.9	36.7	m
a		164	164	164	164	164	164	164	164	164		kN/m^2
b		206	198	192	188	184	182	180	179	177		kN/m^2
c	164	42	34	28	24	21	18	16	15	13	12	kN/m^2
d	268	73	96	121	148	176	204	233	263	292	322	kN/m^2

Example in Hasliberg

This example shows an installation of several barriers in a row in order to obtain a larger retained volume totalling 12,000 m^3 (see also Wendeler et al., 2008; Monney et al., 2007).

Fig. 12: Installed series of debris flow nets at Milibach, Hasliberg (BE).

Example in Merdenson

The flexible barriers can also be used for stabilising a river bed as an alternative to concrete, riprap or wooden steps.

Fig. 13: Installed debris flow barriers for bed stabilisation at Merdenson.

Example in Illgraben

With the aid of the two barriers shown, the debris flows in Illgraben were fed back to their original river bed. In an initial measure, the lower barrier was set up to achieve an initial filling height. The top barrier set up after the next debris flow event could then raise and guide the channel bed at the channel edge far enough so that the debris flows over the original concrete check dam again.

Fig. 14: Controlled return of the debris flows in Illgraben into the original river bed.

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