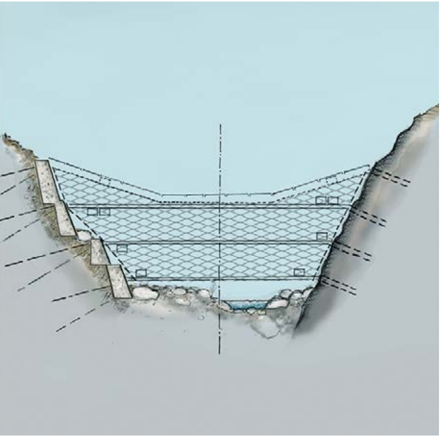

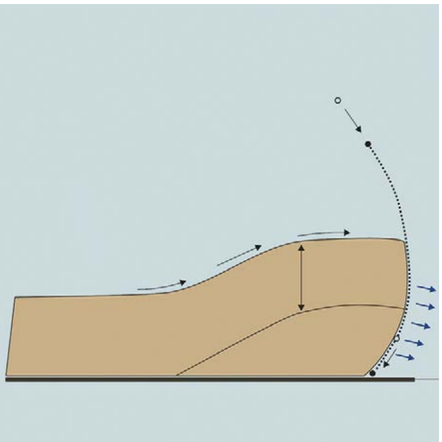

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Research for people and the environment: The Swiss Federal Institute for Forest Snow and Landscape Research WSL monitors and studies forest, landscape, biodiversity, natural hazards and snow and ice. WSL is a research institute of the Swiss Confederation and part of the ETH Domain. The WSL Institute for Snow and Avalanche Research SLF is part of the WSL since 1989.

Table of Contents

Summary

Debris flows and hillslope debris flows endanger people and property in mountainous regions. Within the framework of integral risk management, structural, organizational, or nature-based protection measures can be used, in addition to the considerations of natural hazards in spatial planning. The short warning times for debris flows and hillslope debris flows as well as their high impact and corresponding destructive forces are an important reason why structural measures must assume an important protective function.

Debris flow and hillslope debris flow protection nets have only been available on the market in Switzerland for a few years and complement the range of possible measures. A characteristic feature of this type of measure is the permeability of the nets, which retain the coarser solids, but allow water and suspended solids to flow through and thus drain the material. In addition to bedload retention, there are other possible applications for net barriers, e.g. for stabilizing the river bed or for redirecting the hazard process.

When planning protection measures, it is important that the advantages and disadvantages of different types of structures are presented transparently and are assessed on a site-specific basis. Debris flow and hillslope debris flow protection nets are relatively new types of measures. For this reason, comprehensive and long-term experience in the case of an event as well as the necessary know-how in planning, realization, service and maintenance are not yet generally available to an expert audience. With this practical guide, we want to close this knowledge gap and show planners, authorities and clients the experience already gained. According to the practical guide's motto: from practitioners - for practitioners!

The practical guide is divided into a general and a technical part. It aims to address both a general and a technically oriented audience, providing an overview of the state of the art of these specific protection nets in Switzerland. The focus lies on the gravitational natural hazard processes of debris flows and hillslope debris flows and CE-marked standard systems for net barriers.

In the general part, important framework conditions such as approval procedures and responsibilities are described, and it is further explained how net barriers are correctly designed and constructed. The focus of this part lies on the aspects of load-bearing capacity, serviceability, durability, overload cases and local conditions. Subsequently, the authors present possible damage patterns and their causes, as well as the prevention of damages. A decision support chart summarizes the most important aspects of the general part, discusses advantages and disadvantages and answers frequently asked questions.

The technical part describes scenario building for debris flow and hillslope debris flows processes, followed by explanations on net barrier-specific details. More details are given on the design of net barriers, for example regarding the residual height or the basal opening of debris flow protection nets. The dimensioning of the net barriers is based on the safety concept and load models, and the design of individual components is explained in detail. As is the case for all protection structures, inspection and maintenance are indispensable for their long-term use. Thus, the document covers decisive aspects with respect to service and maintenance of net barriers. Special structures complement the range of applications of net barriers and we present and illustrate selected examples. A design procedure chart for hillslope debris flows and debris flow barriers provides support for specific dimensioning and summarizes the technical part of this practical guide.

General part

1 Introduction

1.1 Background and purpose of the practical guide

Debris flows and hillslope debris flows endanger people and property in many places in the Swiss Alps and Pre-Alps. Protection measures play an important role in the holistic management of natural hazards [30]. Besides taking into consideration natural hazards in spatial planning, structural or organizational protection measures can be considered. Nature based solutions such as afforestation complement the spectrum of protection measures. The difficult forecasting of time and place of occurrence as well as the sudden occurrence of debris flows and hillslope debris flows are reasons why structural measures have to assume an important protective function. Due to their high densities and velocities, both hazard processes may cause large **impact pressures** on structures.

Rockfall and snow protection nets are established structural measures and have been in use already for a long time. Debris flow and hillslope debris flow protection nets have only been available on the market for a few years and have complemented the range of possible measures. The characteristic feature of this type of protection nets is that the solids of debris flows and hillslope debris flows are retained and the water flows through the nets, or more specifically the retained material is drained after a certain time. In addition to bedload retention, there are other possible applications for **net barriers**, e.g. to stabilize a river bed or to redirect the hazard process. Net barriers are particularly characterized by their flexible behaviour under load and, compared to conventional rigid construction methods such as concrete structures, by lower installation costs and reduced assembly efforts. Other points such as maintenance, accessibility, durability, area of application and details in the construction are decisive points that must be considered during design. It is therefore important that the advantages and disadvantages as well as the limitations in the application of net barriers are known. Such, a target-oriented and economically viable system of measures can be determined on this basis. However, comprehensive and long-term experience in the case of an event and the necessary know-how in planning, realization, service and maintenance have so far not yet been generally available to an expert audience.

This practical guide is intended to close this knowledge gap and to show planners, authorities and clients the experience already gained with net barriers in the case of an event, but also for design, implementation, service and maintenance. In addition to detailed technical information and practical help, particular attention is drawn to risks and opportunities of use and implementation of net barriers. According to the practical guide's motto: from practitioners – for practitioners!

1.2 Natural hazard processes considered

This practical guide focuses on the gravitational natural hazard processes of debris flows and hillslope debris flows. Debris flows are fast-flowing mixtures of solids (bedload and driftwood) and varying proportions of water in steep torrent channels. The discharge rises abruptly, forming a front of the debris flow with a high concentration of solids, and is therefore clearly distinguished from pure water runoff or bedload transport. Furthermore, debris flow are often characterized by a surge-like flow behaviour [21].

In contrast to debris flows, hillslope debris flows form outside of channels on open and steep slopes. They can detach spontaneously from water-saturated soil layers and flow at relatively high velocities. They may start as shallow to moderate spontaneous landslides, but transform into a flowing mass due to their water content. In terms of flow characteristics, hillslope debris flows are comparable to debris flows, but are typically smaller in volume [2].

Since **net barriers** have been increasingly used for the retention of driftwood in recent years, a special structure for this application is presented in this practical guide. To a certain extent, combined loading of the net barriers by different gravitational processes can also be guaranteed. However, this must be verified by means of calculations for each load case. Other gravitational natural hazard processes such as rockfall, avalanches and floods are only mentioned in the practical guide as far as they may have an unfavourable effect on the stability of net barriers depending on the location. They must therefore also be included in the design process.

1.3 Content and structure of the practical guide

This practical guide provides an overview of the state of the art of debris flow and hillslope debris flow protection nets in Switzerland. The practical guide is divided into a general and a technical part and focuses on the technical and functional aspects of **net barriers**. Other requirements (e.g. nature and landscape protection) are only touched upon and can be found in specific documents such as in [4]. Also, general knowledge about design, construction, maintenance and especially quality assurance of protection measures is required and not explained in detail, unless net-specific aspects are explained.

In the general part, the approval procedures for net barriers and corresponding responsibilities are described first. Subsequently, the authors show how debris flow and hillslope debris flow protection nets can be applied, which damages to the structures may occur and how they can be prevented. The decision support chart summarizes the most important aspects of the general part and frequently asked questions are answered.

The technical part covers scenario building for debris flows and hillslope debris flows, assessment of **system parameters** and dimensioning of components. In addition, the inspection and maintenance of protection structures are described. In general, the practical guide focuses on currently available CE-marked standard systems in Switzerland. However, since the use of net barriers can go far beyond standard applications, selected special structures are described and illustrated by way of examples. Notes on the design procedure summarize the contents of the technical part.

The glossary explains important terms, which are marked in **dark gray** and **bold** in the text; abbreviations and formula symbols used are defined in the corresponding directories. For further literature and references, please refer to the reference section at the end of this document.

In general, the term “**net barrier**” is used for different hazard processes and construction types. In this document, the term refers to debris flow and hillslope debris flow protection nets in general. The term “**net types**” is used to describe structures within the same **process family**, which are, however, designed for different type of impacts or load cases (e.g., from the process family of debris flow protection nets, the net types for load capacities of 60 kN/m^2 or 180 kN/m^2).

Manufacturers of net barriers are continuously developing their standard systems for the market. Up to today, numerous standard systems and several special structures have been implemented in Switzerland, and some of them have already proven their worth in case of events. The practical guide represents a status as of July 2020. Updated information can be found on the landing page of this practical guide (www.wsl.ch/practical-guide-debris-flow-hillslope-protection-nets) or obtained directly from the manufacturers of net barriers. If necessary, updated information on the state of the art or research findings will also be published on this landing page.

2 Approval procedures and responsibilities

2.1 Approval procedure for net barriers

When using a certified and approved construction product, the client and designer benefit from the standardized performance and the corresponding guarantee of quality [6]. It is important that labels, markings and documents supplied with the product are carefully filed, as the original documents must be presented as evidence in case of a complaint.

Until now, no harmonized standards for **net barriers** under loading of debris flow or hillslope debris flows are available throughout the world. In the European Union, it is possible to evaluate properties of construction products outside the scope of existing standards. The body responsible for this evaluation is the European Organization for Technical Assessment (EOTA). In cooperation with an applicant, the EOTA developed an assessment procedure, which is described in an assessment document (European Assessment Document, EAD). Once EOTA has adopted the EAD, manufacturers of construction products can request their specific products or product families to be assessed. The result is a European Technical Assessment (ETA). As for the EADs, the current ETAs are listed on the EOTA website (www.eota.eu).

For debris flow and hillslope debris flow protection nets, EAD No. 340020-00-0106 was published on the EOTA website in June 2016 [12]. Based on this EAD, assessment bodies (in Switzerland, for example the Empa) can issue European technical assessments (ETA) for hillslope debris flow and debris flow protection nets. The EAD does not only deal with the individual net components and their arrangement, but also with the necessary test procedures for both **barrier types** (built in a scale of 1 : 1). This enables to measure important influencing parameters that need to be declared (essential characteristic values according to [12]). For both **net types**, only large-scale test procedures are allowed. However, if based on large-scale field tests, a product series adjustment is also permitted by means of calibrated finite element methods.

The intended **minimum service life** of 25 years for debris flow and hillslope debris flow protection nets is not only defined in the ETA for the specific product, but is also generally described in the EAD. The EAD also specifies the responsible testing bodies (testing, assessment and inspection bodies = Conformity Assessment Body, CAB) and defines the testing procedures. Finally, the tasks of the manufacturer to ensure production quality, i.e. the procedure of factory production control (FPC), are described. Both the valid ETA and the annual production control are prerequisites for the continuous **CE-marking** that the construction product is bearing. In support of this, the manufacturer prepares the Declaration of Performance (DoP) with all characteristic values and usually submits it together with the **certificate of conformity** including continuous factory production control (FPC certification).

2.2 Involved bodies, competences and responsibilities

To ensure the permanent quality and serviceability of a **net barrier** installed in the field, a wide variety of players must be involved and made accountable, from production and planning to installation and operation of the net barrier. Possible tasks of the project participants as well as information on further sources of information are listed in Table 1. Only if all parties involved are aware of their respective responsibilities, high-quality and durable solutions can be created and guaranteed. It should be noted that the areas of responsibilities may vary depending on the hazard process, the location of the measures and the project constellation and must therefore be defined on a project-specific basis. Further information and specific explanations regarding forestry, fishery, nature conservation, revitalization and more can be found in the Manual Program Agreements in the Environmental Field (valid for Switzerland) [4].

Table 1. Tasks of the experts involved and references to further sources of information.

Who	Task (selection)	For explanations refer to
Manufacturer	Self-monitoring of production with FPC	EAD
	Documentation of protection nets	EAD, ETA
	Calculation of decisive anchor forces	Manufacturer specs.
	Assessment report (Proof of technical requirements and documentation)	EAD, ETA, DoP
	Identification of the net elements	EAD, ETA
	Packing and shipping instructions	EAD
	Installation manual and supervision of installation, including technical acceptance	Manufacturer specs.
Assessment body	Initial inspection of the product	EAD
	Initial inspection of the plant and FPC	EAD
	Periodic external audit by CAB	EAD
Authorities	Catalogue of protection structures	
	Supervision of construction management	
	For further information, please refer to the Manual Program Agreements in the Environmental Field	[4]
Client/owner	Definition of objectives of the measures and conditions of use	
	Definition of requirements (i.a. selection and award criteria, usage agreement acc. to SIA)	
	Determination of the **corrosion protection class** of the anchors	
	Maintenance and service works	
Planner	Design of protection net structure	
	Determination of type and number of anchor tests	
	Dimensioning of anchors and foundations	
	Supervision of construction works and quality control	
Construction company	Tests on sample anchors	
	Record of drilling and **injection** works	
	Construction of foundation and anchors	
	Installation of nets	
Interest groups	Situational involvement of interest groups	

3 Application of debris flow and hillslope debris flow protection nets

3.1 Load-bearing capacity of standard systems

Flexible **net barriers** can withstand high dynamic and static loads. As mentioned above, the information in this practical guide refers to **CE-marked** standard systems. Special structures are discussed in Chapter 9 and described more detailed in Appendix B.

CE-marked standard systems for debris flow and hillslope debris flow protection nets are available on the market from various manufacturers. The respective geometries and load-bearing capacities of the net barriers guaranteed by independent testing are described in Table 2 and Table 3 (as of July 2020). Further developments in net barrier technology are possible and current values/systems must be requested from the barrier manufacturers.

Table 2. Geometries and load-bearing capacities of debris flow protection nets (as of July 2020).

Nominal height	Nominal width	Impact pressure	Anchor forces
max. 6.0 m	Up to 15 m (without posts)	Up to 160 kN/m^2	Up to 350 kN
max. 4.0 m	Up to 25 m (with posts)	Up to 160 kN/m^2	Up to 350 kN
max. 6.0 m	Up to 24 m (with posts)	Up to 180 kN/m^2	Up to 350 kN

Table 3. Geometries and load-bearing capacities of hillslope debris flow protection nets (as of July 2020).

Nominal height	Nominal width	Impact pressure	Anchor forces
2.0–4.0 m	Up to 30 m (with intermediate suspension also longer)	Up to 150 kN/m^2	Up to 250 kN

According to [7], net barriers and other lightweight protection structures against debris flows and hillslope debris flows are not considered as water retaining facilities under the current Swiss legislation. Thus, in Switzerland, hillslope debris flow protection nets are not subject to the Directive on the Safety of Water Retaining Facilities.

3.1.1 Technical layout of a debris flow protection net

The support system of current standard systems consists of support ropes stretched across the channel, which are laterally tied to the channel flanks using anchorages. The retention net is shackled between the support ropes. By using **secondary meshes** with smaller mesh sizes than the primary retention net, fine material can also be retained. Two types of standard systems are currently available in Switzerland, depending on the nature of the channel: Systems up to 15 m span for narrow, V-shaped channel sections and systems up to 25 m span for wider, U-shaped channel sections. The latter are installed with one or more posts over which the support ropes run. The individual components of a standard system are illustrated in Figure 1. Both appropriate corrosion protection and **abrasion protection** of the net components ensure a product-specific **service life** and relatively low maintenance costs compared to rigid structures.

3.1.2 Technical layout of a hillslope debris flow protection net

The standard hillslope debris flow protection net includes articulated posts bolted to concrete foundations. The posts are anchored in the retention space with upslope anchor ropes including, if necessary, integrated **energy absorption elements**. The **primary net** is attached to the upper and lower support ropes. The **secondary mesh** for restraining the fine material is locally attached to the primary net (folded in the shape of an accordion bellow). The **uphill apron net** is additionally mounted on the lower support rope and on the primary net and embedded in the ground upslope using suitable anchoring elements. The individual components of a standard system are illustrated in Figure 2.

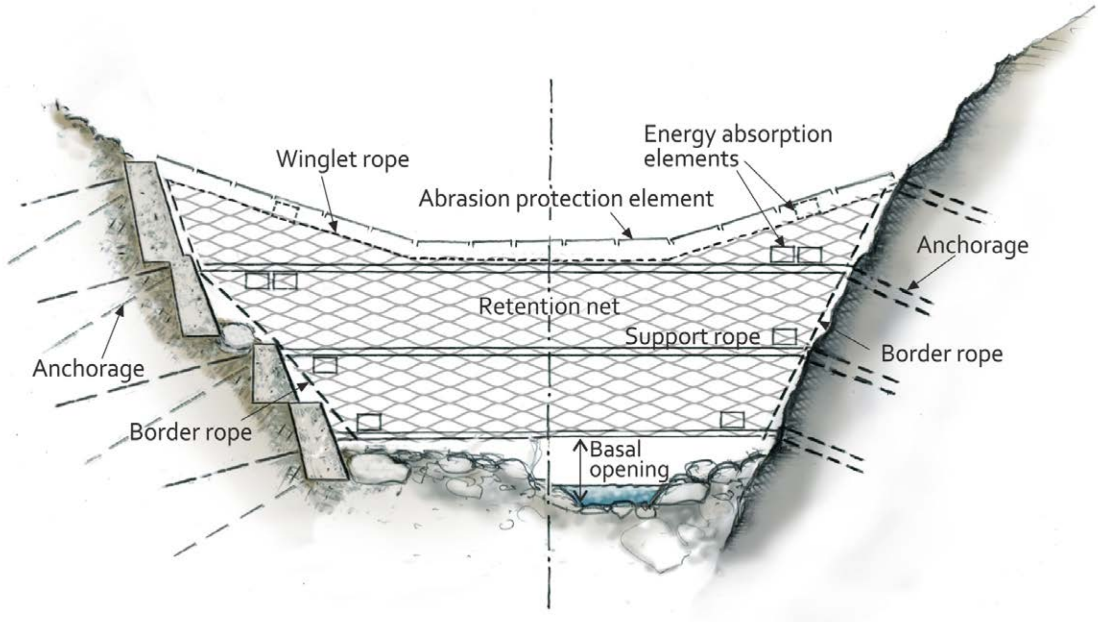


Fig. 1. Schematic view of the components and arrangement of a debris flow protection net for narrow, V-shaped channels, based on [12].

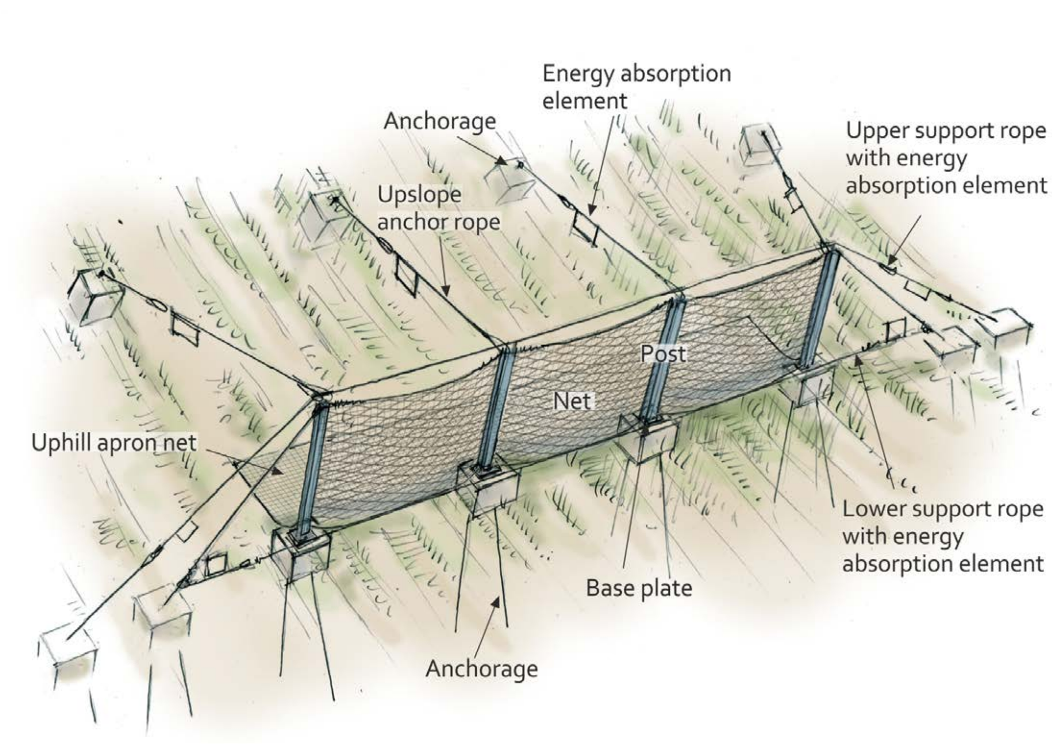


Fig. 2. Schematic view of the components and arrangement of a hillslope debris flow protection net, based on [12].

3.1.3 Documents required for net products

The following documents are required for net products and must be submitted to the building owner:
- System manual (manufacturer-specific)
- Installation manual (manufacturer-specific)
- Maintenance manual (manufacturer-specific)
- Valid Declaration of Performance (DoP) of the manufacturer, preferably with continuous **certificate of conformity** for the factory production control and valid ETA number.

In addition, it is recommended that at least the use of the net barrier is recorded in a usage agreement between the building owner and the planner.

3.2 Serviceability and durability

3.2.1 General requirements

The fundamental requirements of serviceability and durability are met when the unrestricted use of a structure for the intended purpose and for the agreed **service life** is ensured at a reasonable maintenance cost. While structural safety verifications can be fulfilled using static calculations, the requirements for serviceability must also be reviewed on a project-specific basis. Regarding standardized **net barriers**, the following aspects, among others, must be taken into account when verifying serviceability:

- Shape and position of the overall structure
- For debris flow protection nets, erosion resistance of the channel banks
- Protection against scouring of the **basal opening** (for debris flow protection nets) or in the spillway section (if dimensioned for overflows)
- Corrosion resistance of the superstructure and anchorages, increase of **service life** by choosing a higher **corrosion protection class**
- Functional impairment of the overall structure, e. g. due to
  - Deformations of the overall structure
  - Differential settlements due to dead weight or tilting of the foundations
  - Cracks in the concrete foundations and subsequent reduction in impermeability
  - Frost resistance of the concrete structure
  - Alkali aggregate reaction of the concrete structure

Approaches to the serviceability and durability of debris flow protection nets can be found in [13], among others. Careful planning, necessary maintenance and regular inspections of the net barriers prevent a potential reduction of durability and serviceability.

3.2.2 Requirements for anchorages and foundations

Only the superstructure is included in the product evaluation ETA (see Chap. 2.1). In planning and execution, great attention must therefore be paid to the dimensioning and the construction of the anchorages and foundations. The conditions for anchorages and foundations are product and site-specific. Ideally, a detailed geological profile of the barrier location is available and pull-out tests of anchors are performed to determine the outer skin friction of the soil. The following list includes important factors to be considered to ensure the durability of the load transfer of the resulting forces from the superstructure to the soil:
- Manufacturer's data on anchor forces of net barriers including safety factors
- Assessment of the soil's geotechnical parameters (skin friction, etc.)
- Use of type-tested and approved anchor grouts (see list of approved anchor grouts acc. to FOEN [5]), on site grout testing, monitoring of grout's installation temperature and curing time for quality assurance
- Definition of the **corrosion protection class** according to SIA standard 267 [29] with the client

- Alignment of the anchors in the direction of the cable
- Sufficient anchor spacing to prevent violation the sphere of influence
- Use of flexible anchor heads to prevent reduction of the anchor's load-bearing capacity
- Possibly, use of self-drilling anchors if the borehole is not stable, or cased drilling with a **grout sock**
- Implement **post-injections** of grout to obtain a force-locked grout column
- If applicable, ensure corrosion protection, especially in the anchor head area, with small concrete foundations
- Implement erosion protection of the anchorage body to maintain the required anchorage length
- Carry out tensile tests on anchors
- Caution during anchor installation in winter: ice lenses may form on the on the anchor bar

The anchorage lengths and thus also the borehole lengths depend significantly on the soil properties. In order to keep the anchorage lengths within a technically reasonable and economically justifiable range, preference should be given to installation sites that meet the following requirements for the ground:
- Rock or loose rock, stable, sufficient skin friction.
- Little cover of soil and low proportion of organic material in the surface layer.
- No or only few fissures, favourable orientation of possible shear surfaces
- No fissure or pore water in the boreholes
- No geological strata that can react sensitively to drilling or grout input
- No zone of sources

3.2.3 Requirements for net types

For the structure to be considered in land use planning, a **service life** of 50 years must be guaranteed according to PROTECT [23]. For hillslope debris flow protection nets, first steps to implement this approach for limited service lives are described in [35]. The net barrier manufacturer must provide evidence of adequate corrosion protection of the net components. In addition, proper construction and, if the structure can be overflowed, product-specific **abrasion protection** help to preserve the structure during its **service life**. After an event, the net barrier must be inspected and, if necessary, repaired.

3.3 Consideration of local conditions in planning

3.3.1 Layout and arrangement in the terrain

The following are selected important factors for the layout and arrangement of **net barriers** in the terrain or in the channel respectively.

Debris flow protection nets
- Do not arrange net barriers in channel bends in order to prevent erosion on the outer bank. If applicable, additional stabilization measures on the channel's embankment are necessary.
- Consider **basal opening**
- Ensure **abrasion protection** in case of possible overflow
- Ensure flow paths and appropriate protection against scouring downstream of the net barriers
- Consider other site-related natural hazard processes in dimensioning (e.g. windfall of trees, avalanches, etc.)
- Ensure accessibility for service and maintenance
- Include increased maintenance costs in case of high debris flow activity of a channel in economic considerations
- Establish a material management concept for the operational phase and identify landfill sites for the material

Hillslope debris flow protection nets
- Consider arrangement of an **uphill apron net**
- Ensure a**brasion protection** in case of possible overflow
- Consider surface runoff or draining water from the barrier by means of drainage or diversion
- Ensure wildlife corridors with appropriate passages and net overlap
- Adapt intermediate suspension to wildlife crossing
- Review gullies and elevations in terrain during stakeout
- Review sliding layer depth versus anchorage length
- Consider other site-related natural hazard processes in dimensioning (windfall from trees, avalanches, etc.)
- Ensure accessibility for service and maintenance
- Establish material management concept for the operational phase and identify landfill sites

The following general aspects have been shown when installing flexible net barriers:

- The drilling work for the necessary anchors in rock or soil can be carried out with a light drilling rig and a walking excavator
- Due to the low volume and weight of the installation elements, material can be transported to the site by truck or helicopter, which proves often to be an economically viable solution.
- Large excavations in advance can be avoided
- Large-scale installation and handling sites are not necessary
- The duration of the construction works is limited to a few months, while the actual installation of the net is taking place within a few days.

3.3.2 Ecological and ecomorphological conditions

Net barriers made of wire net structures fit relatively well into the landscape visually. Debris flow protection nets are installed to provide a retention space and are built with a corresponding **basal opening** (see Chap. 6.2.2) above the channel base. They allow most animal species to pass and do not impair fish passage. Natural bedload transport is usually not restricted by such net barriers, and the original condition of the channel bed is preserved. If, however, the channel bed needs to be stabilized below the net by means of a block ramp or other means, the permissible bed angles and drop heights of these structures must be complied with in order to ensure fish passing (in consultation with the competent authorities and depending on the fish population). If the net barriers are left in the stream bed when filled or are mechanically filled during construction, and thus serve as bed stabilization in the form of a step-like structure, then the same aspects apply with regard to ecological impacts as with other staircase- and step-like structures.

Hillslope debris flow protection nets have a similar ecological impact on wildlife as rockfall protection nets. Above all, wildlife passages and wildlife resting zones must be considered in the planning of these linear structures. An intermediate suspension with support rope separation must be adapted to animal passage accordingly. Small organism such as insects, amphibians, reptiles, and small mammals such as stoats and mice may pass the net barriers through their mesh openings without restriction.

When selecting the installation site, it must be clarified on a project-specific basis whether special planning measures are required for water and nature conservation reasons (e.g. galvanized elements in protection zones or closed seasons for wild animals). The corresponding requirements can be found in the current Swiss Legislation (WPA, NCHA and WBG) and [4].

3.4 Overload of net barriers

Technical measures are designed for a design event, which is defined during the planning of the measures. However, larger events in the sense of larger volumes or higher loads are possible and should not lead to a collapse-like failure of the net barriers or to a deterioration of the actual situation with larger bedload quantities. One reason for an overload or overstress can be the exceeding of the design event. This in turn leads to exceeding of the load-bearing capacity or the volume capacity of a net barrier. As a result, individual components may fail (e. g., failure of cables, net components, anchors etc.). A simultaneous, collapse-like failure of all system components is unlikely. In the case of net barriers, overflow, lateral bypass of a barrier or washout of the channel banks can also cause a net barrier to be impaired reducing its protective function (exceeding of the geometrical system limits).

It is important that the consequences of an overload case are described in the project and that it is clarified how these can be managed by technical, organizational or spatial planning measures. Therefore, project-specific statements are to be made on the following topics (selection):

- Is part of the debris flow or hillslope debris flow material deposited below the net barrier?
- May further material be mobilized below the protection structure?
- May the overflowing material be discharged without damage?
- Is the situation significantly worsened in the case of an overload for the infrastructure to be protected?
- Are additional structural or planning measures therefore necessary?
- Are additional organizational measures (e. g. alarms, intervention points, emergency planning) necessary and need to be provided for?

Overflow is not covered for all net barriers by their corresponding standard declaration of performance for **CE-marked** net barriers:

- For most CE-marked debris flow protection nets, the overflow of a barrier by the design event is verified by field tests and simulations.
- Hillslope debris flow protection nets are generally not dimensioned for overflow.

If overflow is not guaranteed by the manufacturer, this case must be considered and verified separately during dimensioning (see also Chap.s 6.2.5 and 6.3.3). Information on the current declarations of performance can be obtained from the net barrier manufacturers. The behaviour of a debris flow, a hillslope debris flow and a net barrier in the event of overflow (and especially in the event of overload) may be estimated by suitable modelling.

4 Damages to net barriers and their prevention

4.1 Overview of damage patterns

In the period from 2007 to summer 2020, about 80 debris flow and 30 hillslope debris flow protection nets were installed in Switzerland. On these, experience could be gained, damages were observed and lessons learned. Experience shows that primarily the damage patterns to system elements and reduction of the serviceability of **net barriers** shown in Figure 3 may occur.

Damages to the superstructure of this type of protection nets, such as rope and net failures, buckled posts and likewise damages, should not occur in certified and carefully designed net barriers if the design values are not exceeded. Therefore, damages due to overload are not dealt with in the following sections.

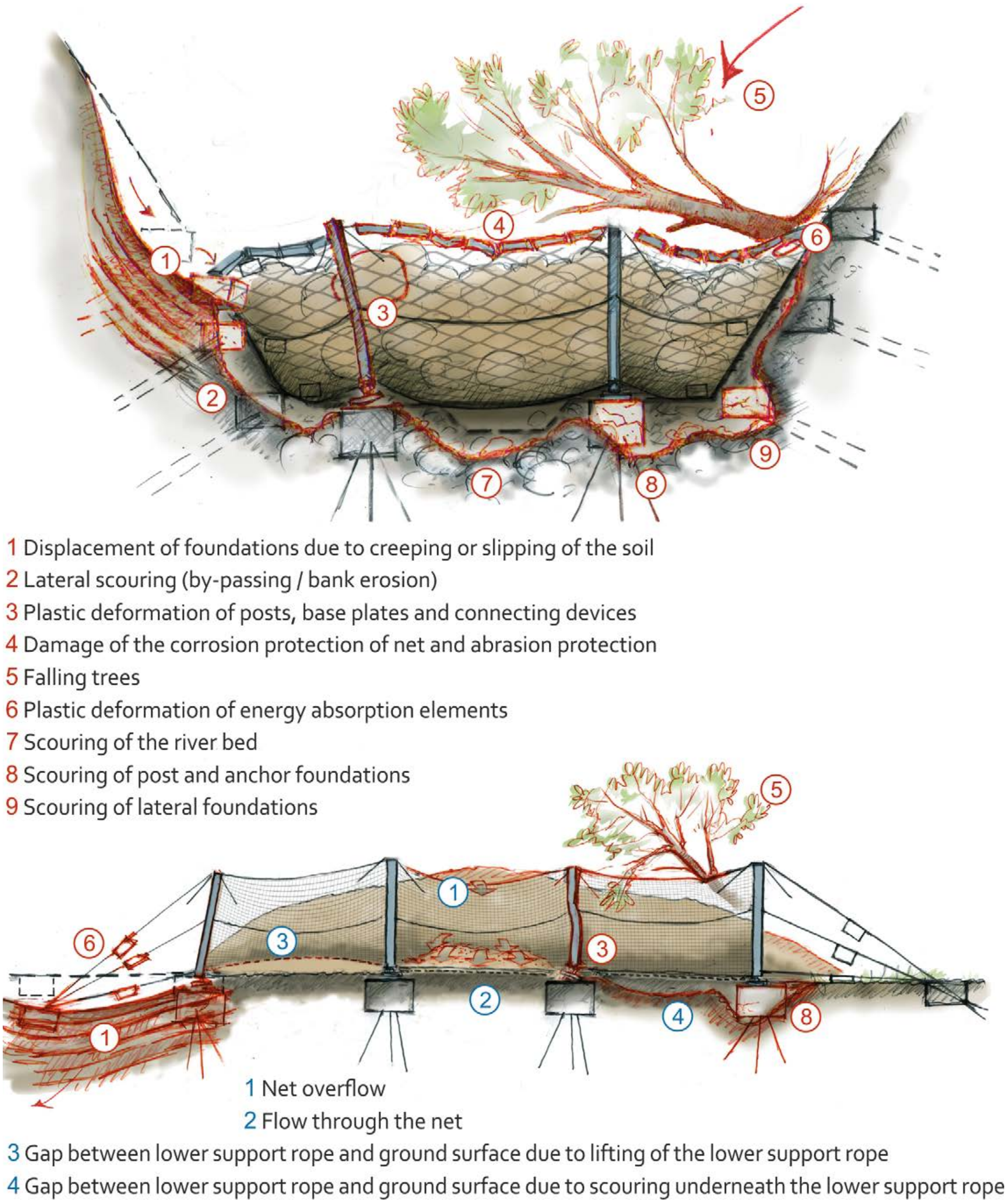


Fig. 3. Overview of possible damage patterns and reduction of serviceability of a debris flow protection net (top) and a hillslope debris flow protection net (bottom).

4.2 Damages and measures for their prevention

Most of the damages and impairments of serviceability of **net barriers** described in Figure 3 can be prevented by careful planning, design, layout and construction. Elastic and plastic deformations of net barriers, especially of **energy absorption elements**, are part of the load-bearing behaviour of net barriers and are necessary for the system to work properly. These elements can be replaced after an event (see also Chap. 8). Table 4 shows individual damage patterns and possible impairments of serviceability and describes measures for their prevention.

Table 4. Possible damages and measures for their prevention.

Damages to system components due to deformations, damage to corrosion protection

Damage
Damage to the corrosion protection of individual components due to abrasion, using the example of a deformed **abrasion protection** of a debris flow protection net.

Prevention measures
Can only be prevented to a limited extent since abrasion always occurs during overflow. Net parts and abrasion protection elements can usually be replaced if damaged.
Image: [B]

Damage
Plastically deformed **energy absorption element**, using the example of a hillslope debris flow protection net.

Prevention measures
None. In the case of energy absorption elements, plastic deformation is part of the load-bearing behaviour and is necessary for the system to work properly. Plastically deformed energy absorption elements can be replaced.
Image: [D]

Damage
Plastic deformation of posts, base plates or their connecting elements, using the example of a hillslope debris flow protection net.

Prevention measures
If necessary, reinforcement of post profiles, base plates and connecting elements. Plastically deformed posts, base plates and connecting elements can be replaced after an event. For the arrangement of an adequately back-anchored concrete foundation, see Figure 16.
Image: [D]

Damage
Tilting of the post foundation (right side of the image) with subsequent shearing of the base plate, on the example of a hillslope debris flow protection net.

Prevention measures
Sufficient embedment of the foundations into the ground as well as sufficient embedment of the micropiles (pressure and tension anchors) into stable soil layers.
Image: [G]

Damages to the entire system due to backwashing and scouring of foundations as well as slipping or creeping of the lateral embankment.

Damage
Backwashed anchorage foundation of a support rope anchorage, using the example of a debris flow protection net.

Prevention measures
Sufficient deep embedment of all anchorage foundations. Provide for a sufficient erosion protection up and downstream of the barrier. If possible, place the upslope anchor ropes outside of the channel bed, on the embankment of the channel.
Image: [C]

Damage
Scoured post foundation, using the example of a debris flow protection net.

Prevention measures
Sufficient deep embedment of all post foundations into the ground. Placement of the post foundations at the edge of the channel; integration of the foundations into the scouring protection, which is formed as a stone rip-rap embedded in lean concrete.
Image: [B]

Damage
Scouring of the channel bed underneath a debris flow protection net, resulting in a significant enlargement of the **basal opening**.

Prevention measures
Selection of a barrier location with as little soil cover as possible and with a stable channel bed. Otherwise, scouring protection with sufficient embedment into the ground and sufficiently dimensioned width upstream and downstream of the barrier location. Empirical values and recommendations are described in [13].
Image: [G]

Further damages or reduction of serviceability

Reduction of serviceability
Lateral washout of a debris flow protection net due to bypasses and bank erosion.

Prevention measures
Selection of a barrier location with as little soil cover as possible. Otherwise, permanent stabilisation of the slope around the anchor points (erosion protection), so that they cannot slide or be backwashed. Construction of protection nets preferably on straight channel sections (i. e. not in curves or bends of the channel).
Image: [G]

Damage
Overflow, on the example of a hillslope debris flow protection net, which was dimensioned for a smaller **load case**.

Prevention measures
Reinforcement of components of the hillslope debris flow protection net, installation of **abrasion protection** elements, selection of a **net type** with higher load-bearing capacity and/or greater nominal height.
Image: [H]

Damage
Tree impact on a net barrier

Prevention measures
Regular clearing along net barriers.
Image: [D]

Damage
Displacement of foundations and/or anchors due to creeping or slipping of the slope, using the example of a debris flow protection net.

Prevention measures
If possible, selection of the barrier location outside of creeping and sliding slopes. Consider sliding layers when designing anchorages.
Image: [E]

5 Decision support chart for the planning of net barriers

5.1 Flow chart

The following overview summarizes central aspects to be used as basic decision criteria for or against the use of debris flow and hillslope debris flow protection nets during planning. General aspects to be considered, such as inspection of protection structures and their maintenance or overload, are not explicitly listed.

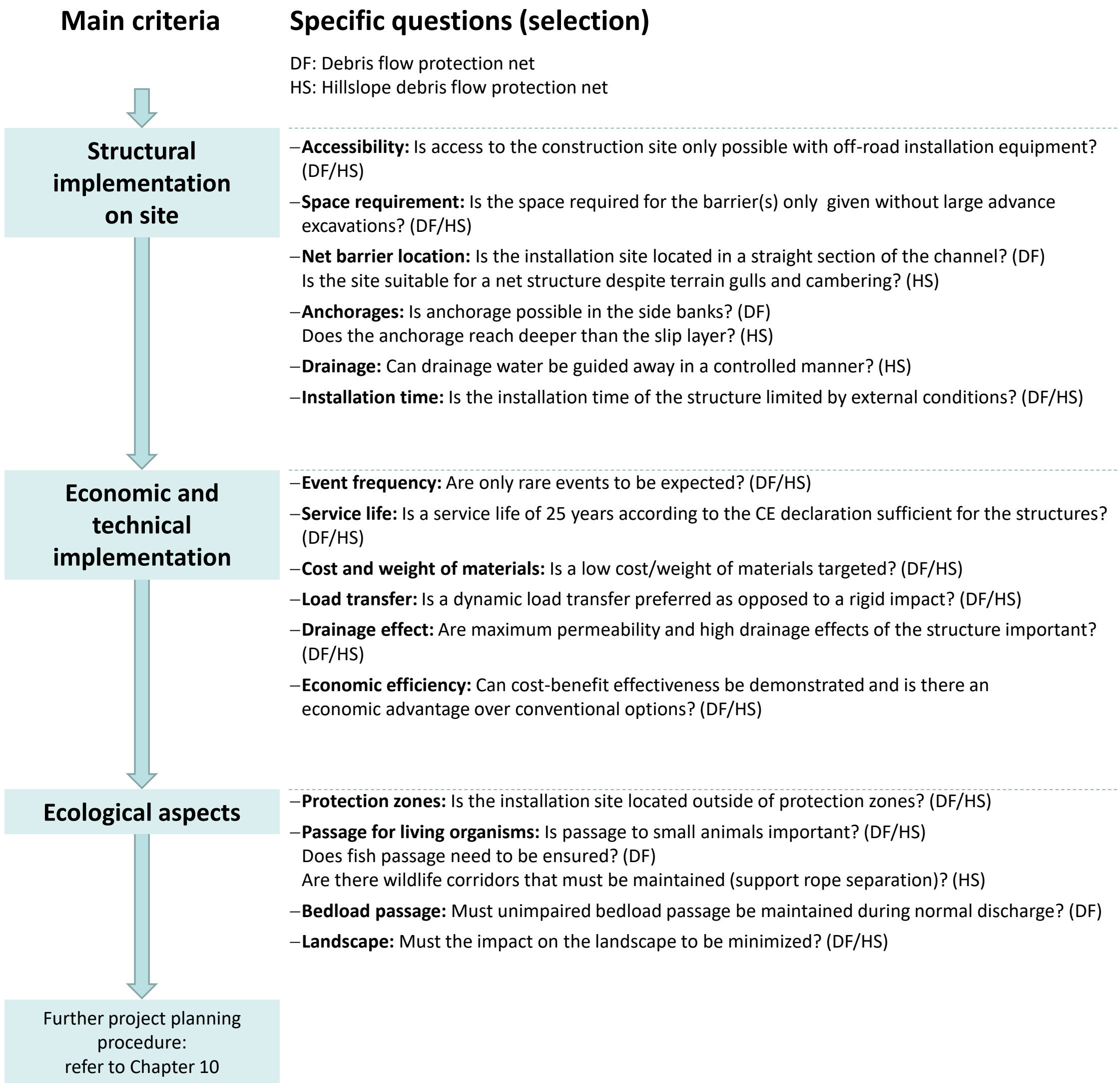


Fig. 4. Decision criteria for debris flows and hillslope debris flow protection nets. The abbreviations indicate to which process type the respective question applies.

5.2 Qualitative evaluation of net barriers compared to rigid structures

Regarding the decision criteria mentioned in Figure 4 and other aspects, flexible **net barriers (CE-marked** standard barriers, see Chap. 3.1) have advantages and disadvantages compared to rigid protection structures. For a qualitative comparison, both types of measures were compared (Table 5). Obviously, the evaluation depends on the specific circumstances and must be reviewed on a project-specific basis.

In Table 5, we compare a rigid reinforced concrete structure with **basal opening** and spillway section with a **CE-marked** debris flow protection net with the same geometry, retention volume and load-carrying capacity at the same site in a steep torrent in the pre-Alpine area. Accessibility for emptying after an event is assumed to be given upstream of the barrier. The comparison is intended as a guideline, is not meant to be exhaustive, and only covers criteria where significant differences between both types of structures exist.

Table 5. Qualitative comparison between net barriers and rigid, reinforced concrete structures based on different assessment criteria.

Assessment criterion	Qualitative evalution	
	Net barrier (standard system)	Reinforced concrete structure
1. Structural implementation at the site		
Installation site and use of resources	Transport volume and use of resources are lower. Therefore, even remote locations can be economically accessed by helicopter.	Larger transport volume and use of resources. Implementation at remote locations is therefore more complex and expensive.
Space required	Space required for installation site and structure usually smaller	Space required for installation site and structure usually larger
Machines and equipment	Often use of lighter equipment (e.g. drilling rig), use of walking excavators possible	Usually heavier construction equipment (e.g. concrete mixer, crawler excavator) necessary, possibly installation of transport cableways etc. necessary
Construction time/ work safety	Shorter construction time and therefore shorter duration of work in the endangered area. Can be realized without advance excavations, therefore generally fewer critical states during construction.	Generally longer construction time and therefore longer duration of work in the endangered area. Due to advance excavations, generally more critical states during construction.
2. Economic and technical implementation		
Dimensions of structure and retention volume	Limited for standard systems, otherwise construction of special structures necessary	Very large dimensions and retention volumes also possible for standard structures
Possibilities of extension/expansion	Extension/expansion only possible to a limited extent	Extension/expansion generally possible to a larger extent, but to be reviewed statically
Experience in planning	Rather new technology with fewer standards, comparative and empirical values available	Long-established technology with established standards and many empirical values available
Construction costs	For standard system generally lower	For comparable dimensions generally higher
Maintenance costs	Strongly dependent on impact frequency and required service life	Less dependent on impact frequency
Service life	25 years	80 years
Material consumption	Material consumption per structure for same width and height generally smaller	Material consumption per structure for same width and height generally larger
Impact/loads	Impact on a flexible and dynamically reacting structure, thus reduction of peak forces	Impact on a rigid structure, thus higher dynamically acting forces and peak forces

Assessment criterion	Qualitative evalution	
	Net barrier (standard system)	Reinforced concrete structure
2. Economic and technical implementation		
Drainage effect and susceptibility to clogging	Passage of water possible over entire net area, therefore better drainage effect	Reduced drainage effect, higher susceptibility to clogging
Retention and its effect on maximum discharge	Limited retention effect on water/flood wave, therefore higher discharge downstream, where bedload mobilization is possible	Attenuation of discharge downstream of the structure, and therefore less bedload mobilization downstream
3. Ecological aspects		
Passable for small animals and fish	Equivalently passable for fish, better passable for small animals	Equivalently passable for fish, passable for small animals in a reduced way
Impact on landscape	More transparent structure, visual impact smaller	More massive structure, visual impact greater
4. Inspection of protection structures and maintenance		
Operational maintenance	Regular control and inspection effort equivalent, but smaller robustness of system elements. In case of frequent events, greater repair effort necessary.	Regular control and inspection effort equivalent, but greater robustness of system elements. More suitable for frequent events.
Emptying	Effort equivalent	Effort equivalent
5. Overload / residual risk		
Overload/residual risk	For both types of structures, possible event sequences in case of overload as well as the remaining residual risks have to be clarified on a project-specific basis.	

5.3 Possible applications of net barriers

Based on the qualitative assessment and practical experience, these flexible protection nets are particularly suitable for the following selected types of application and measures:
- Measures in terrain that is difficult to access
- Temporary measures
- Emergency measures
- Complementary measure to rigid structures within the framework of an integral protection concept
- Sensitive situations, where rigid measures are not an option due to landscape or biosphere issues

The use of net barriers as measures for property protection, especially for hillslope debris flows, is possible. For Switzerland, the approval procedures vary from canton to canton. It is important that inspection and maintenance by the (often private) landowners are clearly regulated and ensured.

5.4 Frequently asked questions about net barriers (FAQ)

Decision-makers and stakeholders are often faced with the fundamental question of whether **net barriers** can be implemented in a specific case. The following answers to frequently asked questions may support the evaluation in favour or against the use of net barriers. The focus lies on net-specific questions. The list of questions and answers is by no means exhaustive and must be updated if required. Further information is available from the net manufacturers and on the landing page of this publication.

– **How to ensure a large retention volume without special construction solutions?**
Several debris flow protection nets arranged in series (**CE-marked** systems that cover the overflow load case) may together generate a larger retention volume than a single protection net.

– **What is the service life of a net barrier?**
Without impact, a **service life** of 25 years of the structure can be assumed. After an event, the barrier must be emptied and repaired. Once the net barrier has been properly repaired, it must be re-evaluated regarding its further service life.

– **What is the advantage of a net barrier over rigid structures in terms of the costs to be expected?**
In many cases, net barriers can be implemented as equivalent alternatives to rigid concrete structures. For evaluation, it is important to consider the entire life cycle, including maintenance costs. For a specific project, a cost-benefit analysis is useful. Alternatively, the barrier's life cycle costs should be determined to show its economic viability. In terms of installation, material consumption and work duration, the use of net barriers often has a positive impact on costs. However, the critical factor in cost-effectiveness is how frequently the structure is impacted and filled. Due to their shorter **service life**, less robust system elements and accordingly more repair effort, net barriers are less cost-effective especially in catchments with more frequent events.

– **Are net barriers subject to construction permit and eligible for subsidies?**
As for Switzerland, net barriers are always subject to a construction permit. However, the eligibility for subsidies does not result from the type of construction, but from the requirements that a project must fullfill (suitability, economic efficiency, compliance with the law) and general conditions. In the past, protection measures using net barriers were in many cases able to fullfill the requirements for subsidies. It is advisable to clarify in advance with the relevant authorities whether net barriers can be approved as a protection measure and whether they are eligible for subsidies.

– **How quickly can a net barrier be constructed?**
The procedure for obtaining a construction permit (design, publication of construction permit, objection periods, etc.) is comparable to a rigid structure and therefore takes a similar amount of time. A standardized net barrier can be installed within a few weeks once the construction permit has been issued and weather conditions are favourable.

– **Where will the debris material be deposited after an event?**
The issue of depositing the expected wet material from the retention area of the net barrier must be clarified at an early stage, as is also the case for rigid structures. Therefore, suitable access routes and landfill sites need to be defined already during planning. As for bedload management, sites for re-feeding bedload downstream of the barrier need also be considered and possible costs must be taken into account.

– **How ecological and sustainable is a solution using nets compared to rigid structures?**
The relatively large mesh openings and the **basal opening** of debris flow protection nets allow a good passage for fish and small animals.
For sustainability considerations, a project-specific ecological impact assessment should be carried out simultaneously to the study of project variants.

– **How do debris flow protection nets fit into the landscape?**
In contrast to massive protection structures made of steel and concrete, debris flow protection nets are relatively unobtrusive visually and usually blend well into the landscape. They are hardly visible from a distance.

– **How are net barriers emptied?**
Net barriers are usually emptied from the upstream side by means of a walking excavator or a conventional crawler excavator. After an initial relief, the net barriers can be opened and damaged elements may be replaced. Anchorages and foundations usually remain undamaged.

– **Do net barriers belong to the family of structural protection measures and do they have to be filed in the cantonal register of protection structures (for Switzerland)?**
For some years, net barriers have extended the range of structures designed to protect against debris flows and hillslope debris flows. Maintenance, emptying and repair must be ensured in the same way as for rigid protection structures. Net barriers must therefore also be entered in the corresponding cantonal registers of protection structures.

– **Where can information on suitable modelling of flow processes be obtained?**
Research institutions, scientific networks and associations continuously research and publish on flow processes and their modelling. A selection of publications can be found in the reference section of this practical guide.

– **How permeable is a debris flow or hillslope debris flow protection net, and how large should the basal opening be designed for a debris flow protection net?**
The permeability of net barriers is strongly process-, area- and material-dependent and general statements are therefore not possible. With respect to the permeability of nets, small-scale experiments on the relation between mesh size and relevant grain size were carried out at WSL (see [37] for further details).

The influence of the flow depth on the clogging of the **basal opening** of debris flow protection nets was investigated in [37]. Specific information on the dimensioning of the basal opening can be found in Chapter 6.2.3.

Technical part

6 Scenario building and dimensioning of system parameters

6.1 Scenario building for debris flows and hillslope debris flow processes

Hazard maps and supplementary information in technical reports or fact sheets provide basic information on event scenarios and flow parameters. For the actual dimensioning and determination of the design event, however, further clarifications must be made to ensure that the evaluation depth of the assessment is appropriate to the problem to solve and corresponds to the planning stage. The evaluation of the effect of the protection measures is carried out according to PROTECT [23]. Furthermore, it is mandatory to clarify the behaviour in the case of a structure overload, which must be taken into account for the design and dimensioning. Uncertainties in the assessment of natural hazards in general and in the estimation of event sizes in particular must equally be considered. They are best dealt with using possible ranges of parameter values and must be declared openly.

Debris flows and hillslope debris flows are characterized by sudden surges of a mixture of water and solids. The fraction of solid content predominates and results in high densities of the mixture. As a result, large, heavy individual components can be transported at or near the flow surface. The water content of the mixture, in combination with the channel or slope gradient, defines the flow velocity. The combination of high flow heights, velocities, densities and, partly, large individual blocks, results in massive forces that act directly on the structure, locally and/or in a distributed manner. The determination of the flow parameters is therefore the central element for the dimensioning of the structures. Further information can be obtained, e. g., from [21]. Additionally, resulting impact areas and parameters can be determined and evaluated using numerical models.

In scenario building, the frequency and event volumes of debris flows are decisive event variables and have a particular effect on the choice of suitable protection measures. For detailed investigations, proven methods such as SEDEX [14] and Gertsch [17] are available. They are based on estimates in the field or on theoretical considerations and then compared with the values from empirical formulas. With respect to the volume of solids, a clear distinction must be made for debris flows between the overall event and individual surges. Furthermore, it must be clarified whether viscous or granular mixtures are to be expected, how events develop and whether driftwood plays a decisive role.

In Alpine regions, event volumes for debris flows range in the order of a few 100 m^3 up to several 100,000 m^3. Flow velocities on alluvial fans reach 1 to 15 m/s and corresponding peak discharges are in the range of 10 to 1000 m^3/s. The maximum diameter of a single block extends approximately to the value of the flow height. The relevant dimensioning parameters and expected magnitudes for debris flows are shown in Table 6.

Table 6. Order of magnitude of relevant debris flow process parameters (based on various sources).

Parameter	Unit	Order of magnitude	Comment
V_{surge}	[m^3]	100–100,000	Volume per surge, total volume of event V_{total} may be several times higher
Q_{max}	[m^3/s]	10–1000	Peak discharge or maximum discharge at the surge front
υ	[m/s]	1–15	Front velocity
ρ	[kg/m^3]	1600–2200	Density of debris flow mixture, at the front
ρ	[kg/m^3]	2200–2650	Density of single block, based on local geology
h_{fl}	[m]	0.5–10	Flow height at the front
d	[m]	up to a maximum of h_{fl}	Single block diameter

A basic disposition for hillslope debris flows is given if unfavourable geological characteristics are present in a study area with slopes steeper than 20° [2]. Hillslope debris flows usually occur only once at the same site, but precise prediction of occurrence remains difficult. Usually, a disposition approach [2] is used to assess the location(s) of occurrence, which is primarily based on geotechnical properties. In addition, a survey of previous hillslope debris flow occurrences in the study area is important for the analysis. The disposition and probability of occurrence in the starting zone are to a certain extent similar to those of shallow to medium-depth spontaneous landslides. According to the method presented by AGN [1], a stepwise approach for the assessment is recommended. Resulting impact areas and parameters can be determined and evaluated using numerical models.

The thickness of the mobilizable masses of hillslope debris flows ranges usually between 0.5–3 m, and rarely exceeds 10 m. Their relocated volume is generally limited. The relatively high water content results in high flow velocities (1 to 15 m/s), which have a corresponding destructive effect. These high values of water content also favour the reach of a hillslope debris flow, and the surface of the impact zone may exceed the one of the starting zone by a factor of 10 to 100 [8]. The relevant dimensioning parameters and expected magnitudes for hillslope debris flows are shown in Table 7.

Table 7. Order of magnitude of relevant hillslope debris flow process parameters (based on various sources).

Parameter	Unit	Order of magnitude	Comment
V_{total}	[m^3]	10–10,000	Total volume of event
Q_{max}	[m^3/s]	1–100	Peak discharge or maximum discharge at the surge front
υ	[m/s]	1–15	Front velocity
ρ	[kg/m^3]	1600–2200	Density of hillslope debris flow mixture, at the front
ρ	[kg/m^3]	2200–2650	Density of single block, based on local geology
h_{fl}	[m]	0.3–3	Flow height at the front
d	[m]	$< h_{fl}$	Single block diameter

6.2 Design layout of debris flow protection nets

6.2.1 Residual height

The residual height h_b’ is defined as the smallest distance between the upper support rope and the channel base or the lower support rope after a filling event of a debris flow protection net. The data on the residual height depend on the support system, flow parameters, grain size distribution and degree of filling of the debris flow protection net. Standard values for the residual height can be obtained from the system manufacturer.

6.2.2 Hydraulic freeboard

The hydraulic freeboard is the distance between the upper support ropes and the top edge of the embankment, measured while the debris flow protection system is not under load. It is used to ensure that the debris flows cannot escape from the channel when the net barrier is overflowed (see also Section 6.2.5). It is important that the sum of the residual height h_b’ and the expected flow height h_{fl} of the overflowing debris flow is smaller than the sum of the nominal height and the selected hydraulic freeboard.

6.2.3 Basal opening

The **basal opening** h_d is the distance between the lower support ropes and the channel base and is used to pass normal runoff without large amounts of bedload and wood. If a lot of driftwood is expected in a channel, it is recommended to design the basal opening of the net barrier larger than the usual standard values of h_d = 2/3 h_{fl} [36]. Alternatively, a separate driftwood retention above the net barrier should be considered. When designing the basal opening, the capacity of the channel downstream of the net barrier should also always be considered.

6.2.4 Retention volume

The retention volume V_R is determined using the residual height of the net barrier h_b' and the mean channel width b_m at the barrier location. For a rough calculation, the channel gradient l_s upstream of the net barrier and the gradient of the deposited debris flow load l_s' in the retention space are required.

The gradient of the deposited material can be estimated according to [22] with $l_s' = 2/3\, l_s$. Accordingly, the gradient of the debris flow load deposition is $1/3$ flatter than the original channel inclination upstream of the structure. Assuming a straight channel upstream of the barrier, the following geometric relationship is then obtained according to [36] for a rough estimation of the retention space (for a vertical protection net arrangement according to Figure 5 and [36]).

$$V_R = 0.5(h_b^{'})^2 b_m \sin\xi \left(\frac{\sin\xi}{\tan(\theta - \theta')} + \cos\xi\right) \tag{1}$$

with
V_R = Retention volume of the net barrier
h_b' = Residual height, see 6.2.1
b_m = $(b_u + b_o)/2$ mean width of protection net, usually calculated using top width of protection net b_o and bottom width protection net bottom b_u
ξ = Angle between protection structure and stream bed in [°]
θ = Stream section angle in [°]
θ' = Deposition angle in [°]

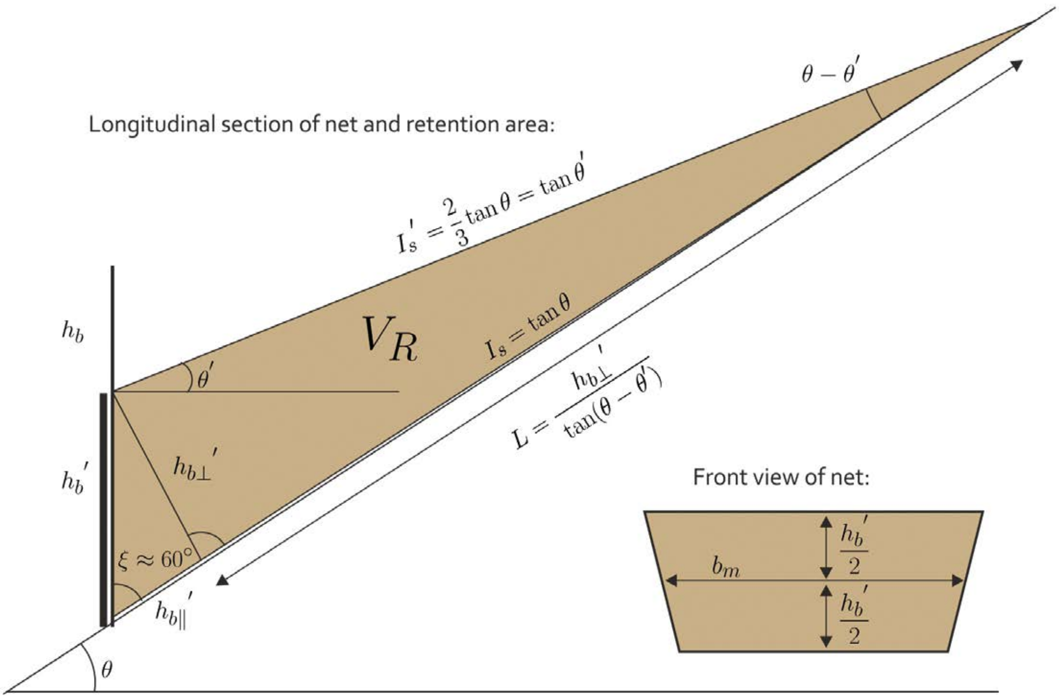


Fig. 5. Longitudinal section of torrent and front view of the net. Figure according to [36].

6.2.5 Overflow

The overflow of a debris flow protection net must be verified as a separate dimensioning load case (see Chap. 7.2.1). The overflow case can become decisive in the case of high barriers and/or large flow heights h_{fl}, since in this case the hydrostatic pressure becomes correspondingly large and may eventually become larger than the dynamic impact. Lower barriers are overflowed earlier, but for these cases the hydrostatic pressure is usually not decisive. The **load case** of overflow is not covered by default in the declaration of performance (DoP) for the **CE-marking** of a debris flow/hillslope debris flow protection net. In addition, it is important that the remaining hydraulic freeboard is planned larger than the maximum height of debris flow during overflow of the net barrier. For constructive design, it is essential to provide for an **abrasion protection** to protect the upper support ropes.

6.3 Design layout of hillslope debris flow protection nets

6.3.1 Residual height

The residual height h_b' is defined as the smallest distance between the upper support rope and the ground surface (or the lower support rope) after a filling event of a hillslope debris flow protection net. The data on the residual height depend on the support system, flow parameters, grain size distribution and degree of filling of the hillslope debris flow protection net. Standard values for the residual height can be obtained from the system manufacturer.

6.3.2 Retention volume

The retention volume V_R is determined using the residual height of the barrier h_b' and the maximum spread of the material at the barrier location b_{max}. Similar to debris flow protection nets (see Chap. 6.2.4), the volume can be approximately calculated as follows:

$$V_R = 0.5(h_b^{'})^2 b_{max} \sin\xi \left(\frac{\sin\xi}{\tan(\theta - \theta')} + \cos\xi \right) \tag{2}$$

with

V_R = Retention volume of the net barrier
h_b' = Residual height, see Chap. 6.3.1
b_{max} = Maximum spread of material along the net barrier
ξ = Angle between protection barrier and slope surface in [°]
θ = Slope section angle in [°]
θ' = Deposition angle in [°]

The simplified assumption for the calculation above is that the flow height remains constant over the entire width b_{max}. The geometrical estimation of the maximum spread b_{max} is carried out as follows: If the starting zone width of a hillslope debris flow b_0 can be estimated, and it is assumed that the hillslope debris flow moves with a maximum spread angle δ of [2–10°], the maximum spread of the material b_{max} can be determined using the distance between the starting zone and the installation site L_0 (see Fig. 6). This results in:

$$b_{max} = 2\tan\delta L_0 + b_0 \tag{3}$$

Alternatively, or as a supplement to the geometric considerations between the starting and the planned installation site of the hillslope debris flow protection net, numerical simulations can be used.

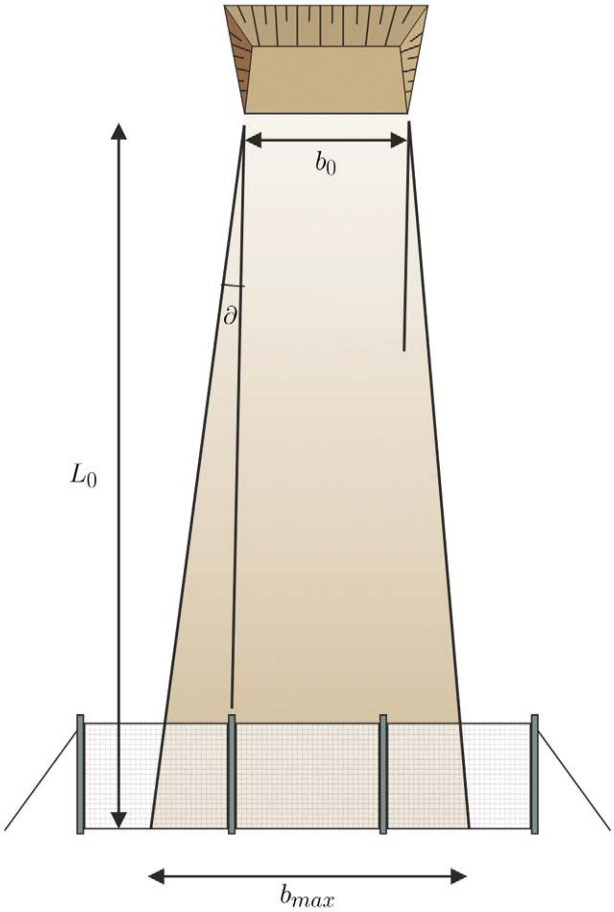


Fig. 6. Sketch of geometric determination of maximum spread. Figure according to [16].

6.3.3 Overflow

Usually, **CE-marked** hillslope debris flow protection nets are not designed for overflow. Therefore, this case is not covered by default in the declaration of performance (DoP) of a hillslope debris flow protection net (see Sect. 6.2.5 regarding overflow for debris flow protection nets).

If, nevertheless, overflow of the net barrier is envisaged, this must be verified as a separate design **load case** (for details of the load model for hillslope debris flow protection nets, refer to Sect. 7.2.2). In addition to potential reinforcements of the support structure, the upper support ropes must be provided with additional **abrasion protection** in this case. In addition, it must be reviewed whether the overflow may result in problematic erosion downstream, and whether suitable structural or organizational measures must be taken for this case.

6.3.4 Bypassing

Lateral bypassing of the barrier should be avoided whenever possible. To ensure this, the minimum barrier length $\mathrm{L_{min}}$ must therefore be designed to be significantly greater than the maximum spread of material behind the barrier $\mathrm{b_{max}}$ (see also Chap. 6.3.2).

A **uphill apron net** as a constructive addition to hillslope debris flow protection nets prevents a net opening between the ground and the lower board of the net, which may occur when the lower support rope is lifted. Underflowing of the net is thus prevented. The installation of a finer-meshed **secondary mesh** on the uphill side of the actual protection net ensures the retention of fine material.

For debris flow protection nets, water flows off in a controlled manner via the channel on the downstream side of the net. However, this controlled drainage is missing in the case of hillslope debris flow protection nets. Therefore, on the downstream side of this type of protection net, an appropriate water catchment and drainage system must be installed so that water from the hillslope debris flow process and any surface water runoff can be collected and discharged without damage.

7 Dimensioning

7.1 Safety concept

In general, a safety concept serves to ensure the stability of a structure regarding structural safety, serviceability and durability. The following section focuses on the ultimate limit state of structural safety. The other two aspects, serviceability and durability, are discussed in Chapter 3.2.

For debris flow and hillslope debris flow protection nets, the following main aspects should be investigated in the ultimate limit state:

– Breaking load of the support ropes with **energy absorption elements** due to excessive tensile and shear forces
– Breaking load of the net structure due to excessive point loads (e.g. punching due to single block impact, pressure peaks and overload)
– Failure of the anchors regarding pull-out and internal resistance of the anchors regarding rupture

For rigid protection structures, the load and the resistance side are dimensioned separately with partial safety factors γ_F for the load and γ_R for the resistance side (e.g. SIA Standard 261, SIA Standard 263 and SIA Standard 267 [25]–[29]). For **net barriers** under debris flow or hillslope debris flow loads, there are so far no defined failure probabilities as defined for rigid structures under certain action scenarios according to SIA Standards. A probabilistic approach is therefore not yet possible for net solutions.

In Chapter 5 of SIA Standard 261/1 [27], debris flows and hillslope debris flows on the load side are always described as exceptional loads on a structure. In [31], debris flows with a short return period (1–30 years) are classified as regular loads, and with larger return periods (>30 years) as exceptional loads. For the basis of the safety concept, the return period (and the frequency of occurrence respectively) as well as the classification as regular or exceptional load are important parameters. In addition, the occurring intensities of the loads are important to assess. In SIA Standard 261/1 [27] and in hazard maps, medium and strong intensities are defined for debris flows, and weak, medium and strong intensities for hillslope debris flows. Site-specific intensities, or flow parameter and loads respectively, need to be assessed and specified by an expert.

For the risk assessment concerning people, environmental consequences and economic damages due to failure of a protection structure impacted by a debris flow or hillslope debris flow event, a classification into risk classes is proposed in [36]. As for the risk classes, e.g. accepted failure probabilities according to the Joint Committee of Structural Safety JCSS [18] may be used and assigned to the risk classes:
– Risk class 3/failure probability $p_f = 10^{-6}$ in the case of great danger to human lives; for protection measures in the immediate vicinity of settlements, roads and industrial zones.
– Risk class 2/failure probability $p_f = 10^{-5}$ with medium danger to human lives; for protection measures in the further vicinity of settlements, roads and railroad lines
– Risk class 1/failure probability $p_f = 10^{-3}$ with low risk to human lives; for forests, alluvial zones and pastures

These risk classes are compared with the return periods of debris flows or hillslope debris flows and, following [31], the partial safety factors γ_F on the load side are assigned according to Figure 7. For the explicit protection of new buildings by means of a debris flow or hillslope debris flow protection net, SIA Standard 261/1 [27] needs to be consulted, where structure classes are defined depending on the use of the structure. On the resistance side, the partial safety factors γ_R are recommended according to the corresponding SIA Standards (SIA Standards 261, 262, 263 and 267 in [25]–[29]).

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

Fig. 7. Recommended partial safety factor γ_F on the load side, considering the risk class and the return period of the debris flow or hillslope debris flow event. Based on [31]/copied from [36].

7.2 Load models

7.2.1 Debris flow protection nets

The basis for the next subchapters is given in the WSL report 8 [33]. It fully describes the design concept for flexible net structures of PhD thesis No. 17916 at ETHZ [36] by Corinna Wendeler, published in 2008. This work was realized at WSL under the supervision of Dr. Perry Bartelt and Dr. Axel Volkwein as part of a joint CTI research project with Geobrugg AG. The pressure coefficients α are lower for **net barriers** than the values for c_p published in SIA Standard 261/1 [27], which correspond to the same factor, but apply to **impact pressures** against rigid obstacles (wall, dam, etc.).

7.2.1.1 Quasi-static load model

An approach which determines the pressures acting on the debris flow protection nets and thus the forces acting on them, and which represents very well the situation for a simplified engineering model, is described in [36]. In this model, the debris flow is discretized with a constant flow height h_{fl}, a constant density ρ and a constant flow velocity v. It hits the net barrier with an "initial impact" (see Fig. 8). After the debris flow has stopped, the net barrier is modelled by being filled with the subsequently following material (see Fig. 9). This continuous process is **discretized** in time in the simplified load model in such a way that the net barrier is filled in individual flow height surges assuming a uniform distribution of the flow height (see Fig. 9).

The acting hydrostatic pressure p_{stat} and hydrodynamic pressure p_{dyn} (in N/m^2) are assumed to be uniformly distributed over the channel width. The following calculation formulas result:

$$p_{dyn} = \alpha \rho v^2 \tag{4}$$

with

ρ = Density of the debris flows with ρ = 1600–2200 kg/m^3

α = Pressure coefficient
(granular debris flows α = 2.0; viscous flows with ρ < 1900 kg/m^3; α = 0.7–1.0)

υ = Mean velocity of the debris flow front in m/s

and

$$p_{stat} = a h_{fl} \rho g \tag{5}$$

with

a = Earth pressure coefficient a = 1.0

g = Gravitational constant g = 9.81 m/s^2

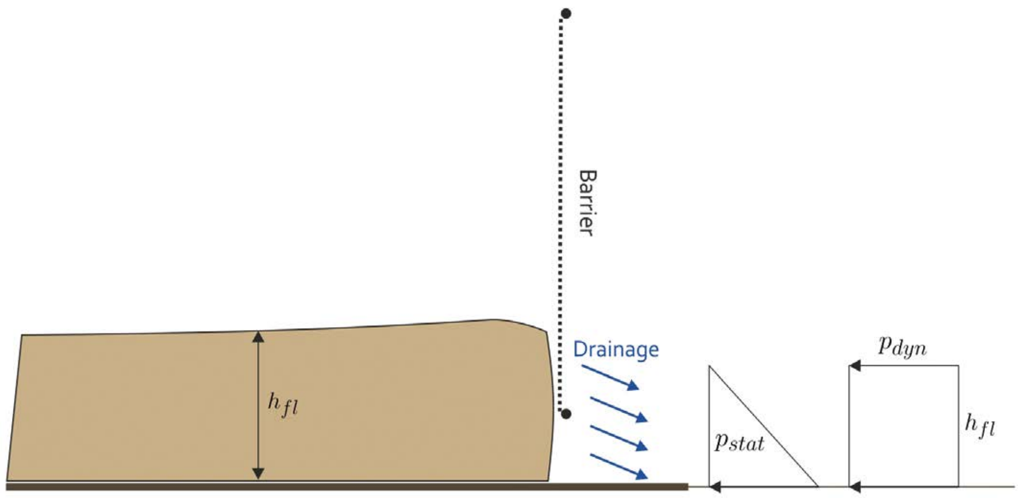


Fig. 8. Initial impact of the debris flow on the barrier using a pressure surge model consisting of hydrostatic pressure $\mathrm{p_{stat}}$ and hydrodynamic pressure $\mathrm{p_{dyn}}$. Figure after [36].

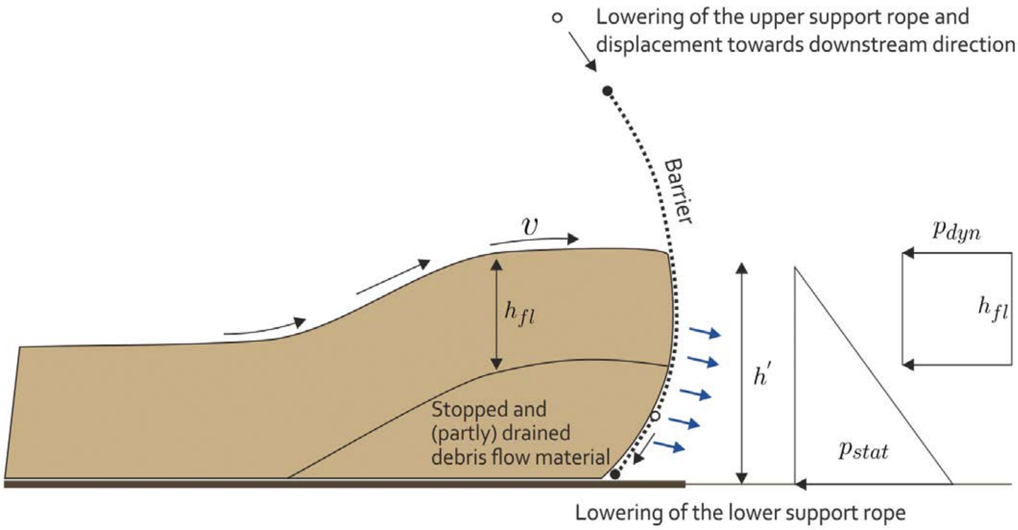


Fig. 9. Time-discretized filling process in the pressure surge model including expected deformations of the barrier. Figure after [36].

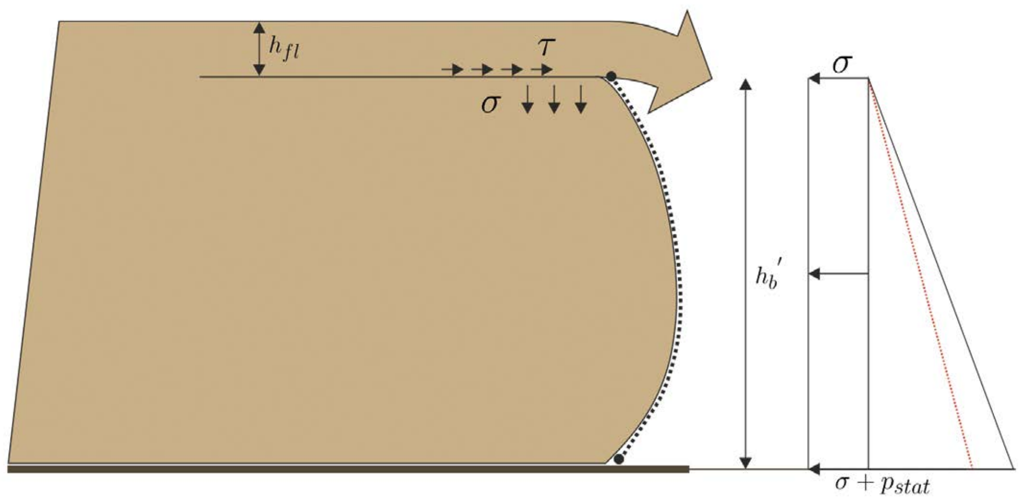


Fig. 10. Load situation during overflow of a barrier, which reaches its remaining residual height due to backfilling. Figure according to [36].

For special geometries with a locally deeper channel beds or very shallow channel banks, the above theory must be tested individually on a project specific basis.

For the overflow **load case**, an additional shear stress $\tau = h_{fl}\ \rho\ g\ \tan\ \theta$ (in the flow direction) and a surcharge load with $\sigma = h_{fl}\ \rho\ g$, (perpendicular to the flow direction) are acting on top of the filled barrier. The shear stress component is often neglected because of its small magnitude ($\tau \approx 1/10\ \sigma$).

7.2.1.2 Single block impact

The single impact of a block or another component, e.g. a tree trunk, is usually only significant when the impact occurs directly on a support rope. If the support ropes are separated further than the design block size, a punching shear test must be performed separately for the net. If the block of mass m collides directly with a support rope/support rope bundle of length L at velocity υ, most of the kinetic energy of the block is transferred to the rope elongation energy, while a part of the energy is also absorbed by the **energy absorption elements**. The component of the energy absorption elements will be neglected in the following as a simplifying assumption, staying on the safe side.

The rope elongation energy $E_{pot,rope}$ (in J) can be determined with

$$E_{pot,rope} = 0.5 k_s \Delta L^2 \tag{6}$$

with
k_s = $E\ A/L$ spring stiffness of the rope of length L
E = Modulus of elasticity of the rope
A = Effective cross-sectional area of the rope
ΔL = Elastic elongation of the rope

The rope force F_{rope} (in N) can be calculated using the approach of the spring law $k_s = F_{rope}/\Delta L$:

$$F_{rope} = \sqrt{\frac{m v^2 E A}{L}} \tag{7}$$

with
m = Single block mass
υ = Mean front velocity of the debris flow
E = Modulus of elasticity of the rope
A = Effective cross-sectional area of the rope
L = Rope length

Simplified, it is assumed that the same spring stiffness k_s prevails over the rope length L and the energy absorption of the brakes is neglected.

7.2.2 Hillslope debris flow protection nets

7.2.2.1 Quasi-static load model

The quasi-static load model for hillslope debris flow protection nets works analogously to the formulas in Chapters 7.2.1.1 and 7.2.1.2. The only difference is that hillslope debris flow protection nets usually do not need to be verified for the overflow **load case**, since hillslope debris flows show significantly smaller volumes than debris flows. The impact width or maximum spread of material at the barrier location of a hillslope debris flow can be determined according to descriptions in Chapter 6.3.2.

7.2.2.2 Fluid-structure interaction model (FSI-model)

As an alternative to the quasi-static load model, the interaction of the hillslope debris flow material with the **net barrier** can be represented by the Fluid-Structure-Interaction-Model (FSI-Model). This model was developed as part of PhD thesis of Albrecht von Boetticher [34] at WSL in a joint CTI research project with Geobrugg AG under the supervision of Dr. Axel Volkwein.

The maximum retention volume V_R is calculated considering the current terrain's topography. Both the volume reduction due to the expected lowering of the barrier's top support ropes to the residual height h_b' and the inclination of the deposited hillslope debris flow material i_s' are considered (see Fig. 5). This results in the horizontal length of the retention space l_r. With a maximum impact width in the retention space of b_{max} the filling time t_f for a surge volume V_{surge} can be determined by:

$$t_f = \frac{V_{surge}}{h_{fl} b_{max} v} \tag{8}$$

with

V_{surge}	=	Surge volume
h_{fl}	=	Flow height
b_{max}	=	Maximum spread of the hillslope debris flow at the net location
υ	=	Mean flow velocity of the hillslope debris flow front

For the "initial impact", it is assumed that the material is hitting the net barrier with a distinct front, and that the net barrier is subjected to a corresponding impact over the flow height h_{fl} and impact width b_{max}. The impact of the subsequently following material is **discretized** into single surges for overlapping filling stages.

The loads from single overlapping filling stages, which hit the mesh with flow height h_{fl}, frontal flow velocity υ and density ρ (force-time approach according to Wendeler [36]), is converted into overlapping pressures at the respective net barrier height. As for debris flows, the pressure corresponding to a filling level x is composed of a static and a dynamic component:

$$p_x = p_{stat} + p_{dyn,x(t)} \tag{9}$$

The dynamic part of the **impact pressure** of a filling stage $p_{dyn,x(t)}$ is decreasing over time t_x. This favourable effect can be considered in a simplified way by reducing the dynamic impact pressure of the filling stage linearly over the deceleration time t_b from the moment when the surge reaches the net (extended force-time approach according to [34]).

The surge pressure after the initial impact $p_{dyn,1(t)}$ is then given by:

$$p_{dyn,1(t)} = max\left(\frac{t_{b1}-(t-t_1)}{t_{b1}}, 0\right) \cdot p_{dyn} \tag{10}$$

The deceleration time t_b depends on the **impact pressure** which, in reality, is decreasing in a non-linear manner. The impact pressure simplified as linearly decreasing would underestimate the braking time. Therefore, the braking time should be assumed as the time required to decelerate a block of mass m and block velocity υ_f with an average braking acceleration α_b. Accordingly, the braking time can be determined as follows:

$$t_{b,i} = \frac{v_f}{a_{b,i}} = \frac{v_f \rho h l_{r,i} b_{max}}{k p_{dyn} h b_{max}} \tag{11}$$

with

v_f	=	Block velocity
$a_{b,i}$	=	$k\ p_{dyn}\ h\ b_{max}/m$ braking acceleration for surge i
p_{dyn}	=	Hydrodynamic flow pressure
m	=	$\rho\ h\ l_r\ b_{max}$ mass of the block
k	=	0.1, calibration value from tests in Veltheim (Switzerland) [9].

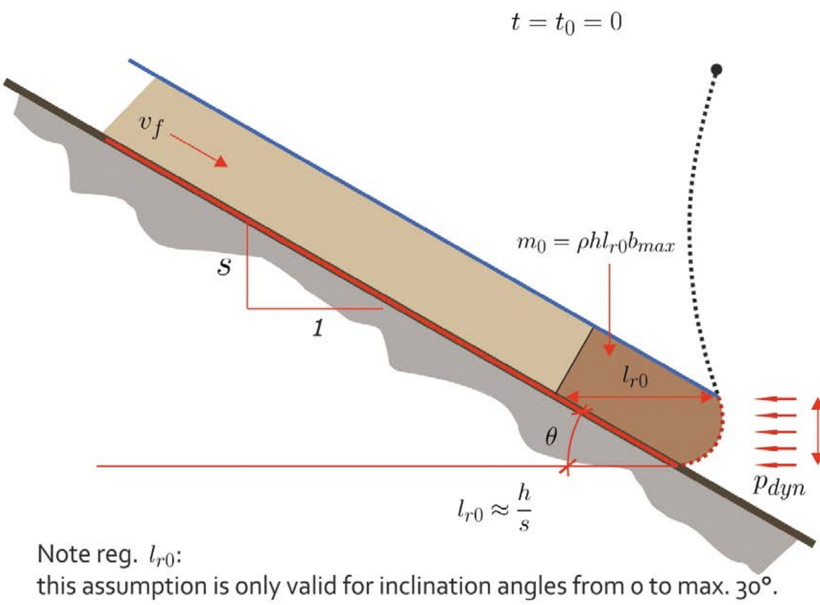


Fig. 11. Schematic representation of FSI model discretization of the first impact, following [34].

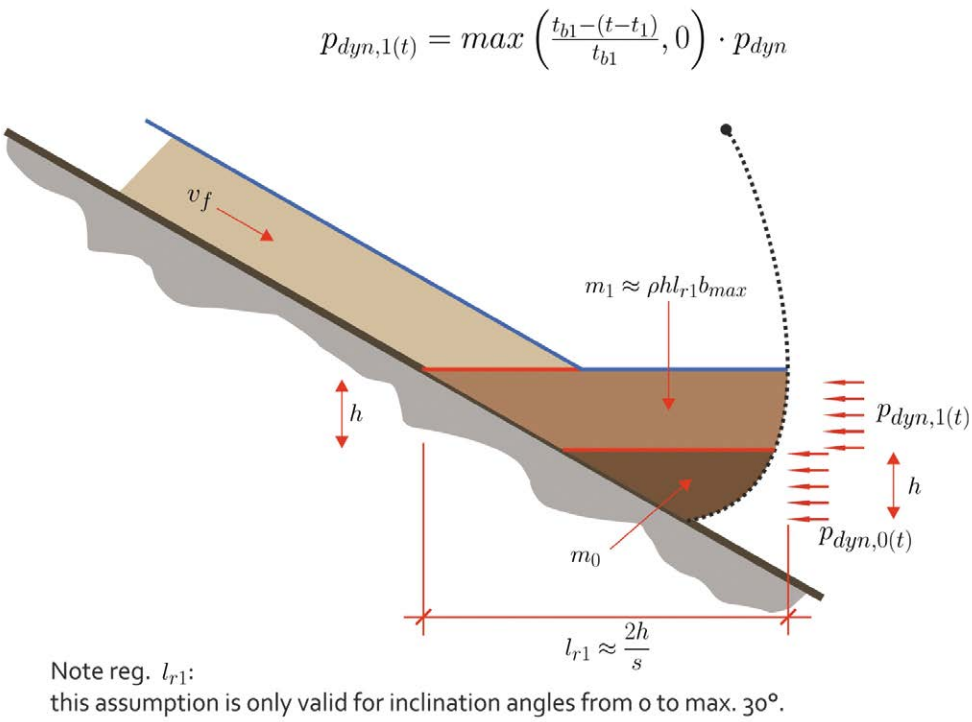


Fig. 12. Further surge discretization using the FSI method after stopping the initial impact of mass m_0 following [34].

The time of occurrence of individual surges cannot be readily estimated. Basically, it can be assumed that subsequent material pushes over the material slowed down by the net barrier. At low Froude numbers <1, it can be assumed in a simplified way that the braking effect of the net barrier is acting on the material of the first filling surge up to a distance of $l_{r0} = h/s$ back into the retention space. Therefore, the subsequent load stage forms at a distance of l_{b1} upstream of the net barrier. A third surge is formed analogously at a distance $l_{r1} = 2\ h/s$ upstream from the barrier, at the time of arrival of the second surge. The impact times of the surges can thus be determined at $t_0 = 0$ [s], $t_1 = l_{r0}/v$, $t_2 = t_1 + l_{r1}/v$, and so on.

The **impact pressures** p_0, p_1, p_2 ... act on the net barrier over the corresponding heights $0\text{-}h$, $h\text{-}2h$, $2h\text{-}3h$ etc., until the net barrier is overflowed. Such, the critical point in time of the overflow with maximum load on the support ropes can be determined during the calculation or simulation.

A plausibility check of the estimated load superposition in the calculation is essential, both regarding the load and the coordination of the arrival time of the last surge with the total filling time t_f. In case of doubt, the reduction of the dynamic pressure must be applied over a longer period of time by reducing the parameter k.

If the approach for the braking time is inserted into the formula for the dynamic pressure, the dynamic pressure for a filling stage x is given by:

$$p_{dyn,x(t)} = max\left(\frac{\frac{v_f \rho l_{rx}}{k p_{dyn}} - (t - t_x)}{\frac{v_f \rho l_{rx}}{k p_{dyn}}}, 0\right) \cdot p_{dyn} \tag{12}$$

Finally, the net barrier being overflowed at an overflow height h_b' and with a flow height h_{fl} is subject to the hydrostatic pressure p_{stat} over the cumulated height $h_b' + h_{fl}$. In addition, a shear load τ acts due to the overflowing hillslope debris flow:

$$\tau = h_{fl} \rho g \tan\theta \tag{13}$$

where θ represents the slope angle of the hillslope debris flow. θ may vary depending on the vegetation and the friction angle of the material [11].

7.3 Dimensioning of components

7.3.1 Support ropes

The support ropes transfer the loads acting on the protection net to the anchorages. Depending on the expected load, support rope bundles may consist of several individual ropes. Several support rope bundles are usually evenly distributed over the net barrier height h_b. The positioning of support ropes should be optimized regarding the expected deformations of the net barriers. **Energy absorption elements** that are integrated into the support ropes and allow for large deformations enable an optimum alignment of the ropes. It is essential to ensure a good structural connection of the ropes to concrete elements, rope anchors or self-drilling anchors in order to transmit the rope force into the anchorages, if possible in the direction of tension.

The ropes can be dimensioned analytically according to [36] based on the following verifications. The pressures acting on the protection net are transferred to the support ropes by means of mean **influential zones**. The load on the horizontal ropes can be assumed to be equally distributed, provided that the filling process takes place over the entire width of the net barrier. A differential equation for ropes suitable for this purpose is then solved iteratively using Newton's method, until the calculated rope forces match the rope and brake elongations to be expected for these forces [20]. The following applies for the rope equation (see also Fig. 13):

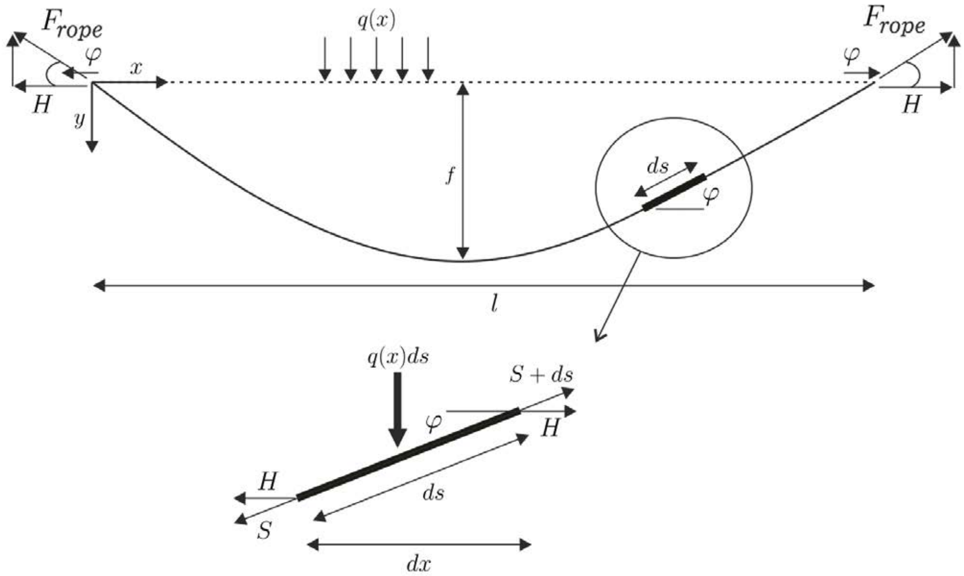


Fig. 13. Representation of the rope equation for equal load on the deflected rope, according to [20] and [36].

$$H^3 + H^2 EA \left[1 - \frac{1}{s_0}(l - \alpha_t \Delta t s_0)\right] = \frac{EA}{2s_0} \int_0^l Q^2 dx \tag{14}$$

with

H	=	Horizontal rope force
E	=	Modulus of elasticity of the rope
A	=	Effective cross-sectional area of the rope
s_0	=	Horizontal rope length
α_t	=	Temperature coefficient for steel
Δt	=	Temperature gradient
Q	=	Values of the integral according to [20]

The upslope anchor ropes cannot be dimensioned in this way because they are not subjected to a continuous uniform load. Their dimensioning is explained in the following chapter. The practical use of the rope equation can be taken from the design example in Appendix A.

7.3.2 Upslope anchor ropes and posts

The forces in the upslope anchor ropes result from decisive post forces and a small force component from bypassing of debris flows (in the case of upslope anchor ropes that are anchored in the channel). This part is usually neglected. The load on the upslope anchor ropes is usually determined considering the overflow **load case** for a filled net barrier. The pressures are transferred to the posts using the mean width of the **influential zones** of the posts. A **verification on torsional buckling** of the posts, using normal force and force in the direction of flow of the debris flows is therefore required for the post verification. The post's upper support force is received by the upslope anchor ropes and must be converted respecting the actual angles of the attached ropes (see Fig. 14).

7.3.3 Protection net

The dimensioning of the actual protection net of the barrier is determined by the arrangement of the horizontal support ropes. The simplified **verification of the net** is considering the net as a rope, using the span from the upper to the lower support ropes and the maximum deflection of the net barrier (see Fig. 15). The design load case with middle support ropes as shown in the design example in Appendix A must be considered separately. By means of the rope equation (Fig. 13) and the net parameters per linear meter, the acting force on the net surface can be determined.

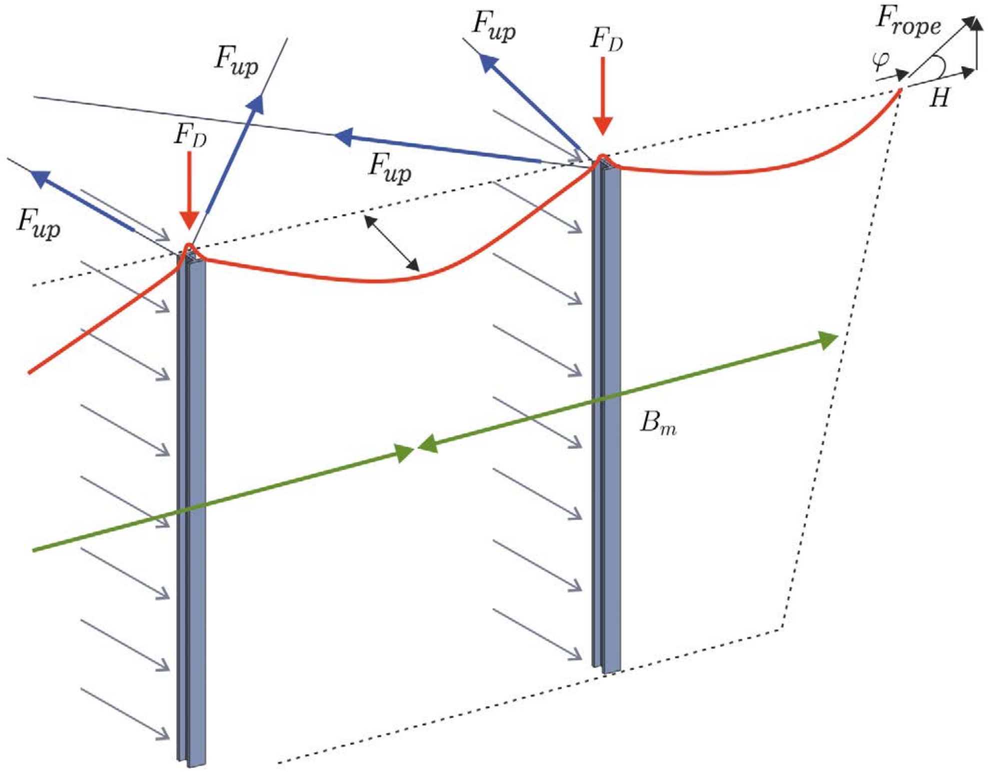


Fig. 14. Debris flow protection net with posts and corresponding force vectors from the support and upslope anchor ropes, following [36].

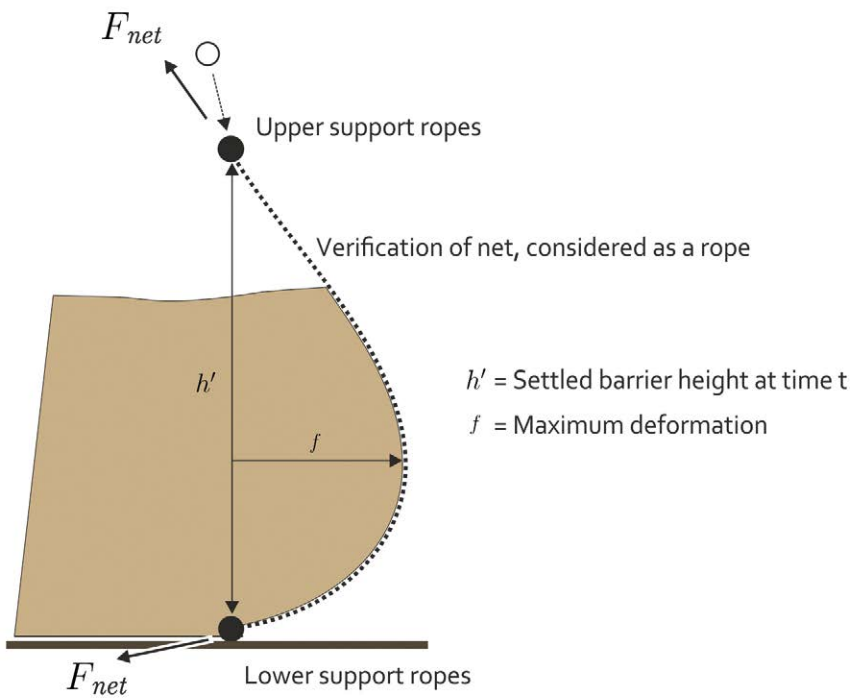


Fig. 15. Section of the debris flow protection net for the verification of the net itself and its corresponding force component.

7.3.4 Anchors and foundations

We recommend assuming the anchor loads for both debris flow and hillslope debris flow protection nets according to the manufacturers specifications. In addition, trial anchors should be tested whenever possible. The number of trial anchors depends on the ground conditions, the size of the construction project and the potential risk of failure [3] but should at least comply with the specifications of SIA Standard 267 [29]. Testing of fully bonded, untensioned soil and rock anchors (nails) are described in SIA Standard 267/1 Geotechnical Engineering/Supplementary Specifications [29].

Due to the uncertainties in the occurring loads, it is recommended for net barriers that the entire ultimate breaking load of the ropes is transferred to the soil using **energy absorption elements**. As for the anchorages, their ultimate design loads need to be clarified. In addition, the recommended foundations serve to transfer the loads from the rope forces into the anchorage and also as corrosion protection for the anchor head. In the case of soil, it is advisable to review whether a lateral, continuous concrete foundation should be built in order to prevent the anchorage from scouring at the channel banks. Moreover, a minimum reinforcement bar of 10 mm diameter should be installed within the foundations every 10 cm to minimize crack widths. The **compressive strength class of concrete** should be selected according to the corresponding **corrosion protection class**. References on the dimensioning and constructional design of the anchorages can be found in [36], [3] and [29].

7.3.5 Post foundations

The post foundations protect the pressure and tension anchors from scouring and corrosion. At the same time, they transfer the pressure forces into the ground as an area load. Dimensioning of the post foundation must take into account the post's compression forces as well as the tensile forces from the lower support ropes that act on the foundation. In the case of eccentric post connections to the base plate, the corresponding torque must be taken into account in the design of the pressure and tension anchors. In terms of reinforcement, it is also recommended that the minimum reinforcement required is installed to limit crack widths.

7.3.6 Example of structural foundation design

The geometric conditions of foundations for protection nets depend to a large extent on the geometric conditions of the base and anchoring plates of the individual manufacturers. An example without verification of calculations is shown in Figure 16 and Figure 17 for post foundations, with one pressure and two tension anchors that are installed at an angle of 45° to each other.

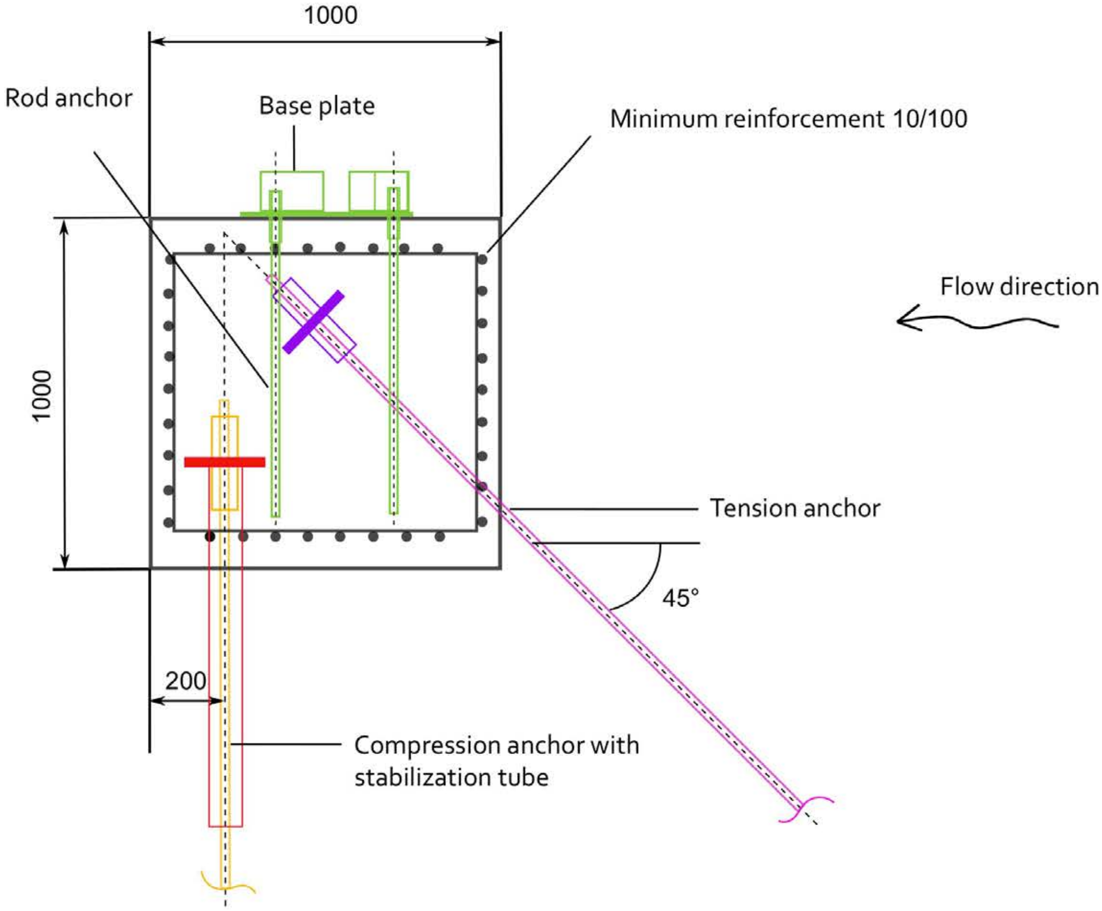


Fig. 16. Side view of a reinforced concrete foundation with one pressure and two tension anchors, based on [15].

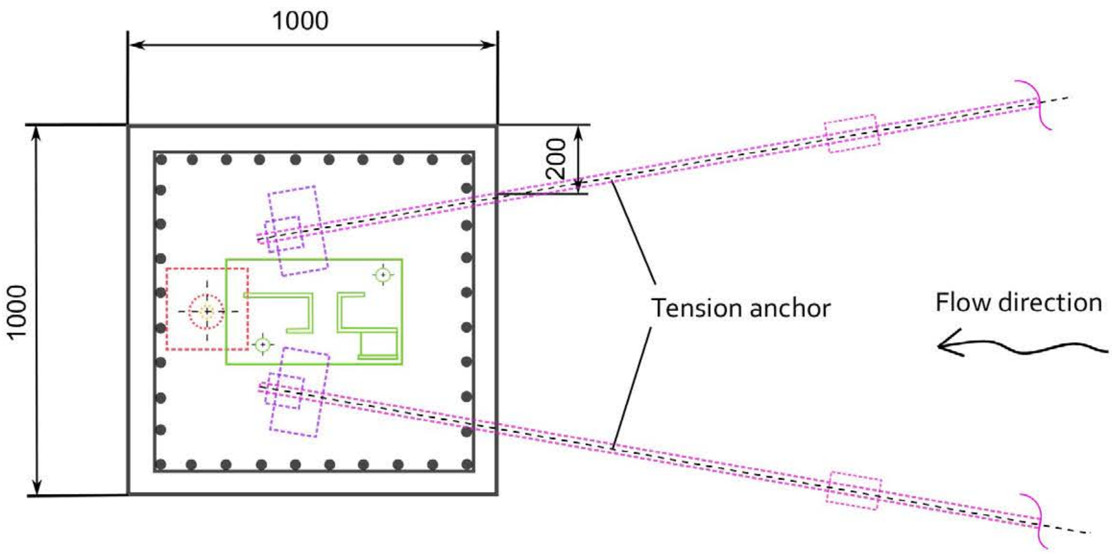


Fig. 17. Top view of a reinforced concrete foundation with one pressure and two tension anchors, based on [15].

8 Inspection and maintenance

8.1 Basic conditions

Requirements are placed on protection structures regarding structural safety, serviceability and durability. Regular inspections and appropriate maintenance are necessary to ensure that **net barriers** function properly over their defined **service life** [19].

The responsibilities and periodicity for the inspections as well as for ongoing and structural maintenance are handled differently depending on the canton/authority and the owner of the structure. They must therefore be considered and identified in the planning stage. Ongoing maintenance can be carried out by the owner or by associated specialized service providers such as water supply services or the forestry service. For any structural maintenance (repair of the structure), it is advisable to involve the manufacturer of the net barrier, the responsible authorities and a specialized construction company. It is important to make sure that only trained staff carry out inspection and maintenance. The work safety of all staff must be guaranteed at all times in accordance with the current applicable legal provisions.

Suitable early warning and alarm systems can also be of great benefit for the inspection of protection structures. Based on theory and case studies, the practical guide "Use of early Warning Systems for Gravitational Natural Hazards" issued by the Swiss Confederation [24] describes various possibilities for such systems.

8.2 Tools for inspections

The following existing tools can be used for inspections as well as for ongoing and structural maintenance:
- Manual for the inspection and maintenance of forest infrastructure [19]
- Maintenance manuals of the system suppliers

For debris flow and hillslope debris flow protection nets, the same or similar system components are generally used as for rockfall protection nets. For the inspection of these types of protection nets, the same forms for damage assessment can be used as for rockfall protection nets (see also [19]). The maintenance manuals of the system suppliers usually also contain corresponding forms (example in Appendix C). In the case of damage, the repair of the structure can be handled in a similar way as for rockfall protection nets.

8.3 Measures after events

After an event (partial or complete filling, see examples in Table 8), the following steps are necessary for repair:
- The owners or the associated technical services inform the responsible authorities.
- The municipality or the local cantonal authorities are notifying the population suitably
- The safety of the infrastructures to be protected must be ensured (e.g. road closures by the municipality or the canton)
- The owner is commissioning a construction company for emptying of the barriers
- The construction company is ensuring the work safety of staff
- The construction company is emptying the net barriers
- The construction company is replacing all damaged components of the net barrier
- The manufacturer of the net barrier is approving/re-commissioning the structure in consultation with the cantonal authorities.

After a net barrier has been professionally repaired, it must be reassessed regarding its future **service life**.

Table 8. Situation after partial or complete filling of a net barrier.

	Congestion of the basal opening due to partial filling of a debris flow protection net. Image: [C]
	Filled and overflowed debris flow protection net. Image: [D]
	Debris flow protection net filled by bedload transport. Image: [G]

8.4 Emptying of debris flow and hillslope debris flow protection nets

Like all retention structures, also protection nets must be emptied and repaired after they have been partially or completely filled. When emptying hillslope debris flows and debris flow protection nets (see also Table 9), the following points must be considered:
- Site access, material removal and transport, disposal sites, and sites for re-feeding bedload must be defined during the planning stage.
- Due to the filling of the net, the support structure is under tension. Therefore, special care must be taken during all emptying operations. The system or maintenance manuals of the net barrier manufacturers provide information on the methods for the opening of the net barrier.

As with other retention structures, the following points must be considered:
- Protection nets filled by debris flow and hillslope debris flow are emptied from the uphill side whenever possible. Even though emptying from the downslope side is often possible, this is usually more difficult to carry out while fully respecting work safety.
- If the hazard situation allows for it, emptying of the net barriers should be carried out within a short delay after the event, in order to make the retention space available again as quickly as possible.
- Particularly high attention must be paid to work safety.
- The preparation of an emptying concept with corresponding working steps and emergency scenarios is recommended.

Table 9. Emptying of debris flow and hillslope debris flow protection nets after an event.

Emptying of a debris flow protection net from the uphill side using a walking excavator.

Image: [G]

Emptying of a hillslope debris flow protection net from the downslope side using an excavator.

Image: [G]

9 Special structures

Special requirements demand special solutions. This is especially true for **net barriers** when the system limits according to Chapter 3.1 are reached. In Switzerland, several special structures have been realized by 2020. A selection of them is presented below. More detailed information is shown in the characteristic data sheets in appendix B. It is important to note that special structures usually have a highly complex support structure and require detailed consideration and dimensioning. Moreover, a numerical simulation of the structural system may provide more detailed information.

Suspension rope net
Hüpbach torrent in Oberwil, Simmental, Switzerland
Image: [F]

Multi-level net barriers
Trachtbach torrent in Brienz, Switzerland
Image: [G]

Net structure with longitudinal concrete discs
Grönbach torrent in Merligen, Switzerland
Image: [F]

Net structure with concrete pillars
Innere Sitebach torrent in Lenk, Switzerland
Image: [F]

Stepwise installed nets serving as supplementary structure
Illgraben torrent in Leuk, Switzerland
Image: [A]

Erosion control and filter structure
Durschtbach torrent in Simplon, Switzerland
Image: [G]

Structure for combined loads
Baltisberg/Härzigwald, Switzerland
Image: [H]

Driftwood protection net
Chiene torrent in Reichenbach, Switzerland
Bild: [F]

10 Design flow chart

After the decision to install a **net barrier**, it will be dimensioned. The design flow charts for debris flow and hillslope debris flow protection nets shown in Figure 18 and Figure 19 may support the design process.

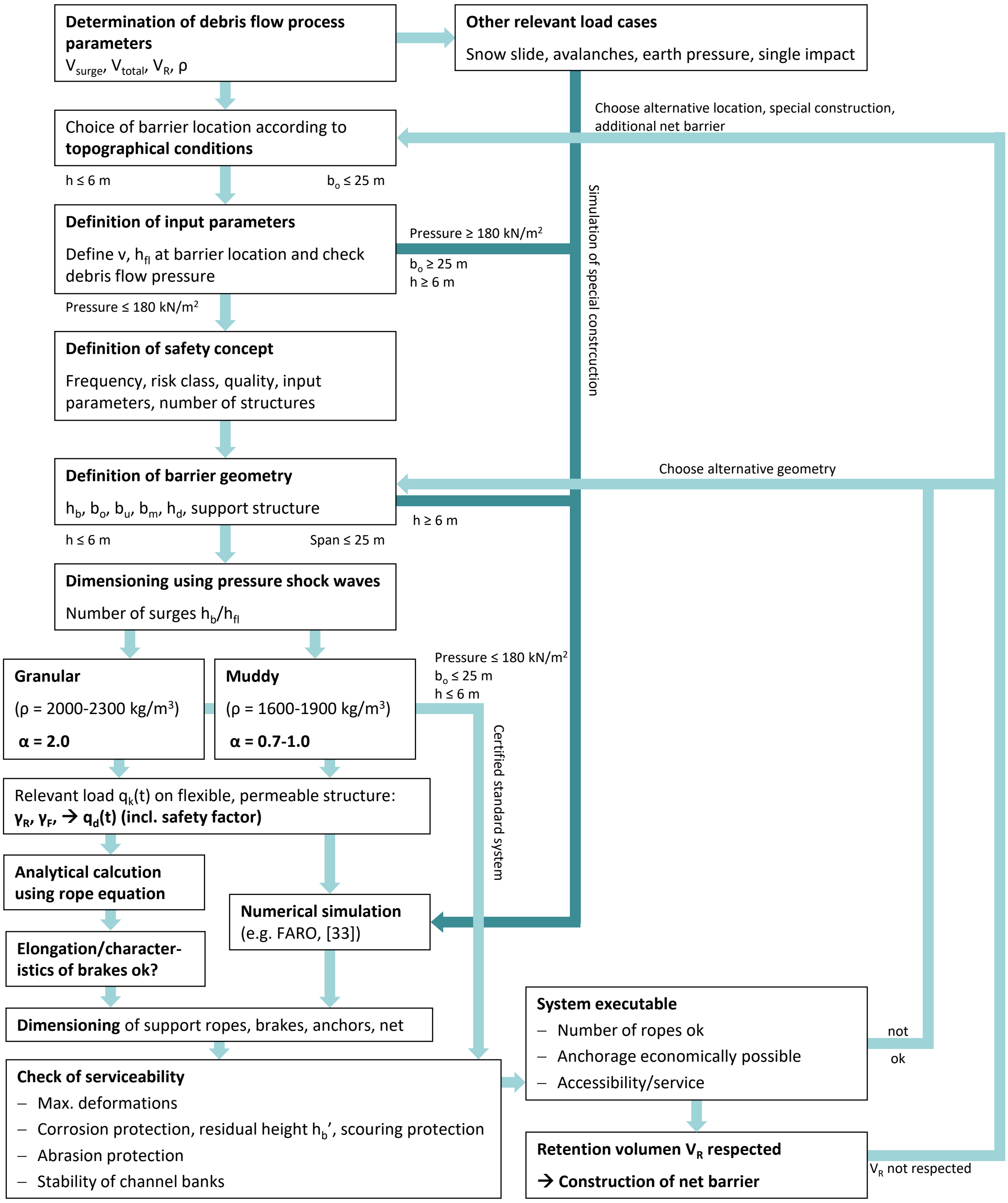


Fig. 18. Design flow chart for debris flow protection nets, according to [36].

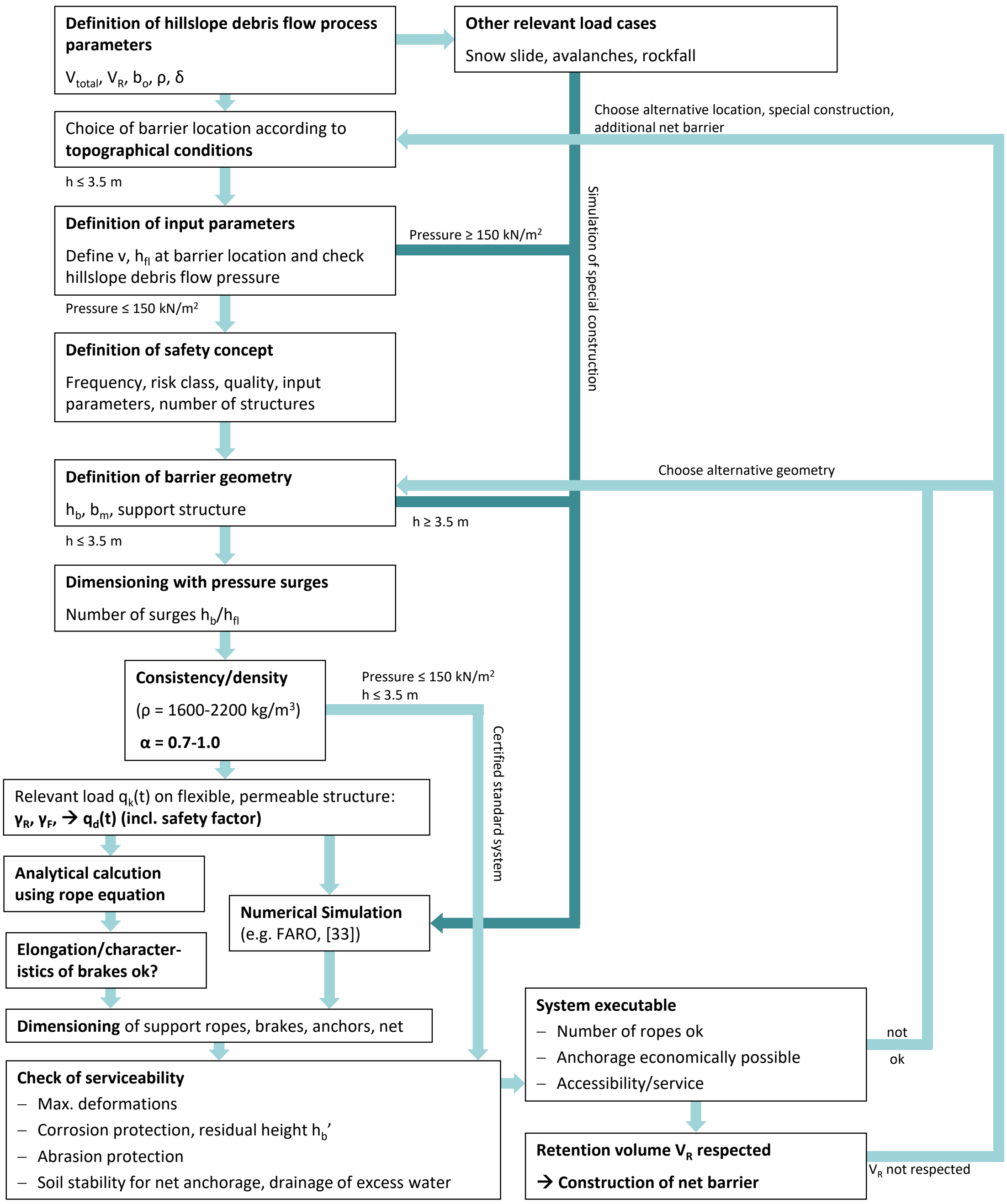


Fig. 19. Design flow chart for hillslope debris flow protection nets, according to [36].

11 Conclusion and outlook

In addition to spatial planning, organizational and nature based protection measures, protection structures are an important element for integral protection against natural hazards. Properly designed and maintained, they are fullfilling a long-term protective function. Depending on their implementation within the process area, natural hazards may be deflected, slowed down, stopped, or can be prevented from developing in the first place. In the past decades, many settlements and traffic routes in Switzerland have been protected by means of structures installed in the rupture or outbreak zones, or by structures installed near or at the properties being protected. In addition to the traditional, rather rigid types of structures, lighter and flexible solutions such as net barriers have been developed in the recent past.

This practical guide provides an overview of the state of the art concerning debris flows and hillslope debris flow protection nets in Switzerland. Important topics such as possible applications, limitations as well as the design and dimensioning of this type of protection nets are covered. Decision support charts help for considerations whether, for a specific situation, a net barrier is an appropriate protection structure, and which aspects should be taken into account for its planning and implementation. The authors point at the fact that inspection and maintenance of net barriers are indispensable for long-term use, as is the case with all protection structures. The practical guide deals with various type of net barriers, since, in addition to CE-marked standard systems, there are a number of special structures that extend the range of applications of net barriers.

The lessons learned from natural hazard events and the behaviour of protection structures in the case of an event form a valuable sum of experiences. This enables us to improve the protection against natural hazards within the framework of integral risk management. Authors and translator would like to thank all financing partners for supporting the original version of this report in German as well as this translation to English. The practical guide benefits from the comprehensive knowledge of experts on debris flows and hillslope debris flow protection nets. We would like to thank all those who have contributed to this joint effort: from practitioners – for practitioners!

It is important that the experience gained with net barriers continues to be collected and exchanged. In this way, the knowledge gained from the past provides a valuable key for the future and is basis for the continuous further development and improvement of debris flow and hillslope debris flow protection nets.

12 Directories

Glossary

Term	Explanation
Abrasion protection	Protective element on the upper support rope of a net barrier to prevent damage to the rope due to overflow
Barrier type	Classification of a structure by type of construction (e.g. rigid structure or flexible net barrier).
Basal opening	For debris flow protection nets: Opening between channel base and bottom support rope to allow normal discharge and minor, non-critical events to pass underneath the net barrier.
CE-marking	Product conformity declared by the manufacturer in accordance with EU Regulation N° 765/2008. The product complies with the applicable requirements defined in the European Community harmonization guidelines for the affixing of the marking.
Certificate/ Declaration of conformity	The declaration of conformity is a written confirmation at the end of a conformity assessment, with which the responsible entity for the provision of a product, or a service (e.g. manufacturer, distributor, operator, contractor) or an organization (e.g. testing laboratory, operator of a quality management system) bindingly declares and confirms that the object (product, service, body, quality management system) meets the properties specified in the declaration.
Compressive strength class of concrete	For the classification of concrete compressive strength, the characteristic strength at the test age of 28 days is used. As samples, concrete cylinders with a diameter of 150 mm and a length of 300 mm ($f_{ck,cyl}$) or of concrete cubes with an edge length of 150 mm ($f_{ck,cube}$) are used.
Corrosion protection class	According to SIA Standard 267 [29], gradual classification of an anchorage to determine the corrosion protection measures required. The protection class depends on the planned service life, the structural class and the potential corrosion hazard (of the element).
Discretization	Discretization is the division of the calculation area into small parts (sections), so an idealized model is available as a computational model. In addition, the time step width is defined as the size of the time step or the length of the time interval in a dynamic simulation. The progress in time which is divided into individual sections (discretized) and the solution which is calculated stepwise for successive time steps corresponds also to a discretization in the Finite Element Method (FEM).
Energy absorption element	Component, usually made of metal, which absorbs the forces occurring in the net structure and absorbs the energy through plastic deformation of the element (often colloquially referred to as a braking element).
Grout sock	Flexible fabric hose used to reduce the loss of anchor grout in the borehole.
Influential zone (of a load)	In a static sense, a certain surface area of the retained material from which, from a calculation point of view, an action on a certain structural component under investigation is exerted.
Impact pressure	Short-term peak pressure value on the impact area of the net surface.
Load case	In structural analysis, a load case is defined as a set of load arrangements, deformations and imperfections that can act simultaneously on a structure.
Net barrier	Structure for the containment of a gravitational natural hazard consisting of anchors and flexible steel wire nets. In this document, the term refers to debris flow and hillslope debris flow protection nets.
Net types	Net types are structures within the same process family, which are, however, designed for different impacts or load cases.

Term	Explanation
Post-injection (of grout)	Repeated injection of anchor grout into the borehole to increase the bond between anchor grout and borehole. In addition, this procedure also increases the bond between the grout column and the anchor.
Primary net	Net element for the main load transfer and material retention, mostly coarsely meshed
Process family	Classification of protection nets according to their use in a specific natural hazard process (e. g. debris flow protection nets, rockfall protection nets). Within the process family, a subdivision is made according to net types.
Secondary mesh	Mounted on the primary net on its uphill side, a finer meshed, additional net for the retention of fine material
Service life	Expected time limit on the full serviceability of a net barrier.
System parameter	Structural variables such as protection net size (span and height), resistance strength, net type, anchorage load, etc.
Uphill apron net	Auxiliary net mounted loosely on the uphill side of the net barrier to prevent underflowing of a net barrier.
Verification of the net	Structural safety verification for the net element only
Verification on torsional buckling	Verification according to SIA Standard 263 [28], which examines the combined stress due to bending and compressive loading on the post.

Abbreviations

Abbreviation	Explanation
AGN	Arbeitsgruppe Geologie und Naturgefahren; Working group Geology und Natural Hazards (in Switzerland)
CAB	Conformity Assessment Bodies
CTI	Former Swiss Commission for Technology and Innovation in the former Swiss Federal Office for Professional Education and Technology
DoP	Declaration of Performance
EAD	European Assessment Document
EMPA	Eidgenössische Materialprüfungsanstalt; Swiss Federal Laboratories for Materials Science and Technology
EOTA	European Organization for Technical Assessment
ETA	European Technical Assessment
ETH	Eidgenössische Technische Hochschule; Swiss Federal Institute of Technology
FAN	Fachleute Naturgefahren; Natural Hazards Experts (Swiss Association)
FEDRO	Swiss Federal Roads Office
FOEN	Swiss Federal Office for the Environment
FPC	Factory Production Control
JCSS	Joint Comitee of Structural Safety
NCHA	Swiss Federal Act on the Protection of Nature and Cultural Heritage
SIA	Swiss Society of Engineers and Architects
WBG	Wasserbaugesetz; Act on Hydraulic Engineering
WPA	Swiss Water Protection Act
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research

Symbols

Symbol	Explanation	
Greek letters		
α	Pressure coefficient for debris flow or hillslope debris flow impact on net structure	[–]
α_t	Coefficient of thermal expansion of the steel wire of the ropes	[–]
δ	Propagation angle of debris flow or hillslope debris flow	[°]
ξ	Angle between protection structure and stream bed	[°]
ρ	Density of the debris flow or hillslope debris flow at the front but also: Density of the single block based on local geology	[kg/m^3]
σ	Overflow load of the debris flow with flow height h_{fl}	[N/m^2]
τ	Surge stress of the debris flow or hillslope debris flow at the stream botton and during overflow	[N/m^2]
θ	Stream section angle or slope angle at the barrier location	[°]
θ'	Deposition angle	[°]
γ_F	Partial safety factor for load side of the debris flow/hillslope debris flow	[–]
γ_R	Partial safety value on the resistance side	[–]
Latin letters		
A	Effective cross-sectional area of the rope	[m^2]
a	Earth pressure coefficient, a = 1.0	[–]
$a_{b,i}$	Average braking acceleration during surge impact i	[m/s^2]
B_m	Contributing width of the post	[m]
b_m	Mean width of protection net, determined from values of top width b_o and bottom width b_u, where: $b_m = (b_u + b_o)/2$	[m]
b_{max}	Maximum spread of the material along the net barrier	[m]
b_o	top width of the protection net	[m]
b_u	bottom width of the protection net	[m]
b_0	Width of the starting zone of a hillslope debris flow	[m]
c_p	Pressure coefficient for debris flow/hillslope debris flow according to SIA Standard 261/1 [27]	[–]
d	Diameter of a single block	[m]
E	Modulus of elasticity of the rope	[N/m^2]
$E_{pot,rope}$	Potential elongation energy of the rope during a single block impact	[J]
F_D	Pressure force of the post	[N]
F_g	Material's weight due to the net expansion	[N]
F_{net}	Force in the net, per linear meter	[N/m]
F_{up}	Force in the upslope anchor ropes	[N]
F_{rope}	Force in the horizontal ropes	[N]
G	Gravitational constant	[kN/m]

Symbol	Explanation	
f	Maximum deformation of the barrier	[m]
g	Gravitational constant	[m/s^2]
H	Horizontal rope force according to rope equation	[N]
H'_0	Lowered barrier height during the filling process	[m]
h	Nominal height of the net barrier	[m]
h'	Barrier height at the time t. When the barrier is filled, this corresponds to $h' = h_b'$	[m]
h_b	Original height of the barrier before loading	[m]
h_b'	Residual height, or settled barrier height	[m]
h_d	Height of the net barriers basal opening	[m]
h_{fl}	Flow height	[m]
I_s	Channel inclination upstream (of the structure)	[–]
I_s'	Inclination of the retained material	[–]
k_s	Spring stiffness of a rope of length L	[N/m]
L	Rope length	[m]
ΔL	Elastic elongation of the rope	[m]
L_0	Distance between starting zone and impact area of a net barrier (for hillslope debris flows)	[m]
L_{min}	Minimum length of the net barrier	[m]
L_r	Length of the retention area, measured parallel to the stream bed	[m]
l	Effective span of the rope under consideration	[m]
l_{r1}, l_{r2}	Individual horizontal lengths of the retention volume per surge, for the FSI-model	[m]
l_r	Horizontal length of the retention volume, for the FSI-model	[m]
m	Mass of a single block	[kg]
m_0, m_1	Mass of a discretized filling surge	[kg]
n	Number of ropes	[–]
p_0, p_1	Impact pressure according to discretized impact number, for the FSI-model	[N/m^2]
p_{dyn}	Hydrodynamic pressure of the debris flow	[N/m^2]
p_f	Accepted probability of failure of a net structure depending on the risk classification	[–]
p_{stat}	Hydrostatic pressure of the debris flow	[N/m^2]
Q	Values of the integral according to the rope equation according to [20]	[–]
Q_{max}	Peak discharge or maximum discharge at the front of the debris flow or the hillslope debris flow	[m^3/s]
q	Equal load on the rope resulting from the debris flow pressure	[kN/m]
R	Resultant due to the overflow load case	[kN/m]

Symbol	Explanation	
S	Discretized rope section S	[m]
s	Gradient of the slope	[–]
s_0	Initial length of rope with sag of $L/30$, its own weight considered	[m]
t_f	Discretized actual filling time, for the FSI-model	[s]
t_b	Deceleration (braking) time, for the FSI-model	[s]
t_x	Discretized filling time for a debris surge of volume V	[s]
Δt	Temperature gradient	[–]
V_R	Retention volume of the net barrier	[m^3]
υ	Mean front velocity of the debris flow or hillslope debris flow	[m/s]
υ_f	Block speed, for the FSI-model	[m/s]
V_{surge}	Volume per surge of a debris flow	[m^3]
$V_{surge,FSI}$	Volume per surge, for the FSI-model	[m^3]
V_{total}	Total volume of the event (for a debris flow or a hillslope debris flow)	[m^3]

13 References and image sources

[1] AGN, 2004: Gefahreneinstufung Rutschungen (Hazard Classification of Landslides). By extension Arbeitsgruppe Naturgefahren AGN (Working group on Natural Hazards). Working report for the Federal Office for Water and Geology FOWG, Bern. 44 p. (in German).

[2] FOEN (ed.), 2016: Protection against Mass Movement Hazards. Guideline for the integrated Hazard Management of Landslides, Rockfall and Hillslope Debris Flows. Federal Office for the Environment FOEN, Bern. The environment in practice, No. UV-1608-E. 98 p.

[3] FOEN (ed.), 2018a: Grundlagen zur Qualitätsbeurteiltung von Steinschlagschutznetzen (Basics for the Quality Assessment of Rockfall Protection Nets and their Foundation). Federal Office for the Environment FOEN, Bern. Knowledge on environment No. 1805. 42 p. (in German).

[4] FOEN (ed.), 2018b: Handbuch Programmvereinbarungen im Umweltbereich (Manual Program Agreements in the Environmental Field 2020–2024). Communication of the FOEN as enforcement authority to applicants. Federal Office for the Environment FOEN, Bern. The environment in practice No. 1817. 294 p. (in German).

[5] FOEN (ed.), 2019: Typenliste Ankermörtel (List of approved Types of Anchor Grout). Federal Office for the Environment FOEN, Bern. The environment in practice No. 1007. 5 p. (in German).

[6] FOCL (ed.), 2017: Wegleitung zur Bauproduktegesetzgebung (Guide to Legislation of Construction Products). Federal Office for Buildings and Logistics BBL, Bern. 103 p. (accessed via https://www.bbl.admin.ch/bbl/de/home/themen/fachbereich-bauprodukte/downloads.html, as of 2020/07/27) (in German).

[7] SFOE (ed.), 2015: Directive on the Safety of Water Retaining Facilities. Part A: Introduction. Swiss Federal Office of Energy SFOE. Version 2.0, 2015/03/01. 23 p.

[8] FOSP; FOWM; SAEFL, (eds.), 1997: Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten (Consideration of Mass Movement Hazards in Spatially effective Activities). Recommendations 1997. Federal Office for Spatial Planning FOSP, Federal Office for Water Management FOWN, Swiss Agency for Environment, Forest and Landscape SAEFL, Bern. 42 p. (in German).

[9] Bugnion, L.; McArdell, B. W.; Bartelt, P.; Wendeler, C., 2012: Measurements of hillslope debris flow impact pressure on obstacles. In: Landslides – Journal of the International Consortium on Landslides 9: 179–187.

[10] SAEFL (ed.), 2004: Wegleitung Grundwasserschutz (Groundwater Protection Guide). Swiss Agency for the Environment, Forests and Landscape SAEFL (now Federal Office for the Environment FOEN), Bern. Environmental Enforcement No. 2508. 143 p. (in German).

[11] Dorren, L.; Schwarz, M., 2016: Quantifying the Stabilizing Effect of Forests on Shallow Landslide-Prone Slopes. In: Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice. Springer Verlag, Berlin, Heidelberg. 255–270.

[12] EAD 340020-00-0106, 2016: Flexible Kits for Retaining Debris Flows and Shallow Landslides/ Open Hill Debris Flows. European Assessment Document EAD. European Organisation for Technical Assessment EOTA 2016. 25 p. (Accessed at www.eota.eu, EAD number 340020-00-0106, as of 07/27/2020).

[13] Feiger, N., 2019: Analyse zur Gebrauchstauglichkeit von Murgangnetzen nach 10 Jahren Praxiserfahrung (Analysis of the Serviceability of Debris Flow Nets after 10 Years of practical Experience). Master thesis, ETH Zurich. 30 p. (in German).

[14] Frick, E.; Kienholz, H.; Romang, H., 2011: SEDEX (SEDiments and EXperts), user manual. Geographica Bernensia P42. Department of Geography, University of Bern, Bern. 128 p. (in German).

[15] GEOBRUGG AG (Ed.), 2016: System Manual Debris Flow Barriers VX/UX. Issue 164-N-FO/05, Romanshorn.

[16] GEOBRUGG AG (ed.), 2020: Dimensioning Tool for Flexible Barriers against Shallow Landslides. (Accessed via https://www.geobrugg.com/en/Dimensioning-Tools-115308.html, as of: 27.07.2020)

[17] Gertsch, E., 2009: Geschiebelieferung alpiner Wildbachsysteme bei Grossereignissen – Ereignisanalysen und Entwicklung eines Abschätzverfahrens (Bedload Supply of Alpine Torrent Systems during major Events – Event Analysis and Development of an Estimation Procedure). PhD thesis at the Department of Geography, University of Bern, Bern. 203 p. (in German).

[18] JCSS (ed.), 2001: JCSS (ed.), 2001: Probabilistic Model Code. Part I. Joint Committee of Structural Safety JCSS. (Accessed via https://www.jcss-lc.org/publications/jcsspmc/part_i.pdf as of Aug. 07, 2020).

[19] CANTONS GR, BE, VS (eds), 2012: Handbuch zur Kontrolle und zum Unterhalt forstlicher Infrastruktur (Manual for Inspection and Maintenance of Forest Infrastructure). Office for Forests and Natural Hazards of the Canton of Grisons, Natural Hazards Division of the Office for Forests of the Canton of Bern and Service for Forests and Landscape of the Canton of Valais. 82 p. (in German).

[20] Palkowski, S., 1990: Statik der Seilkonstruktionen (Statics of Cable Structures). Theory and numerical examples. Springer Verlag, Berlin, Heidelberg. 108 p. (in German).

[21] Rickenmann, D., 2014: Methoden zur quantitativen Beurteilung von Gerinneprozessen in Wildbächen (Methods for quantitative Assessment of Channel Processes in Torrents). Birmensdorf. WSL Report 9: 105 p. (in German).

[22] Rickenmann, D., 2016: Methods for the Quantitative Assessment of Channel Processes in Torrents (Steep Streams). IAHR Monograph Series (ed. Peter A. Davies), London. (https://doi.org/10.1201/b21306)

[23] Romang, H. (Hrsg.), 2008: Wirkung von Schutzmassnahmen (Effect of Protective Measures) / PROTECT. National Platform for Natural Hazards PLANAT, Bern. 289 p. (in German).

[24] Sättele, M.; Bründl, M., 2015: Praxishilfe für den Einsatz von Frühwarnsystemen für gravitative Naturgefahren. (Practical Guide for the Use of Early Warning Systems for Gravitational Natural Hazards). WSL Institute for Snow and Avalanche Research SLF, Federal Office for Civil Protection FOCP (ed.), Bern. 61 p. (in German).

[25] SIA 260, 2003: Basis of Structural Design. Swiss standard. Swiss Society of Engineers and Architects sia.

[26] SIA 261, 2003: Einwirkung auf Tragwerke (Loads on Structures). Swiss Standard. Swiss Society of Engineers and Architects sia. (in German)

[27] SIA 261/1, 2020: Einwirkung auf Tragwerke – Ergänzende Festlegungen (Loads on Structures – supplementary Specifications). Swiss standard. Swiss Society of Engineers and Architects sia. (in German)

[28] SIA 263, 2003: Stahlbau (Steel Construction). Swiss Standard. Swiss Society of Engineers and Architects sia. (in German).

[29] SIA 267, 2013: Geotechnik (Geotechnics). SIA 267/1, 2013: Geotechnik – Ergänzende Festlegungen (Geotechnics – supplementary Specifications). Swiss Standards. Swiss Society of Engineers and Architects sia (in German).

[30] Suda, J.; Rudolf-Miklau F. (eds.), 2012: Bauen und Naturgefahren. Handbuch für konstruktiven Gebäudeschutz (Construction and Natural Hazards. Handbook for constructive Building Protection). Springer Verlag, Vienna. 507 p. (in German).

[31] VKF (Hrsg.), 2005: Wegleitung Objektschutz gegen gravitative Naturgefahren (Guideline for Property Protection against gravitational Natural Hazards). Association of Cantonal Fire Insurers, Bern. 105 p. (in German).

[32] Volkwein, A., 2004: Numerische Simulation von flexiblen Steinschlagschutzsystemen (Numerical Simulation of flexible Rockfall Protection Systems). PhD thesis at ETH Zurich. 134 p. (in German).

[33] Volkwein, A., 2014: Flexible debris flow barriers. Design and application. WSL Berichte, 18. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL. 29 p.

[34] Von Boetticher, A., 2012: Flexible Hangmurenbarrieren: Eine numerische Modellierung des Tragwerks, der Hangmure und der Fluid-Struktur-Interaktion (Flexible Hillslope Debris Flow Barriers: A numerical Modelling of the Structure, the Hillslope Debris Flow and the Fluid-Structure Interaction). PhD thesis at the Technical University of Munich, Germany. 186 p. (in German).

[35] Wendeler, C., 2010: In wie weit können trotz der grossen Prozessunsicherheiten bei einer Hangmure flexible Netze zu einer Rückstufung der Gefahrenkarte gemäss PROTECT führen? (To which Extent may flexible Nets lead to a Downgrading of the Hazard Map according to PROTECT despite large Process Uncertainties for a Hillslope Debris Flow?) CAS Property Protection against Natural Hazards. Bern University of Applied Sciences, Bern. 60 p. (in German).

[36] Wendeler, C., 2016: Debris-flow protection systems for mountain torrents. Basic principles for planning and calculation of flexible barriers. WSL Berichte, 44. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research WSL. 267 p.

[37] WENDELER, C.; VOLKWEIN, A., 2015: Laboratory Tests for the Optimization of Mesh Size for flexible Debris-Flow Barriers. In: Natural Hazards and Earth System Science 15: 2597–2604.

Images

The images used originate from the persons, companies and organizations listed below.

[A] Berger Catherine

[B] Feiger Nadine

[C] Hählen Nils

[D] Toniolo Marco

[E] Wendeler Corinna

[F] Emch+Berger AG

[G] Geobrugg AG

[H] Pfeifer-Isofer AG

[I] Teysseire & Candolfi AG

[J] Section of Swisstopo National Map 1:25 000, reproduced with permission from Swisstopo (JA100118)

Appendix A Dimensioning example

Calculation of decisive forces for a protection net with posts

1. Geometry/input parameters

The design example shows a 4 m high system with posts, which is loaded by a debris flow with a flow height of 1 m and a flow velocity of 6 m/s and a density of 2200 kg/m^3. The overflow load case is to be verified.

The geometry of the structure is shown in Figure 20.

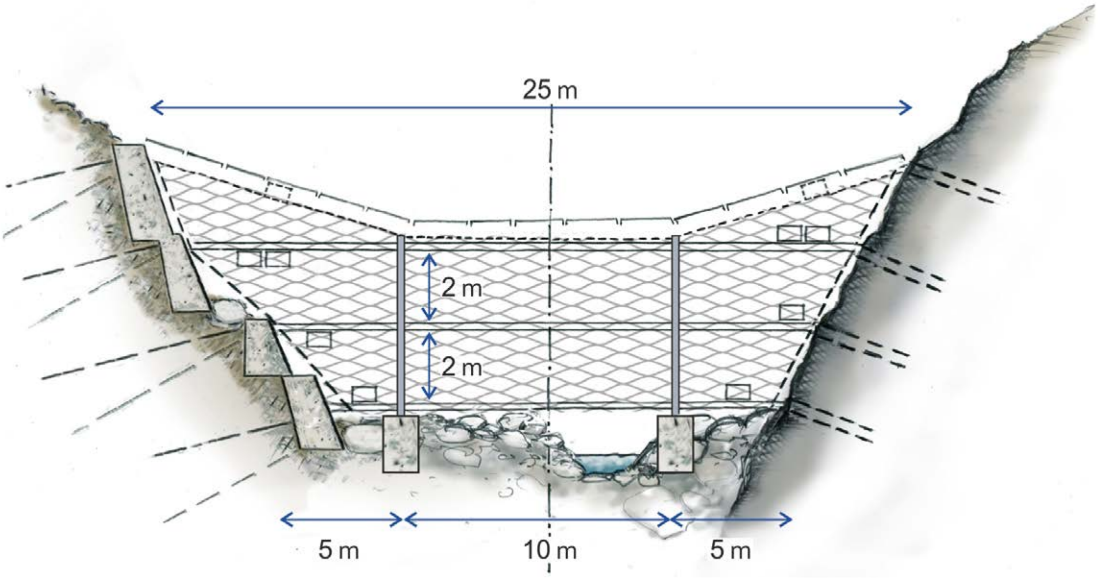


Fig. 20. Schematic representation of the geometry of the net barrier in the dimensioning example.

2. Decisive load cases

The following load cases are investigated to determine the relevant load case for the structural system.

Initial impact (see Fig. 8, Section 7.2.1.1):

$$p_{dyn} = \alpha \rho v^2 = 2.0 \cdot 2'200 \cdot 6^2 = 158\,\frac{kN}{m^2}$$ with α = 2.0 for granular debris flows

$$p_{stat} = a h_{fl} \rho g = 1.0 \cdot 1 \cdot 2'200 \cdot 9.81 = 21.6\,\frac{kN}{m^2}$$ with a = 1.0

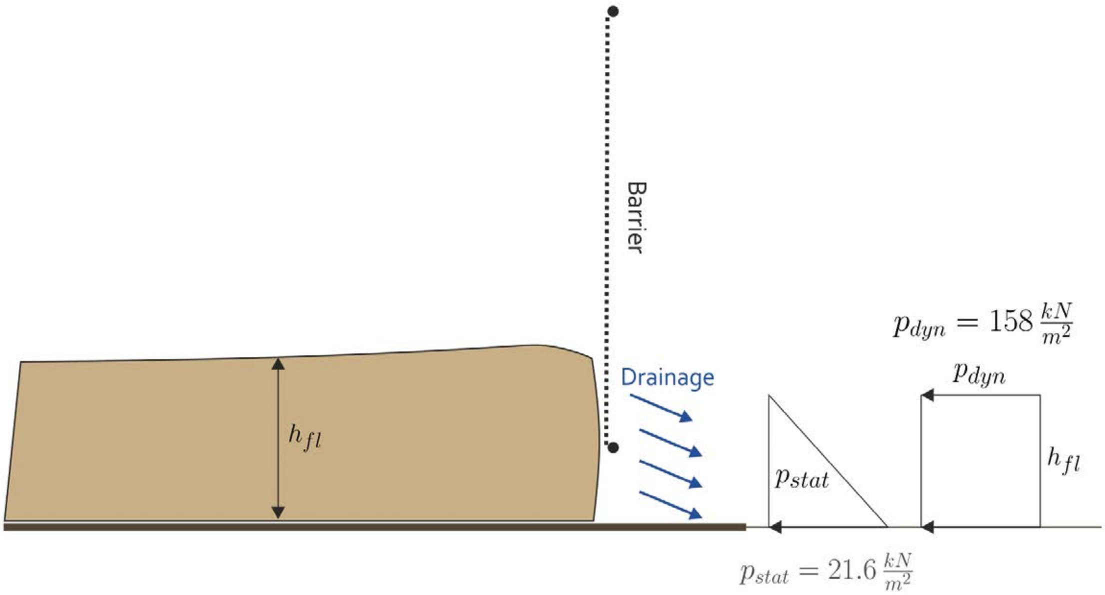


Fig. 21. Load distribution for a dynamic initial impact according to load assumptions.

Since the flow height is 1 m and the distance between the support ropes is 2 m, the initial impact hits the lower support rope bundle completely, if the **basal opening** is of height $\mathrm{h_d} = 0.0$ m. The load is distributed according to the load assumptions. If the flow depth is greater than $\mathrm{h_{fl}} = 1.5 \cdot \mathrm{h_d}$ the barrier becomes congested ([35], [37]). In this case, $\mathrm{h_d} = 0$.

The compression load on the lower support ropes then results in:

$p_{first\,impact} = 21.6\frac{kN}{m^2} \cdot 1m \cdot 0.5 + 158\frac{kN}{m^2} \cdot 1m = 168.8\frac{kN}{m}$ (see Fig. 21)

The further filling process is now considered surge by surge for a flow height of 1 m according to Figure 9.
If the barrier is filled and overflowed by the succeeding debris flow material, the overflow load case is to be calculated. The following loads result from the load model according to [36] with the settled barrier height $\mathrm{h_b}' = 3/4 \cdot 4\ \mathrm{m} = 3\ \mathrm{m}$ and $\mathrm{h_{fl}} = 1.0\ \mathrm{m}$. This results in a total height for the proof of hydrostatic pressure of 4 m (3 m set barrier height plus 1 m flow height as surcharge load) and the following calculation:

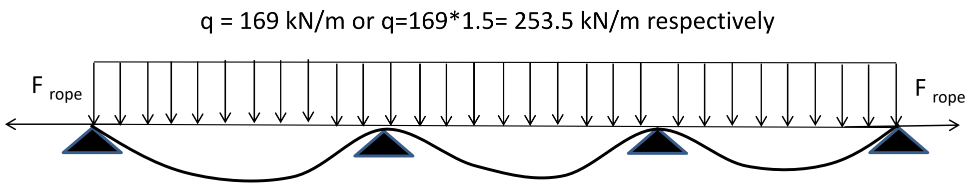
$p_{stat} = a({h_b}' + h_{fl})\rho g = 1.0 \cdot 4.0 \cdot 2'200 \cdot 9.81 = 86.3\,\frac{kN}{m^2}$ with a = 1.0

With a rope spacing of 2 m, the resultant of the load overflow R on the lower support ropes is $\mathrm{R} = 75.5\ \mathrm{kN/m}$ and is therefore not significant compared to the initial impact.

3. Dimensioning of the support ropes

If, regarding to the hazard potential directly below the protection net, a high presence probability of people is to be assumed, then $\gamma_F = 1.5$ is used. If the probability of people being present is low, a smaller safety factor can be used.

The lower support ropes run as a multi-span system because they are guided over the base plates. As an example, Figure 22 shows the rope load according to Palkowski [20] for a multi-span system.



q1 Distributed load first field	254'000	[N/m]	
q2 Distributed load second field	254'000	[N/m]	
q3 Distributed load third field	254'000	[N/m]	
l1 Span first field	7.5	[m]	
l2 Span second field	10	[m]	
l3 Span third field	7.5	[m]	
Equivalent load ∫Q1^2	2.3E+12		
Equivalent load ∫Q2^2	5.4E+12		
Equivalent load ∫Q3^2	2.3E+12		
Length l	25	[m]	
Sag f	0.83	[m]	1/30-1/50 of the total span
Initial length rope so	25.07	[m]	
Elongation energy absorption element brges	2.00	[m]	
s1	27.07	[m]	
H_1	8'179'862.4	[N]	
H_new	1'261'170.0	[N]	

H^3+b*H^2-c

$$H^3 + H^2 \cdot EA \cdot \left[1 - \frac{1}{s_0} \cdot l\right] = \frac{EA}{2S_0} \left(\int_0^{l_1} Q_1 dx + \int_0^{l_2} Q_2 dx + \int_0^{l_3} Q_3 dx\right)$$

$$\int Q_1 = \frac{q^2 \cdot l_1^3}{12}$$

E_Modulus	1.28E+11	[N/m^2]	
Cross-sectional area A rope	2.56E-04	[m^2]	
EA	32'768'000	[N]	
Factor b	2'510'271		
Factor c	5.99866E+18		
Hnew+1	1'261'170.0	[N]	
Frope 1	**1'639'612.7**	[N]	
f_1	1.42	[m]	
Frope_3	**1'639'612.7**	N	
f_2	1.42	[m]	

Fig. 22. Calculation of the lower rope forces according to [20], exemplified in a spreadsheet calculation program, using a schematic rope representation.

From this, the decisive forces are obtained via the Newton iteration of the rope equation of 1300 kN total force for an elongation of 2 m of the **energy absorption elements**. Assuming a breaking force of 350 kN for the ropes with integrated energy absorption elements, the following number of ropes n results (with safety factors respected):

$$n = \frac{1'300\,kN}{350\,kN} = 3.7$$

Consequently, 4 ropes with a breaking load of 350 kN are required.

4. Dimensioning of the upslope anchor ropes

The load on the upslope anchor ropes is determined by the last surge impact before the barrier is completely filled (see Fig. 23). A settled barrier height $\mathrm{h_b}' = 3/4 \cdot 4\ \mathrm{m} = 3\ \mathrm{m}$ is already taken into account. In the case horizontally installed upslope anchor ropes, the horizontal force component would be approximated to $\mathrm{F_{up}} = 1548\ \ \mathrm{kN}$ assuming a mean influential width of 8.5 m. This force must now be transformed vectorially into the actual direction of the upslope anchor ropes.

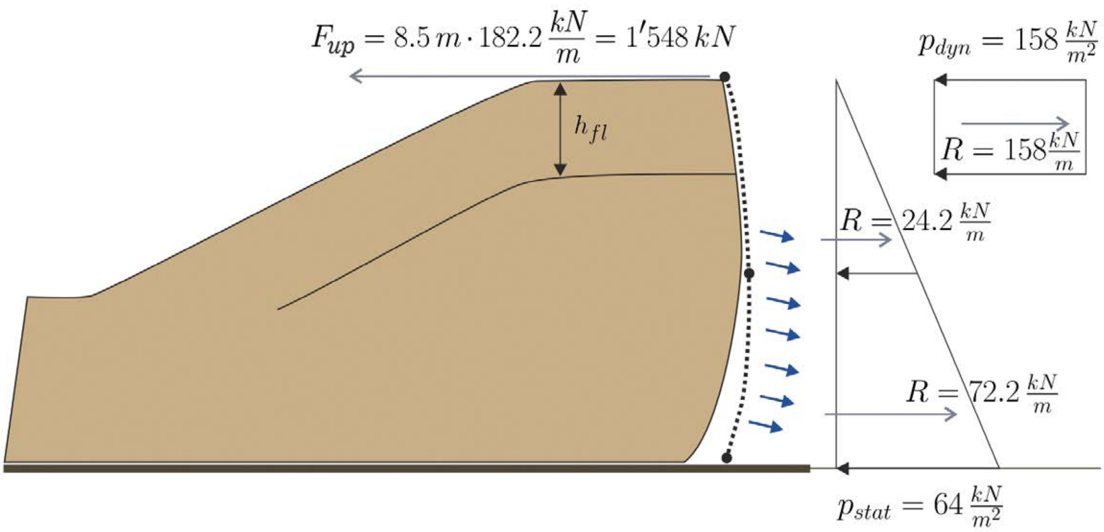


Fig. 23. Last pressure surge flowing into the protection net before the overflow begins. Decisive case for the calculation of the upslope anchor ropes.

5. Dimensioning of the winglet ropes

For dimensioning the winglet ropes, the maximum weight of the barrier is approximated according to Figure 24 and using the approximate weight of the belly of the expanded net Fg at a deflection of f = 2.5 m. Accordingly, $\mathrm{F_g} = 0.5 \cdot \mathrm{g} \cdot \mathrm{f} \cdot \mathrm{h_b}' \cdot \mathrm{b_m} \cdot \rho = 0.5 \cdot 9.81 \cdot 2.5 \cdot 3 \cdot 22.5 \cdot 2200 = 1820\ \mathrm{kN}$. This results in a vertical force component $\mathrm{G} = 1820\ \mathrm{kN}/25\ \mathrm{m} = 72.8\ \mathrm{kN/m}$ for the winglet rope and upper support ropes combined. With a safety factor of 1.5, this results in 109 kN/m over a rope length of 25 m. Using a single-field rope equation and assuming an energy absorption element elongation of 2 m, a maximum rope load of 2043 kN results. This again leads to 6 ropes with a diameter of 22 mm each. Since 4 ropes already result from the initial impact for each surge, 2 additional winglet ropes are required for installation.

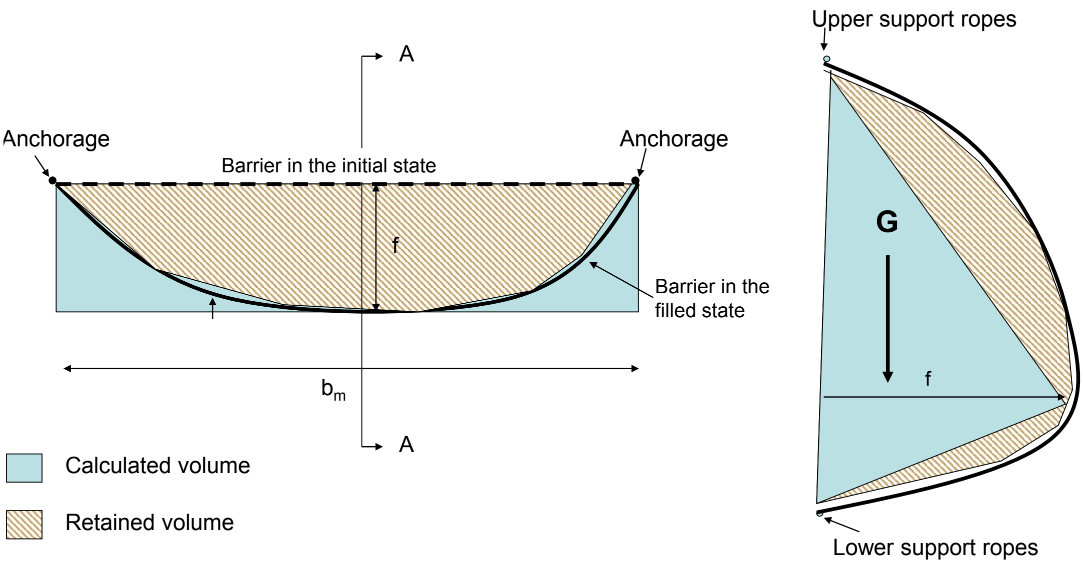


Fig. 24. Net deflection and self-weight of the net's belly. Figure according to [36].

Equivalent load ⌠Q^2	1.5E+13		
q Distributed rope load, single field	109'000	[N/m]	
Horizontal rope length l	25	[m]	
Sag f	0.83	[m]	1/30-1/50 of the total span
Initial rope length So	25.07	[m]	
Elongation energy absorption element br_ges	2.00	[m]	
s1	27.07	[m]	
H_1	1'931'162.2	[N]	Formula 6.32 in Wendeler 2008, [34]
H_new	1'523'443.9	[N]	Formula 6.34 in Wendeler 2008, [34]
H^3+b*H^2-c			Formula 6.30 in Wendeler 2008, [34]
E-Modulus	1.28E+11	[N/m²]	
Cross-sectional area A	2.56E-04	[m²]	
EA	32'768'000	[N]	
Factor b	2510270.9		
Factor c	9.36177E+18		
Hnew+1	1'523'443.9	[N]	Formula 6.33 in Wendeler 2008, [34]
F_rope	**2'043'841.4**	[N]	
f_Deformation	6.56	[m]	

Input fields for calculation
Iteration procedure according to Palkowski, 1990

Fig. 25. Iterated single-field rope equation according to [20], exemplified in a spreadsheet calculation program for the winglet rope dimensioning.

6. Dimensioning of the posts

For the posts, the vertical component of the upper and middle support ropes (if applicable or if they are guided to the post respectively) must be transmitted to the posts as a compressive force. If applicable, the surface load component of the debris flow must also be included as a continuous shear component according to Figure 14. From the rope equation for multi-field systems, the weight due to the net's belly results in a vertical load component of $\mathrm{F_D} = (109\,\mathrm{kN/m} \cdot 10\,\mathrm{m})/2 = 545\,\mathrm{kN}$ (compression force on the posts). The vertical component of the middle ropes on the posts is now neglected for the sake of simplicity, since the entire weight was assumed to be acting on the upper ropes and is therefore already taken into account. In addition, a continuous load from the **influential zones** of the posts must be applied for the last surge impact. From this, the **verification on torsional buckling** must be performed according to SIA Standard 263 [28].

7. Dimensioning of the net

In this example, the **load case** "last surge impact" is decisive for the dimensioning of the net, since for this case, the greatest total pressure is acting on the structure. It is determined from the pressure pattern in Figure 14 using the mean width of the barrier. The behaviour of the net surface is manufacturer specific and the detailed verification is therefore not provided here.

8. Summary of the design results

Table 10. Results of the dimensioning example for a debris flow protection net.

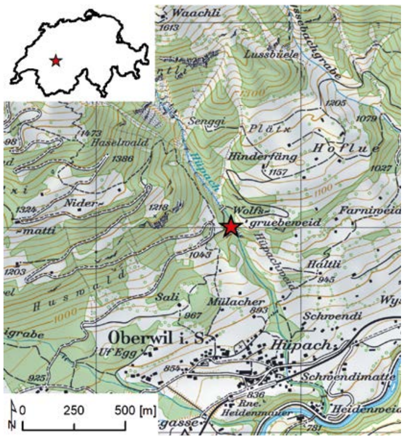
Components to be dimensioned	**Lower support ropes**	**Middle support ropes**	**Upper support ropes**	**Winglet ropes**	**Posts**
	4 ropes 22 mm, min. breaking load 350 kN	4 ropes 22 mm, min. breaking load 350 kN	4 ropes 22 mm, min. breaking load 350 kN	2 ropes 22 mm, min. breaking load 350 kN	2 posts HEA 180 S235

Appendix B Characteristic data sheets for special structures

Appendix B.1 Suspension rope net, Hüpach torrent, Switzerland

Short project description

The debris flow barrier consists of a large-scale steel net suspended from 10 fully locked coil ropes (d = 90 mm, tensile force 1000 t per rope) arranged slackly one above the other. The support ropes are anchored in a laterally surrounding concrete beam by means of a trumpet shape funnel connection made out of steel sheets, which allows the ropes to be anchored without restraint. The load is transferred from the steel cables into the concrete foundation, from which it is transferred into the soil using fully grouted soil nails up to 15 m long. Debris flow and driftwood are spatially retained solely by the flexible retention net. Thus, the dynamic load transfer results in smaller anchor and total forces. In addition, it was possible to dispense with a concrete beam crossing the stream, thus ensuring the greatest possible permeability over the entire net area that is not backfilled.



Project location (Source [J]).

Flood relief in case of overload is possible over the entire 42 m net width, but is channelled in the middle of the net due to the deflection of the suspended ropes. Thanks to the permeably designed support structure and the low concrete consumption, it was possible to install an economically very viable structure despite its remote location. The large-scale yet transparent structure blends in well with the landscape.

Barrier, upstream side (Image: [F]).

Barrier, downstream side (Image: [F]).

Project characteristics

Watercourse type:	Mountain torrent
Process type:	Debris flow
Loads:	Viscous to granular debris flow, dynamic pressure up to 215 kN/m^2
Location:	Oberwil im Simmental, Hüpach torrent, Switzerland
Dimensions:	Max. impoundment height 14.5 m, max. span 42 m, hydraulic freeboard 2 m, basal opening 3.5 x 1 m
Retention volume:	13,000 m^3
Barrier design:	Fully locked steel cables supporting a retention net, as well as laterally surrounding, reinforced concrete bar, back-anchored with ground nails of type SAS 670/800
Geology:	Malm limestone, partly marl shale of the Dogger
Construction costs:	Approx. 2 million CHF
Construction time:	1 year
Dimensioning:	Debris flow modelling using 2D simulation tool RAMMS, structural modelling using FARO [32].
Remark:	Additional retention downstream implementing a standard system type UX180-H6 with 3000 m^3 retention volume.
Project author:	Emch+Berger AG Bern, Switzerland

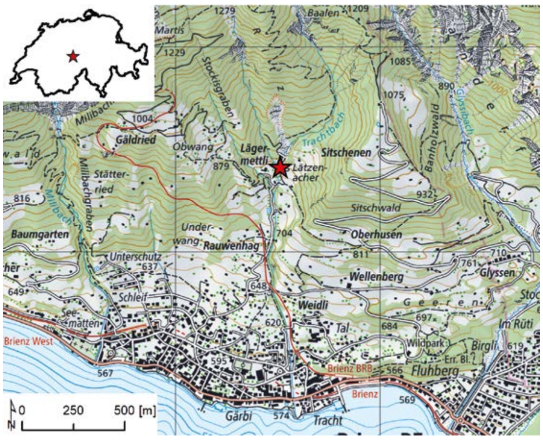
Appendix B.2 Multilevel barrier, Trachtbach torrent, Switzerland

Short project description

After the devastating debris flow events in 2005, four flexible debris flow barriers with a cumulated retention volume of 22,000 m^3 installed in the Trachtbach torrent have been protecting the village of Brienz since 2009. The large Ritzwald landslide is protected by a concrete barrier further below.

The three VX barriers installed in series are designed to enforce material retention in the torrent by complete backfilling.

Small-scale tests on the flow behaviour and congestion properties of the net barriers were carried out at WSL (Laboratory tests debris flow retention Trachtbach. WSL, Corinna Wendeler, Birmensdorf, 28.4.2007).



Project location (Source [J]).

Barrier UX-180-H6 (Image: [G]).

Barrier VX-080-H4 (Image: [G]).

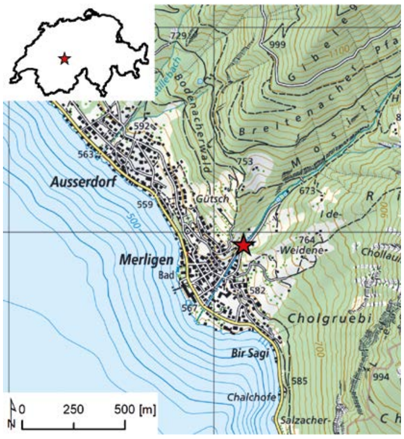
Project characteristics

Watercourse type:	Mountain torrent
Process type:	Debris flow
Loads:	Granular debris flows
Location:	Brienz, Trachtbach torrent
Dimensions:	UX180-H6 with span 31 m and nominal height 6 m, VX140-H5 with span 15 m and nominal height 5 m
Retention volume:	22,000 m^3
Barrier design:	Standard systems UX180-H6 and VX140-H5 with high-tensile ring nets
Geology:	Siliceous limestone and calcareous marly strata of poor quality (Cretaceous and Jurassic formations)
Construction costs:	UX-180-H6 barrier with span 31 m approx. 0.8 million CHF, Total project costs incl. concrete structure approx. 7 million CHF
Construction time:	Construction time of the net barriers approx. 4 months
Dimensioning:	Structural modelling using FARO [32].
Remark	Additional retention downstream implementing a standard system type UX180-H6 with 3000 m^3 retention volume.
Project author:	NDR Consulting / Niederer + Pozzi Umwelt AG, Switzerland

Appendix B.3 Net structure with longitudinal concrete discs, Grönbach torrent, Switzerland

Short project description

The debris flow barrier consists of a rigid, arch-shaped concrete support structure on which the retention nets are fixed using steel cables. The concrete structure consists of four massive guide walls, which are monolithically connected with two transversal ribs. The guide walls project about 7.5 m above the channel base and have a width of about 1.0 m each. The erosion control is ensured by a stilling basin made of blocks layed into backfill concrete, which directly connects to a torrent bed with a transverse closure. The main load is transferred to the subsoil by the steel cables via the concrete discs and the transversal ribs as well as via the tension and compression piles in the middle of the stream. The debris flow and driftwood are spatially retained by the three flexible retention nets. Thus, the dynamic load transfer results in smaller total forces.



Project location (Source [J]).

In the overload case, flood relief is provided over the entire 23.9 m width of the net. The use of a segmented lift gate ensured that nearby Grönweg is passable, while at the same time guaranteeing debris flow retention in the case of an event. The lift gate is normally closed and can only be opened for a few minutes with permission/key. The transparent and permeably designed structure fits relatively well into the landscape.

Barrier, upstream side (Image: [F]).

Barrier, downstream side (Image: [F]).

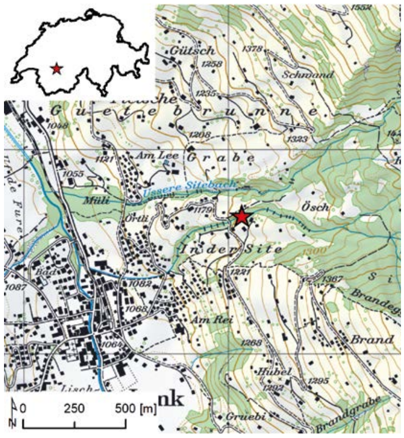
Project characteristics

Watercourse type:	Mountain torrent
Process type:	Debris flow
Loads:	Viscous to granular debris flows, dynamic pressure max. 100 kN/m^2
Location:	Merligen, Grönbach torrent, Switzerland
Dimensions:	Max. impoundment height 7.5 m, overflow section 23.9 m, hydraulic freeboard 2.5 m, basal opening 2 fields of 7.47/7.37 x 1.0 m
Retention volume:	12,000 m^3
Barrier design:	Reinforced concrete, steel support ropes and retention nets, fully grouted micropiles
Geology:	Clay and marl shale of the Palfries formation
Construction costs:	Approx. 2.2 million CHF
Construction time:	Approx. 2 years
Dimensioning:	Debris flow modelling using 2D simulation tool RAMMS, structural modelling using FARO [32].
Project author:	Emch+Berger AG Bern, Switzerland

Appendix B.4 Net structure with concrete pillars, Innere Sitebach torrent, Switzerland

Short project description

The debris flow barrier consists of six concrete pillars, each of which is installed to a reinforced concrete foundation. The five retention nets are stretched between the pillars by means of steel wire ropes. Each of the two border fields is integrated into the adjacent terrain by flanking walls which, among others, prevent material bypassing of the barrier. The main load is transferred into the soil over the steel cables and the pillar discs using in-situ concrete pillars and soil nails. The debris flow and driftwood are spatially retained by the flexible retention nets. This results in smaller total forces from the dynamic load transfer. In the overload case, flood relief is provided by the 3 central net fields over a total width of 22.2 m. The stilling basin is bounded by a pile-supported reinforced concrete wall.



Project location (Source [J]).

The lower reaches are protected against erosion by a rough bed channel with a subsequently installed barrier steps. As a result of the multi-field construction method with independently built parts of the construction, it was possible to install an economically viable structure at this barrier location, in spite of the problem of a superficially creeping slope combined with a deep sliding layer. The transparent and permeably designed structure fits relatively well into the landscape.


Barrier, upstream side (Image: [F]).


Barrier, downstream side (Image: [F]).

Project characteristics

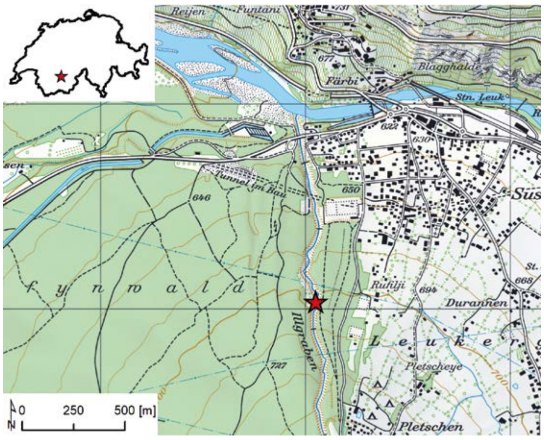
Watercourse type:	Mountain torrent
Process type:	Debris flow
Loads:	Viscous to granular debris flow, dynamic pressure max. 190 kN/m^2
Location:	Lenk im Simmental, Innere Sitebach torrent, Switzerland
Dimensions:	Max. impoundment height 13 m, overflow section 22.2 m, hydraulic freeboard 2 m, basal opening 6.4 x 0.5 m
Retention volume:	40,000 m^3
Barrier design:	Reinforced concrete, steel support ropes and retention nets, in-situ concrete piles as well as back-anchoring using fully grouted soil nails of type SAS 670/800
Geology:	Aalenian shale
Construction costs:	Approx. 3.5 million CHF
Construction time:	Approx. 2 years
Dimensioning:	Debris flow modelling using 2D simulation tool RAMMS, structural modelling using FARO [32].
Project author:	Emch+Berger AG Bern, Switzerland

Appendix B.5 Stepwise installed nets serving as supplementary structure, Illgraben torrent, Switzerland

Short project description

After countless debris flow events in the Illgraben, the concrete check dam No. 25 was completely eroded on its right bank (seen relative to the flow direction) and the concrete flanking walls were bypassed by debris material.

To sustainably secure the channel course over the old concrete check dam, the lower net barrier was installed in 2007 in a first construction phase (left image). Following the filling of the lower net barrier by a naturally occurring debris flow in the following year, the right-hand concrete flanking wall was rehabilitated and a second net barrier was installed on a higher level and slightly off-set to the upstream side (right image).



Project location (Source [J]).

Filled VX barrier for restoration stage 1 (Image: [G]).

Restoration of the wing on the flanking wall and installation of a second, partially filled VX barrier (Image: [A]).

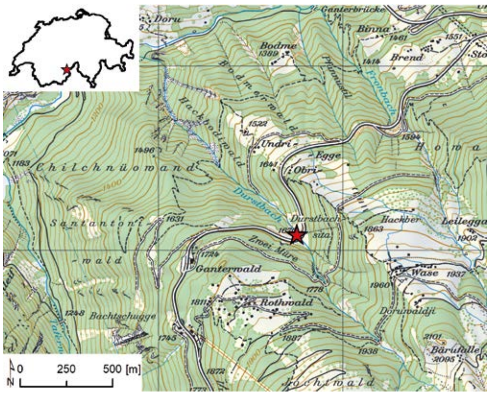
Project characteristics

Watercourse type:	Mountain torrent
Process type:	Debris flow
Loads:	Granular/viscous debris flows
Location:	Leuk, Illgraben torrent (at check dam 25), Switzerland
Dimensions:	15 m span and 4 m net height
Retention volume:	About 4000 m^3, considering both net barriers
Barrier design:	2 VX barriers adapted to the terrain characteristics
Geology:	Triassic dolomite/calcareous deposits and quartzites, leading to strong erosional effects
Construction costs:	Both VX net barriers including construction/concrete works amounted to approx. 200,000 CHF
Construction time:	Construction time per net barrier approx. 1 month
Dimensioning:	Dimensioning based on empirical values of a test barrier installed further downstream
Project author:	Geobrugg AG/WSL, Switzerland

Appendix B.6 Erosion control and filter structure, Durschtbach torrent, Switzerland

Short project description

Pre-filled UX180-H6 barrier installed as protection against erosion and scouring for a bridge structure at the Simplon Pass road. The desired filtering effect by the barrier can be seen distinctly in both images below, as the runoff flows through the unconsolidated stone rip-rap and does not flow over the spillway section of the net barrier. In this way, the bridge of the Simplon Pass road can be permanently protected against scouring.



Project location (Source [J]).

Pre-filled UX-180-H6 barrier, seen from downstream (Image: [G]).

Pre-filled barrier using large blocks, seen from above (Image: [I]).

Project characteristics

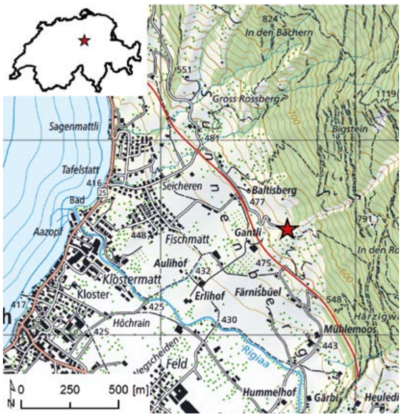
Watercourse type:	Mountain torrent
Process type:	Avalanches/debris flow
Loads:	Overflow from debris flows, avalanches and normal runoff
Location:	Simplon, Durschtbach torrent, Switzerland
Dimensions:	UX180-H6 with 33 m span and 4.5 m height after pre-filling
Retention volume:	1500 m^3
Barrier design:	High-tensile ring net barrier with 4 support profiles to maintain the residual height, based on the CE-marked standard product
Geology:	Moraine/scree
Construction costs:	Approx. 1 million CHF, including all installation/civil engineering works
Construction time:	Construction time of the entire net barrier approx. 6 months
Dimensioning:	The barrier was analytically dimensioned for overflow from avalanches and debris flows.
Project author:	Teysseire & Candolfi AG / FEDRO, Switzerland

Appendix B.7 Net structure for combined loads, Baltisberg/Härzigwald, Switzerland

Short project description

As part of the Swiss Federal Railroads project "Infrastructure Measures Eastern Lake Zug", the railroad track on the Zug-Goldau railway line is to be protected against rockfall with an energy of up to 2000 kJ. In addition, the structure must be able to absorb dynamic hillslope debris flow loads of up to 60 kN/m^2.

Due to the complexity of the dynamics involved in a rockfall event, a barrier certified for this purpose is selected. For the expected hillslope debris flows events, minor design adjustments are made to the system. These must not negatively influence the performance for the rockfall load case.



Project location (Source [J]).

Procedure for verification of the barrier performance: Based on the rockfall protection system "Isostop 2000Ev", which is certified for the Swiss market according to [3]; Numerical simulation of the certified protection system, comparison with the measurement data from the corresponding certificate; Design modification to fullfill the geometric boundary conditions according to the specifications AND at the same time to create a suitable hillslope debris flow protection system, analogous to the "Debris Stop 150-HM" hillslope debris flow barrier, which has been tested and certified according to [12]; Numerical simulations and verifications for the load cases 2000kJ of rockfall and 60kN/m^2 of hillslope debris flow; Testing and approval of the barrier by the Swiss Federal Office for the Environment FOEN.


Barrier, seen from below (Image: [H]).


Retention space (Image: [H]).

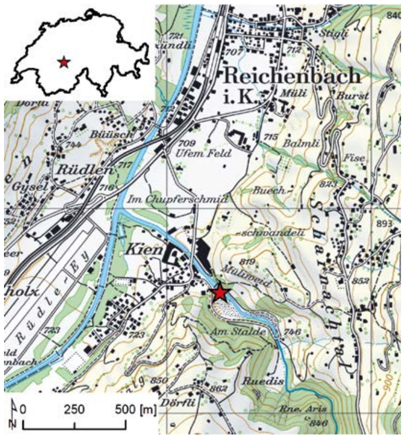
Project characteristics

Site conditions:	Slope with slope angles of up to 40°.
Process type:	Rockfall or hillslope debris flow
Loads:	For hillslope debris flow: dynamic pressure 60 kN/m^2 and flow height 1 m; For rockfall: 2000kJ
Location:	Baltisberg & Härzigwald, Arth SZ, Switzerland
Dimensions:	Six barriers with nominal lengths between 62 and 168 m (support rope separations at least every 6 fields)
Retention volume:	Max. impoundment height 4 m
Barrier design:	Modified standard rockfall protection system ISOSTOP 2000Ev; Reduction of post spacing, doubling of number of upslope anchor ropes, increase of post›s and support rope›s cross sectional areas.
Geology:	Subalpine molasse conglomerate ("Nagelfluh") with block or scree cover
Construction costs:	Approx. 3 million CHF
Construction time:	Six months
Dimensioning:	Structural modelling using FARO [32].
Project author:	Emch+Berger AG, Switzerland

Appendix B.8 Driftwood protection net, Chiene torrent, Switzerland

Short project description

After the devastating floods of August 2005, the lower reaches of the Chiene torrent were completely redesigned over a length of about 1 km, before its confluence with the river Kander. The channel capacity was more than doubled and a bed-load retention area as well as an overload corridor were installed. In addition, a large driftwood retention space had to be provided for. By means of physical simulation tests at the HSR University of Applied Sciences in Rapperswil, Switzerland, the detailed design of the driftwood and bedload retention could be optimized. It was found that the driftwood protection screen must be installed at a sufficient distance from the outlet structure and must extend over the entire width of the retention space. This prevents parts of the final dam from being stacked over with driftwood and eventually be overflowed.



Project location (Source [J]).

The structure of the driftwood protection screen is adapted to its respective function: on the left side, it extends into the mountainside over the final dam as a closed, impermeable structure (concrete beam/stop log at the passage). In the adjacent area behind the dam, the screen is equipped with a water-permeable ring net. Only in the direct inflow to the outlet structure, the driftwood screen is designed to be permeable to bedload. This actual driftwood screen section is founded on the bedrock and consists of 11 concrete posts with a diameter of 1.0 m each and a height of almost 10 m that are each supported by concrete discs on the downstream side. The four horizontal ropes are fixed to the posts using open mounts (for easy replacement later in time).

Barrier, upstream side (Image: [F]).

Barrier, downstream side (Image: [F]).

Project characteristics

Watercourse type:	Mountain torrent
Process type:	Flood carrying driftwood and bedload
Loads:	Dynamic water pressure, added by 2 m of alluvial driftwood
Location:	Kien in Reichenbach im Kandertal, Chiene torrent, Switzerland
Dimensions:	Max. impoundment height 7 m, max. span 90 m, hydraulic freeboard 2 m, outlet structure passage 2 x 5.00 x 0.75 m
Retention volume:	60,000 m^3 bedload/3000 m^3 driftwood
Barrier design:	Concrete structures with ring net and support ropes
Geology:	Alpine limestone (bed and right bank)
Construction costs:	Approx. 1.1 million CHF driftwood screen, approx. 16 million CHF for entire structure
Construction time:	Six months for the driftwood screen, four years for the entire structure
Dimensioning:	HSR University of Applied Sciences Rapperswil using physical modelling tests
Project author:	Emch+Berger AG Bern, Switzerland

Appendix C Checklists for inspection and maintenance

Source: [14]

Appendix C.1 Checklists regular inspection

Date ______________________________

Barrier No./Name of structure______________________________

Person in charge______________________________

Inspection criteria	YES	NO	Comments
Are all shackles secured on the net?			
Have energy absorption elements been activated?			Deformation of energy absorption elements: Elongation……………………… No………….. Elongation……………………… No………….. Elongation……………………… No………….. Elongation……………………… No………….. Elongation……………………… No………….. Elongation……………………… No…………..
Are the causes for the elongation of the energy absorption elements known?			Causes: ………………………………………………………
Is there visible corrosion?			Location of observed corrosion: ………………………………………………………
Has a visual inspection of the anchors, upslope anchor ropes, support ropes and post foundations been carried out?			
Has an inspection of all wire rope clips been carried out using a torque wrench? (After a service life of six months, all wire rope clips should be re-tightened).			

Additional points to observe, only for debris flow protection nets

Inspection criteria	YES	NO	Comments
Are there any major congestions?			
Is it necessary to remove any congestions or to empty the protection net?			
Has the basal opening changed since the last inspection?			Measured dimension of the basal opening: ……………………....................................
Was it confirmed that no energy absorption elements project into the basal opening?			

Additional points to observe, only for hillslope debris flow protection nets

Inspection criteria	YES	NO	Comments
Does the protection net need to be emptied?			
Is the uphill apron hill intact?			
Is the secondary mesh still folded in the shape of an accordion bellow?			

Appendix C.2 Checklist after an event

Event date_______________________________ Inspection date ____________________

Barrier No./Name of structure____

Person in charge____

Inspection criteria	**YES**	**NO**	**Comments**
Have energy absorption elements been activated?			Deformation of energy absorption elements: Elongation…………………....….. No…...……... Elongation…………………....….. No…...……... Elongation…………………....….. No…...……... Elongation…………………....….. No…...……... Elongation…………………....….. No…...……... Elongation…………………....….. No…...……...
Do energy absorption elements need to be replaced? If so, which ones?			
Was the system completely filled and was it overflowed?			
Were support or upslope anchor ropes damaged? Inspection of upslope anchor ropes is often only possible after emptying.			
Has the net been plastically deformed?			
Have posts, base plates, connect-ing elements (bolts, etc.) been damaged?			
Are damages to anchor bars of the base plate or to the concrete foundation visible?			
Is there any damage to the anchorages of the support or upslope anchor ropes?			
Approximately how many cubic meters must be excavated?	m^3		
Are local signs of erosion visible on the structure?			
Only for debris flow protection nets at their abrasion protection elements: Have they been bent, or have the long holes or shack-les been destroyed?			

WSL Berichte in English

Towards an Advanced Inventorying and Monitoring System for the Swiss Forest. Ferretti, M.; Fischer, C.; Gessler, A., 2021. WSL Ber. 106. 55 S.

Results of tests at Chant Sura: 13th September and 4th October, 2019. Sanchez, M.A.; Caviezel, A., 2020. WSL Ber. 97. 81 p.

Debris-flow protection systems for mountain torrents. Basic principles for planning and calculation of flexible barriers. Wendeler, C., 2016. WSL Ber. 44. 267 p.

Flexible debris flow barriers. Design and application. Volkwein, A., 2014. WSL Ber. 18. 29 p.

Latest WSL Berichte

Umweltbericht 2018–2020. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. Environmental Report 2018–2020. Swiss Federal Institute for Forest, Snow and Landscape Research WSL. Jendrolovits, R.; Zurlinden, A., 2021. WSL Ber. 109. 44 S.

Überwachung von besonders gefährlichen Schadorganismen für den Wald – Jahresbericht 2020. Surveillance des organismes nuisibles particulièrement dangereux pour la forêt – Rapport annuel 2020. Monitoraggio degli organismi nocivi particolarmente pericolosi per il bosco – Rapporto annuale 2020. Rigling, D.; Dubach, V., Beenken, L.; Schneider, S.; Hölling, D.; Prospero, S.; Cornejo, C.; Ruffner, B.; Augustinus, B.; Brockerhoff, E.; Queloz, V., 2021. WSL Ber. 108. 99 S.

Waldschutzüberblick 2020. Dubach, V.; Beenken, L.; Bader, M.; Odermatt, O.; Stroheker, S.; Hölling, D.; treenet; Vögtli, I.; Augustinus, B.A.; Queloz, V., 2021. WSL Ber. 107. 57 S.

Geschäftsbericht der Eidg. Forschungsanstalt WSL 2020. Eidg. Forschungsanstalt WSL (Hrsg.) 2021. WSL Ber. 105. 93 S.

Extremhochwasser an der Aare. Hauptbericht Projekt EXAR. Methodik und Resultate. Andres, N.; Steeb, N.; Badoux, A.; Hegg, Ch. (Ed.) 2021. WSL Ber. 104. 226 S.

Programm Landschaftsbeobachtung Schweiz. Methodische und inhaltliche Weiterentwicklung 2018–2020. Wartmann, F.; Hunziker, M.; Kienast, F., 2021. WSL Ber. 103. 215 S.

Schnee und Lawinen in den Schweizer Alpen. Hydrologisches Jahr 2019/20. Trachsel, J.; Zweifel, B.; Techel, F.; Marty, C.; Stucki, T., 2020. WSL Ber. 101: 75 S.

Forum für Wissen 2019. Biodiversität im Schweizer Wald. Bollmann, K. (Red.), 2020. WSL Ber. 100. 101 S.

Herausforderungen Landschaftsentwicklung Schweiz. Zweite Umfrage unter Expertinnen und Experten 2019/2020. Wartmann, F.; Hunziker, M., 2020. WSL Ber. 99: 48 S.

Einsatz von Klebeankern im subventionierten Lawinen- und Steinschlagverbau. Margreth, S., 2020. WSL Ber. 98. 8 S.

Biodiversitätsschädigende Subventionen in der Schweiz. Grundlagenbericht. Gubler, L.; Ismail, S. A.; Seidl, I., 2020. WSL Ber. 96. 216 S.

Steinschlagversuche Galerie Pardé. Versuchsdurchführung, Auswertung und Resultate. Volkwein, A.; Fergg, D.; Kurihashi, Y.; Schellenberg, K., 2020. WSL Ber. 95. 96 S.

Überwachung von besonders gefährlichen Schadorganismen für den Wald – Jahresbericht 2019. Surveillance des organismes nuisibles particulièrement dangereux pour la forêt – Rapport annuel 2019. Monitoraggio degli organismi nocivi particolarmente pericolosi per il bosco – Rapporto annuale 2019. Queloz, V.; Cornejo, C.; Dubach, V.; Prospero, S.; Hölling, D.; Beenken, L.; Ruffner, B.; Rigling, D., 2020. WSL Ber. 94. 61 S.

Waldinventur 2017 im Naturerlebnispark Sihlwald. Brändli, K.; Stillhard, J.; Hobi, M.; Brang, P., 2020. WSL Ber. 93. 52 S.

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