SIXTH FRAMEWORK PROGRAMME

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IRASMOS

Integral Risk Management of Extremely Rapid Mass Movements

Specific Targeted Research Project

Priority VI: Sustainable Development, Global Change and Ecosystems

D2.1 – Catalogue of current structural and non-structural (active/passive) countermeasures against debris flows, rock avalanches, and snow avalanches

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CO	Confidential, only for members of the consortium (including the Commission Services)	

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PRIORITY VI
Sustainable Development, Global Change and Ecosystems

SPECIFIC TARGETED RESEARCH PROJECT

INTEGRAL RISK MANAGEMENT OF EXTREMELY RAPID MASS MOVEMENTS

WORK PACKAGE 2:
COUNTERMEASURES

DELIVERABLE D2.1

Countermeasures

State of the art and description

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Table of contents

List of figures

List of tables

1 Introduction

1.1 State of the art

1.1.1 Debris flows

Up to the 1960s the settlements located on torrential fans were exclusively protected by more or less closed check dams, situated usually at the top of the fans. The task of these check dams was the complete retention of bedload and debris material. These structures were designed with only small slots for water load relieving, distributed all over the cross section of the check dam. Thus, initially it was static reasons, which lead the attention to the emptying of check dams (Kronfellner-Kraus, 1970).

Negative experiences with sediment retaining structures lead from a permanent deposition of sediments to temporary sediment retention aiming at a long-time sediment management. As a result, the "damaging bedload" could be retained for a certain length of time, and the migratory bedload could pass the structures to keep the sediment transport and therefore the torrent's ecology balanced (Aulitzky, 1985). Consequently the goal was to buffer the hazardous discharge and sediment transport peaks and to intervene with the transport process only as intensive as necessary.

Table 1: The approach of intervention with the transport processes changed during the last decades:

"Old" static approach	**"Actual" dynamic approach**
Approach: - Snap-shot, static	Approach: - Development, dynamic
Protection aim: - Water course-morphological conditions - Balance of mass and energy	Protection aim: - Reflection of water courses, valleys and anthropogenic influences at large - Balance of mass and energy
Function: - Sharp rise and subsequent decrease to residual function - Mostly once, short-term	Function: - Multiple functions - Mostly repeated, sustainable
Construction: - stone masonry, concrete masonry, concrete - gravity dam, arch dam	Construction: - reinforced concrete, steel - sectional constructions: fins, beams; angular retaining dam

Thus, new structures had to be designed to allow for a precise discharge of sediment at the check dam in dependence of the respective shear force and transport capacity of the lower reach. However, these new structures must not cut off the sediment transport at all. Thus, vertical slits were integrated into the check dams, and designed in a way that mean discharge can pass without intervention and higher discharge is retained.

The requirements to these structures can be summarized as follows:

- Hazardous discharge and sediment peaks should be retained as well as woody debris
- Regular sediment transport should be possible
- The retention volume of the basin should continuously be available for flood and debris flow events, but solids should be retained during an event and removed again by the mean discharge. These requirements were introduced by Üblagger (1973) as "sorting" and "dosing".
- Maintenance access is necessary for artificial clearing
- Migration of aquatic fauna should not be prevented

The direct result of these requests was the development of the slit beam check dam, which is one of the most commonly used check dam types in European mountain regions. During the last decades, these slit beam check dams were built in series with downstream decreasing distances of the beams. In such a manner, the concept of "sorting" was realized for the first time. However, experience had shown that the function "sorting" couldn't be achieved because of woody debris clogging leading to a total sediment retention with the effect of necessary artificial cleaning of the retention area. As a result, the original function of a self-emptying structure was changed to a check dam for consolidation. In recent years, the functional term of “sorting” was transformed to “filtering”.

New concepts had to be created leading to multiple check dam designs, which were constantly developed due to the experiences gained in the aftermath of events. One of the underlying concepts was to attribute different functions to different structures since the experience had shown that individual structures might not be able to fulfill multiple functions. Accordingly, the structures were adapted to these requirements. As a result, functional classifications were developed following a vertical sequence in a way that the structures supported each other in a chain of functional structures (Üblagger, 1973).

Functions (Kettl, 1984; Fiebiger, 1984):

- Breaking of debris flows
  Reduction of the dynamical energy of debris flows aiming at a reduction of dynamic impact forces on structures and downstream reaches. Moreover, debris flow material can be deposited under controlled conditions at appropriate locations.

- Filtering of bedload material
  Retention of large grain sizes and downstream transport of smaller grain sizes.

- Filtering of woody debris
  Retention of organic material during an event to protect downstream reaches of the channel bed from clogging.

- Dosing of water
  A quantitative change of the unit discharge due to the qualitative change of the discharge hydrograph at a defined location.

- Dosing of bedload material
  Quantitatively dosed transport of temporarily deposited bedload material by discharging high and mean water.

- Stabilizing
  Protection of the level of the stream bed against backward erosion.

- Consolidation
  Raising the level of the upstream channel bed to stabilize sliding slopes.

Due to these functions, series of structures were built as a “mitigation chain”. However, the limited area in torrential channels often requires combinations of tasks in one single multifunctional structure.

Usual combinations of functions are:

- Consolidation and filtering
- Consolidation and dosing
- Filtering organic material and retention
- Filtering and breaking debris flows

In the 1970s and 1980s, the functional requirements “consolidation” and”stabilization” were obtained as a result of the structural design and related statics. From the 1990 onwards, the predetermined functional requirements set the geometry, construction and static system of the structures.
The diversity of modern function-related structures has been enabled by the introduction of new technologies such as reinforced concrete, steel construction and substructure, and the availability of high quality concrete even at remote torrential construction sites (Fiebiger, 1984).

In recent years, the implementation of different adapted functional structures is state of the art.
However, the problem of woody debris clogging is still not satisfyingly solved. On the one hand, independent rakes for filtering organic material had been installed upstream of structures and on the other hand, check dams supported by integrated inclined rakes had been constructed. By these inclined rakes the woody debris should slide up vertically and the subsurface bedload transport will be discharged.
Although these structures have a considerable effectivity related to their protection goal, their functional effectivity could be improved. Consequently, these structures have to be developed further on.

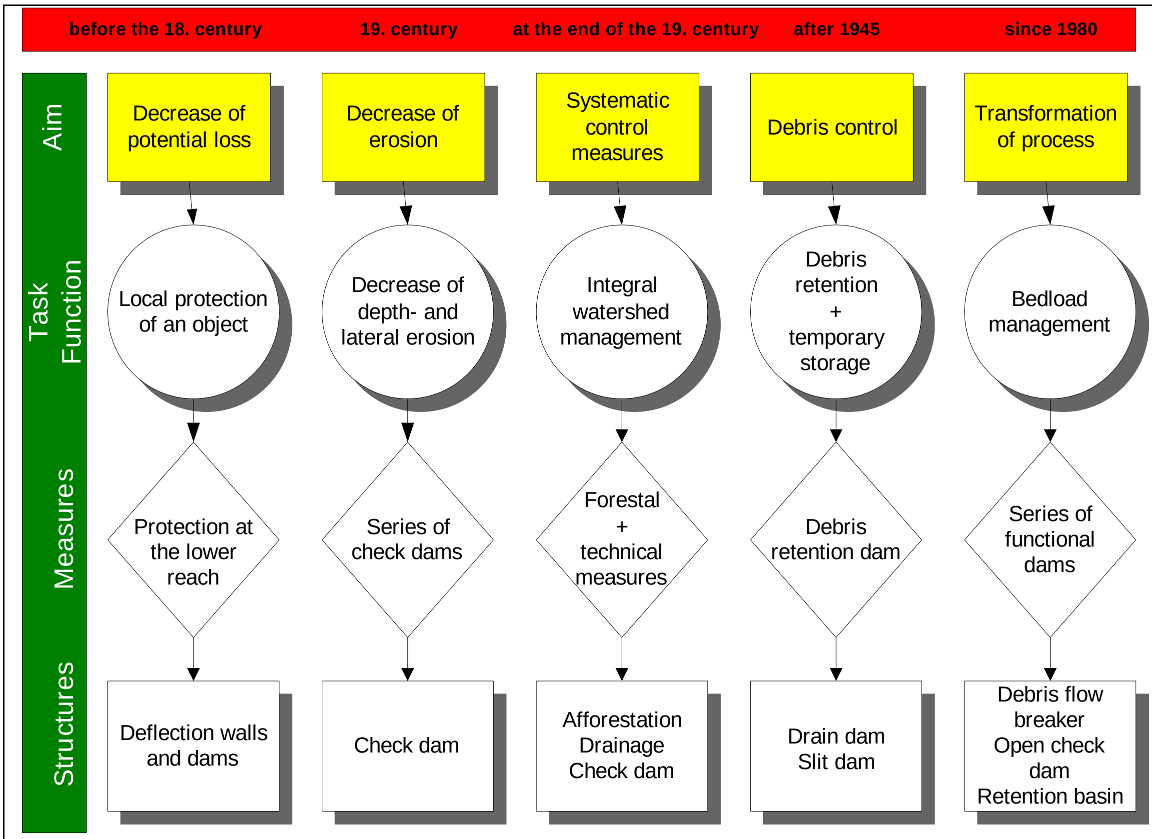

Figure 1: Development of the technical countermeasures from the beginning of the torrent control up to the state of the art (IAN-BOKU).

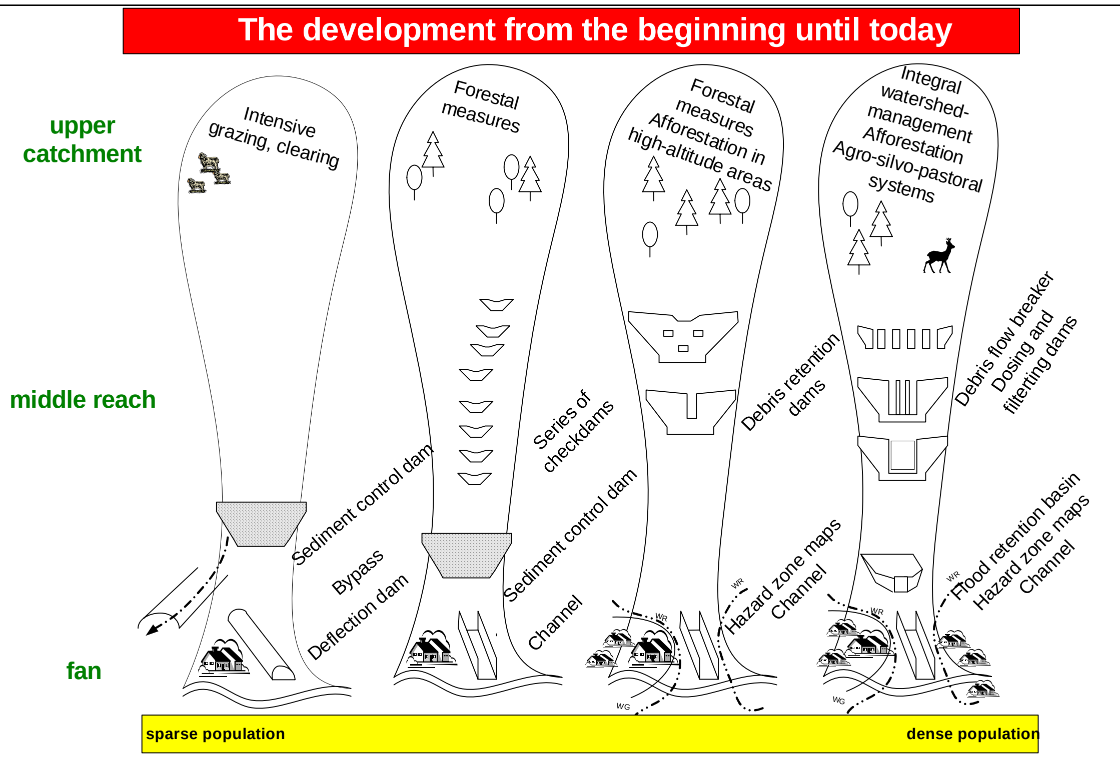

Figure 2: Development of the technical countermeasures from the beginning of the torrent control up to the state of the art (IAN-BOKU).

1.1.2 Snow avalanches

The development of structural countermeasures against snow avalanches started with extended settlement in the alpine areas in central Europe. The first structural measures have been built in the release areas of known avalanche catchments. Therefore supporting structures have been used to retain, sustain or support the snow cover in place and to prevent it from sliding downhill.

This type of structural countermeasure comprises two major types of design: first, rigid structures that sustain only small elastic deformation such as snow rakes (upright crossbeams, so-called rafters), and snow bridges (horizontal crossbeams, so-called bars) and second, rocking structures that are capable to support a limited deflection such as snow nets.

To influence the snowdrift in the release area snow fences are the most common type of technical structure. A snow fence is a linear system that is designed to accumulate or hold snow at a certain location by influencing the wind flow. Other linear systems are jet roofs (linear system to prevent the formation of cornices and an undesirable accumulation of snow immediately under the ridgelines) and wind baffles (discrete system influencing the wind speed and wind direction to prevent deposit of snow and acting on the mechanical behavior of the snow cover) are additional structures used to influence the snowdrift.

Once an avalanche is triggered, massive counter measures are necessary to influence the flowing snow masses. Deflecting or catching constructions are the most common types of counter measures. Dams can be used for both, catching or deflecting flowing snow masses. Catching dams are transversal structures designed to stop or to initiate the stopping of flowing snow, deflecting dams are used to deviate flowing snow out of an endangered area. Avalanche sheds (also called galleries) are designed to protect roads and railroads by allowing avalanches to pass over the object. Another structural measure to protect roads or railroads is a tunnel. Breaking constructions are mostly used to protect roads to reduce the velocity of avalanches reaching the road. The measure usually consists of several rows of mounds or cones constructed in the run-out zone.

Unlike other natural hazards, an artificial release of the snow avalanche can be reached by simple technical measures. The range of this type of counter measure varies from simple explosives to high-tech explosive devices, mostly set up directly in the release area of an avalanche. Arial cableways can place explosives on predefined locations and detonate it above the snow cover. Gas exploders are rather high-tech systems, located on fixed positions on a slope allowing the explosion of a gas mixture above the snow cover. Guns can also be used for artificially triggering snow avalanches. For European countries this type of counter measure is used only in Switzerland.

Afforestation is needed for lower regions to establish a homogenous forest. Most release areas are located high above the timberline and therefore the stabilizing effect of a dense forest cannot cover the whole altitude range of avalanche catchments.

1.1.3 Rock avalanches

There exist few examples of countermeasures for rock avalanches. The main reason for this is that the frequency of this hazard is low leading to that planning of mitigation measures has not been prioritized. Moreover, the triggering mechanisms have not yet been fully understood making it difficult to know how structural countermeasures best could be implemented. The large volume and great forces involved in rock avalanches makes it difficult to implement traditional physical measures used for smaller rock falls, e.g. anchors, rock bolts, nets and concrete ribs.

Based on the nature of failures in rock slopes the most, and normally the only method of managing the risks associated with a rock slope movement, is the development of an effective warning system. Suitable emergency planning is then the only effective tool to reduce the consequences by means of evacuation, road closure and other active measures.

In order to establish a reliable continuous monitoring network, a series of methods needs to be used, both on the surface and in boreholes. The array of sensors needs to provide as complete information as possible in order to cover the entire slope and sectors of the unstable areas. However, there are a series of practical limitations in terms of distance from measured points to the monitoring instrument, local slope conditions, rock fall and snow avalanche hazard and problematic atmospheric conditions.

The design of monitoring systems is largely controlled by the slide scenarios and the deformation pattern at the specific sites. This normally requires a detailed geological and movement investigation program. The possibility to do a forecast during an event is largely dependent on a good understanding of the 3D deformation pattern. This requires a series of different monitoring types that can detect both surface and subsurface deformation.

1.2 Definitions

Integral risk management aims at preventing, intervening and avoiding natural hazards (Amman, 2001) and includes a combination of diverse mitigation measures to guarantee an optimal cost-benefit ratio.
Reducing the risk to an accepted level of residual risk, the design of mitigation measures is essential. Thus, two types of mitigation measures can be distinguished (Zollinger, 1985): active and passive measures.
In Austria, active measures focus on the hazard, passive ones consider the potential damage (Hübl and Steinwendtner, 2000). International comparison shows that until yet no approach was derived to define active and passive measures in a unique system. If one has a closer look in other domains (fire protection, biotechnologies, climbing, buildings…), one can see, that there are real different ways to define the terms "active" and "passive". These terms have been used in European countries for many years now and represent some kind of base of these countries´ mitigation philosophies. The differences of these terms´ meaning in the diverse countries and the confusion and inconsistency resulting from the use of these definitions gets obvious by regarding Table 2. As a resulting problem appears the deriving of a consensus in using unique terms.

Table 2: Different meanings of used terms in different countries.

	Active	Passive	Structural	Non-Structural
Austria	Change of frequency and magnitude of process	Lower consequences		
France	Change of frequency and magnitude of process	Lower consequences		
Italy	Interaction with process	No interaction	Constructions	Actions
Norway	Not used	Not used	Topdown	Non-Physical
Switzerland				

But not only active and passive mitigation measures are used as usual terms in dealing with natural hazards. Considering the natural hazards´ vocabulary, further established terms are "permanent", "temporary", structural" and "non-structural". The meaning of these terms is shown in Table 3.

Table 3: Definitions

Active mitigation measures	Initiation, transport or deposition of debris flow material can be influenced by active mitigation measures. The change of characteristics of magnitude and frequency can be achieved either by influencing the probability of occurrence of a hazardous event (disposition management), or by manipulating the hazardous process itself (event management) (Hübl & Fiebiger, 2005). Active countermeasures should reduce the consequences of the potential hazard.
Passive mitigation measures	Passive mitigation measures are based on the principle of spatial separation of the endangered people and objects from the hazardous area (Wilhelm, 1997). A reduction of potential loss and decrease of vulnerability should be achieved by preventive measures (spatial planning, landuse) and event response (immediate actions in case of an (expected) event).
Structural mitigation measures	Structural measures include all physical measures used to mitigate natural hazards.
Non-structural mitigation measures	Non-structural mitigation measures typically

	concentrate on identifying hazard-prone areas and limiting their use temporarily or permanently. Further forestal measures can be seen as non-structural measures. Non-structural countermeasures are very site-specific and they greatly depend on the organizational and legal structures in each country.
Permanent mitigation measures	Permanent measures comprehend durable technical and silvicultural measures as well as land use planning. Further information of population is subsumed.
Temporary mitigation measures	Temporary measures are adjusted to a certain point of time and the hazard potential of a location. These measures are executed spontaneously. Usually they complete or substitute the permanent measures with respect to an increased economic efficiency.

Usually, these definitions are essentially "phenomenon oriented" and do not depend on man reaction nor potential damages. This appears to be the origin of the differences.
As shown above, the use of these terms is not universal but depends on the culture, on the practice and on the experience of each region.

2 List of countermeasures

2.1 Structural countermeasures against debris flows

Table 4: Structural countermeasures against debris flows

Process	Counter measure	Type
Debris flow	Increase slope stability	Drainage
		Soil bio engineering
	Consolidation / Stabilization	Sill
		Ramp
		Closed check dam
	Transformation of process	Debris flow breaker
		Drop structure
	Organic debris filtration	Open check dam (rake)
	Permanent debris deposition	Open check dam
		Deposition basin
	Temporary debris deposition	Open check dam
	Protection / Deflection	Protection and deflection walls / dams
	Discharge control	Transport channel
	Afforestation	

2.2 Structural countermeasures against snow avalanches

Table 5: Structural countermeasures against snow avalanches

Process	Counter measure	Type
Snow avalanches	Snow drift regulation	Snow fence
		Jet roof
		Wind baffle
	Stabilizing constructions	Snow bridge / rake
		Snow net
		Tripod
	Braking constructions	Avalanche breaker
	Deflecting and catching constructions	Deflecting and catching dam
		Gallery
		Tunnel
	Artificial release	Aerial cableway
		Preplaced explosives
		Gas exploders
		Guns
	Afforestation	

2.3 Structural countermeasures against rock avalanches

Table 6: Structural countermeasures against rock avalanches

Process	Counter measure	Type
Rock avalanches	Removing unstable rock mass by blasting	
	Drainage	
	Diversion of surface water	
	Underground water drainage	

2.4 Non-structural measures

Table 7: Non structural countermeasures

Administrative and organizational methods
Land use planning based on hazard maps
Information and education
Preparedness and emergency plans
Conditions of insurance

Table 8: Non structural countermeasures

Forecasting and operational methods
Monitoring systems and early warning

3 Description of structural countermeasures

3.1 Debris flow

3.1.1 Increase slope stability

3.1.1.1 Drainage

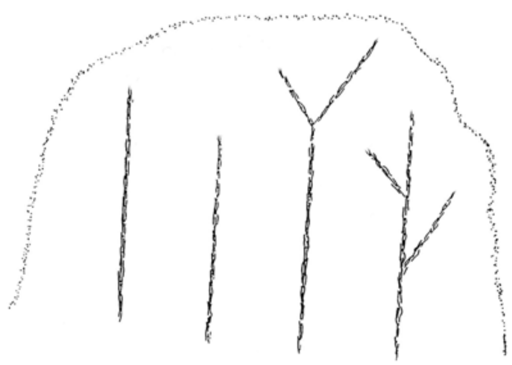

Figure 3: Drainage system, top view (IBLB, 1999)

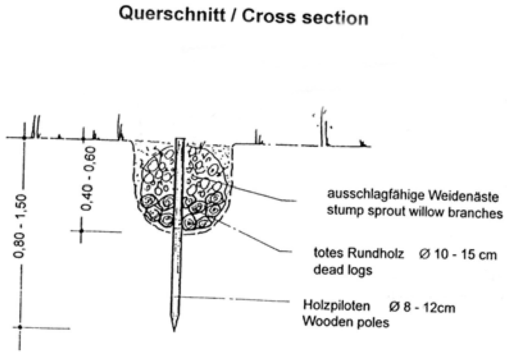

Figure 4: Drainage fascine, cross section (IBLB, 1999)

Description and purpose
The ecosystem of wet and/or unstable areas can be stabilized by drainage systems, which drain the water out of unstable ground layers. In such a way, high pore water pressure along potential shear surfaces can be avoided and consequently reduce the danger of occurrence of sliding layers.

Principles of drainage:
- Collection of wells by a horseshoe-like diversion drainage
- Retention of superficial and subsurface runoff from the area located above the instable area (hillslide)
- Draining subsurface runoff to prevent the formation of shear surfaces

Specific design criteria
The drainage channels are constructed as ditches. Their base is sealed with seal foils or loam layers. On top of the sealed base either suckers or drainage courses are placed. Suckers can be described as semi permeable pipes, whose top side is perforated for water intrusion and the bottom side is sealed for carrying off the percolated superficial and subsurface water. Suckers usually are covered with drainage courses like gravel or small boulders.
After a distance of 30-50 m, the drain ditches are lead into main sewers for controlled evacuation of drained water. The drainage systems can be designed either linear, branched out, triple pole or herringbone like.

Materials
- Synthetic material
- Material of bio-engineering methods

Software available
Unknown, no software available.

Photo gallery

<table>
<tr>
<td>
Figure 5: Drainage system with main sewer in front (IAN-BOKU, 2006)</td>
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Figure 6: Main sewer (IAN-BOKU, 2006)</td>
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<td>
Figure 7: Drainage system (Florineth, 2004)</td>
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Figure 8: Drainage ditch under construction (IAN-BOKU, 2003)</td>
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3.1.1.2 Soil bio-engineering

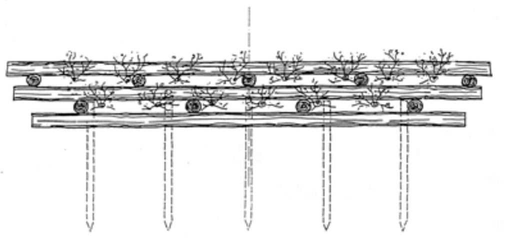


Figure 9: Wooden crib wall, front view (IBLB, 1999)

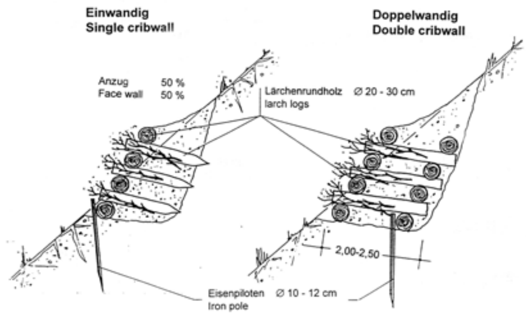


Figure 10: Wooden crib wall, cross section (IBLB, 1999)

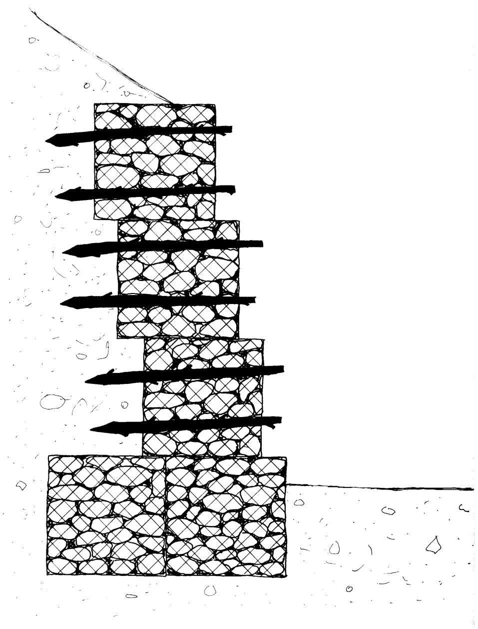


Figure 11: Living gabions (Florineth, 2004)

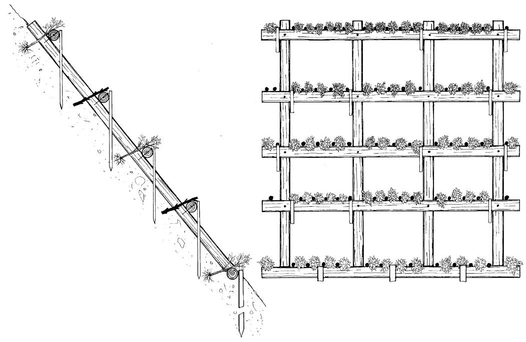


Figure 12: Living slope grid (Florineth, 2004)

Description and purpose
Soil bioengineering is based on the use of dead and alive plant material to cope with erosion. These measures can initiate or accelerate phytosociological successions and processes, reduce erosion and control the ground-water supply.

Amongst others, soil-bioengineering methods can be used for:

- Torrential channels, gullies, rivers and streams
- Slope stabilization and bank-redevelopment
- Road ditch stabilization

The combination of soil bioengineering applications protecting the surface (seeding) and stabilizing structures out of wood is very successful in practice. Up to the time when the seeding or the live plants reach their full efficiency, the wooden technical constructions will stabilize the soil. The success of soil bioengineering measures depends on the stabilizing effect of the previously installed technical structures (Hübl & Fiebiger, 2005).

Longitudinal structures:

- Tree spurs (rough coniferous trees)
- Branch layering in gullies
- Vegetated channels
- Live brush mattresses
- Live slope grids
- Fascines (different techniques)
- Vegetated revetments of different materials
- Log brush barrier construction
- Live pole construction
- Brunch and brush packing
- Double-row palisades

Transverse structures:

- Live groynes
- Live siltation construction
- Live combs
- Brushes and palisade construction
- Brush sills
- Fascine sills
- Log cribwall with brushlayers
- Planted gabions
- Wooden crib dams

Materials

- "Live" material
  - Seed material
  - Bushes
  - Trees
- "Dead" material
  - Branches of bushes and trees
  - Wood
  - Gravel and boulders
  - Wire

Software available

Unknown, no software available.

Photo gallery

Figure 13: Live wooden cribwall under construction (IBLB, 2006)

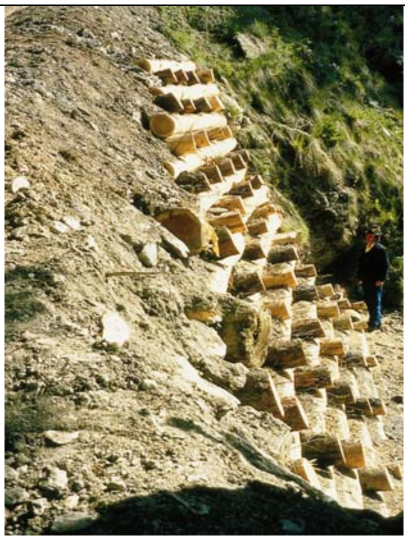


Figure 14: Live wooden cribwall (Florineth, 2004)

Figure 15: Live slope grid (Florineth, 2004)

Figure 16: Brush layer (Florineth, 2004)

3.1.2 Consolidation / Stabilization

3.1.2.1 Sill

Description and purpose

Due to the high energy of discharge in steep torrential channels, lateral and vertical erosion can occur. This erosion causes a lowering of the channel bed and further instable embankments and slopes.

According to the natural slope and bed material, the stream bed can be stabilized by several sills, installed in series with a mostly constant distance. The height-difference from one field to another should not exceed 1 m.

A series of sills is able to reduce the flow velocity by permanent alteration of the hydraulic conditions from sub critical to supercritical flow. Thus, fields in between the sills tend to scouring. Therefore, the design of sills concentrates on keeping local scours as shallow as possible, so that the scours will not disequilibrate the banks and the sills themselves.

Specific design criteria

If there is no sediment transport from upstream and no bed pavement, the scours will develop like shown in the figures below. This process can cause single or multiple failure of the chain of sills.

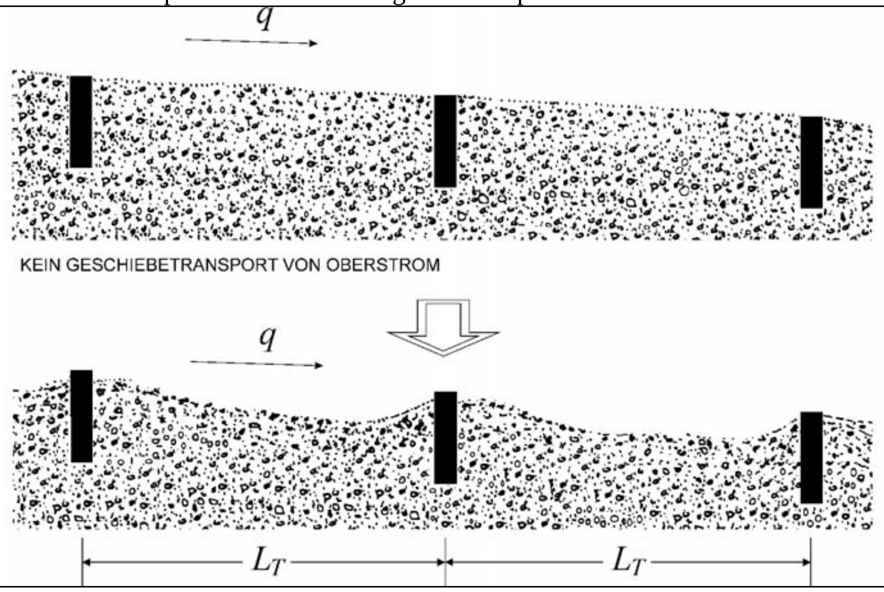


Figure 17: Development of scours between the sills (ÖWAV, 2003)

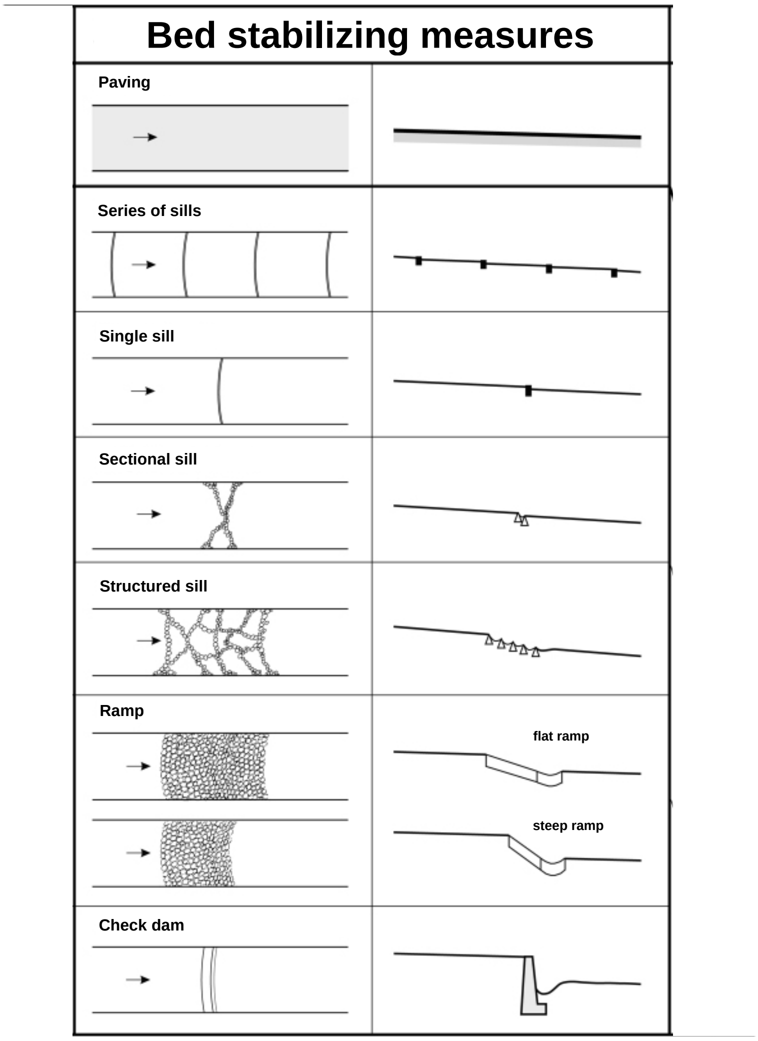


Figure 18: Bed stabilizing measures (ÖWAV, 2003)

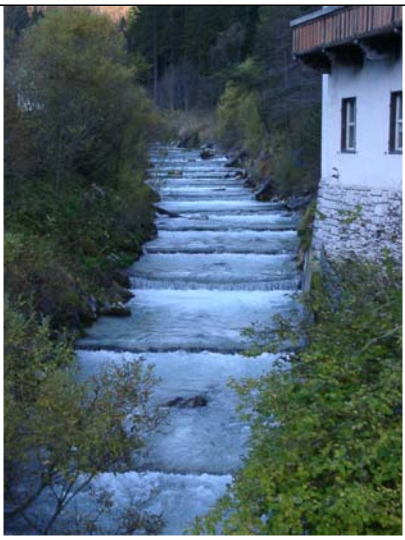
Materials

- Wood
- Boulders
- Stone masonry
- Concrete
- Steel concrete

Software available

Unknown, no software available.

Photo gallery

	
Figure 19: Series of sills out of stone masonry (IAN-BOKU, 2002)	**Figure 20: Series of sills out of stone masonry (IAN-BOKU, 2002)**

3.1.2.2 Ramp

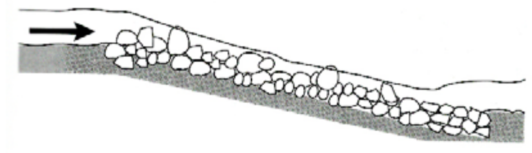


Figure 21: Loose block-ramp (DVWK, 2002)

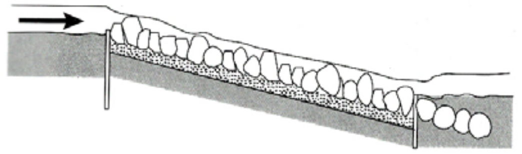


Figure 22: Bedded block ramp (DVWK, 2002)

Description and purpose
The bed of channels, which are endangered by vertical erosion, can be stabilized by local structures such as block-ramps. Block-ramps are hydraulic structures with a coarse surface and a relatively low gradient. In terms of naturlike and ecological structures, ramps should be preferred whenever possible. Two main types of block-ramps exist:

- Loose block-ramp (like a rip-rap)
- Bedded block-ramp

Block-ramps – like most of the other hydraulic structures – are installed for dissipating energy of the water. In the case of block-ramps, the energy-transformation occurs by the turbulence of the discharge, which is caused by the high roughness of block-ramps. The resistance of the ramp body against the mechanical forces of the discharge is the determining factor for stability.

Specific design criteria (ÖWAV, 2003)
Characteristics of loose block-ramps:

- Several layers of boulders
- Boulders are not bedded but are poured
- Water drainage during construction is not necessary
- Stability against flow forces of discharge by the weight of the boulders
- Collapse of structure is signalized by erosion and deformation

Characteristics of bedded block-ramps:

- One single layer of boulders
- Water drainage during construction is necessary
- Relatively constant roughness
- Stability against flow forces of discharge by the weight and additionally by the interconnection of the boulders; often the boulders are placed into a foundation out of concrete
- Collapse of structure occurs suddenly

Materials

- Boulders
- Concrete

Software available
Unknown, no software available.

Photo gallery

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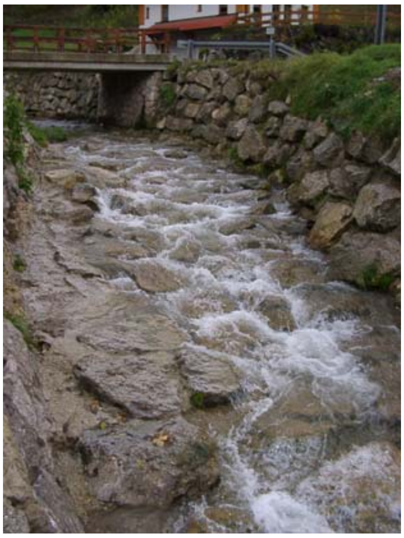
<td>
Figure 23: Bedded block-ramp with foundation out of concrete, (IAN-BOKU, 2002)</td>
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Figure 24: Bedded block-ramp, (IAN-BOKU, 2002)</td>
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3.1.2.3 Closed Check dam

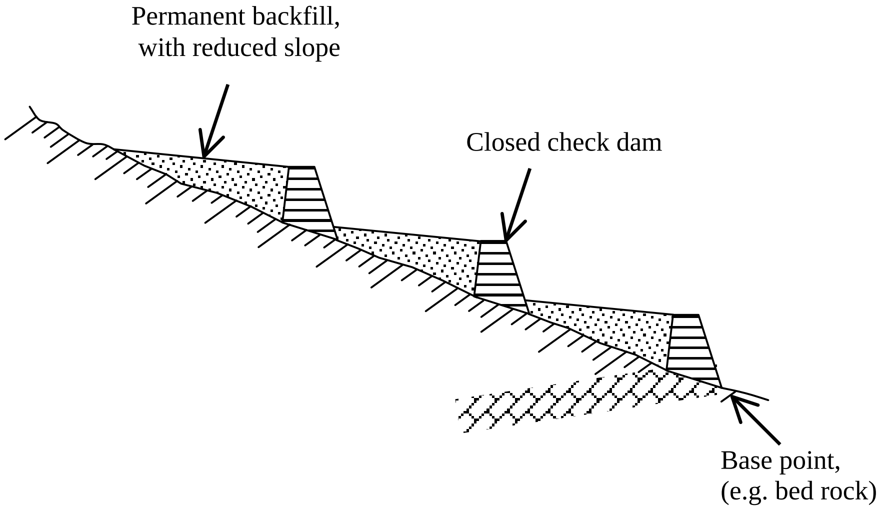

Figure 25: Closed check dam series: Schematic of the principle

Description and purpose
A closed check dam is a structure placed transversally to the torrent, from one bank to the other and permanently backfilled.
Closed check dam series aim at controlling the solid and the liquid discharges and volumes, the velocity and the level of a debris flow, by a local reduction of the channel gradient.

Usually, series of check dams are built and spaced regularly along the channel, allowing a modification of the longitudinal bed profile.
Closed check dams are composed of a weir, two wings and a strong foundation. Mostly, closed check dams are designed as gravity dams or single standing structures, but there exists a wide variety of other structural designs.

The slope gentling due to the check dam induces a flow velocity reduction. As a consequence the erosional capacity of the flow is reduced and the sedimentation is forced, reducing the granular concentration of the flow.
Furthermore, bank erosion is limited as check dams tend to reduce the shifting of the torrent. In other cases, check dams can stabilize the banks, the backfill (or alluviation) acting as an abutment for potential landslides which can provide the flood with granular materials.

Specific design criteria
The height of a check dam is defined according to the designed slope, which is based on a hydraulic study. In a series of check dams, the height and quantity of check dams largely depend on the designed change in slope. Generally, the construction of series of check dams starts from a stable zone up to the zone to be manipulated.

Closed check dams can be considered as soil retaining structures placed in inclined channels and exposed to considerable discharge variations. Specific design criteria are needed for both, structural stability and hydraulic considerations.
Structural stability of the construction depends on site-specific parameters (soil characteristics, soil-structure interactions, slope) and on static and dynamic interactions with the flow.

The aim of a check dam is to modify the slope of the channel. With this purpose, series of check dams are constructed in most of the channels. Depending on the original longitudinal torrential slope and on the desired slope, the amount and height of dams is defined. The distance between two check dams generally is determined depending on the equilibrium slope. For a single dam, the main characteristic is its height which is basically linked to its function.

To fulfill this function, different types of structure can be built:

- free standing check dam
  mainly made of reinforced concrete with or without abutment but also of prefabricated reinforced concrete elements or of prefabricated metallic structures
- gravity dam
  made of concrete, rocks, masonry, prefabricated concrete blocks, gabions, geotextile reinforced soil
- arch-dams
- other types such as wire netting fence, expanded metal fences
  generally used for small height dams and in gullies

The choice between the different types of structures mainly depends on the planned height of the check dam, the torrential cross section, the channel bed and the soil characteristics of the banks, as well as the site accessibility and the costs of the structure.
The structural design of check dams depends on the type of structure. Mechanical interactions between the soil and the structure, the flow and the structure but also interactions with possible snow avalanches have to be considered.
Hydraulics mainly concerns the weir. The design of a weir is defined according to the peak discharge. The downstream erosion depends on the drop height, peak discharge and downstream conditions like flow depth and grain size distribution.
In some cases, a dissipater basin is constructed at the dam toe.

During its intended life, a closed check dam is exposed to different type of static or dynamic impacts from the foundation soil, the backfill material and from the flow. Some of these impact forces vary within a wide range under alternating conditions.

Materials
Closed check dams are mainly made of concrete, steel (section or reinforcement) and rock. Gabions, wire nettings, geotextiles and timber are also used for part or whole structure.
Free standing dams are reinforced concrete structures whereas masonry structures are mainly made of rocks.
Gravity dams either can be built with concrete or rocks, or even with gabion (mainly in Italy).
The weir is generally protected from abrasion using a specific material (steel section, granite or steel section mainly)

All these materials are exposed to abrasion, oxidation and site specific ageing effects (moisture, freeze/thaw cycles …). In some cases the torrential chemical water quality may affect the dam.
A list of the possible constructional materials for check dams and its parts with some explanations (*pro and contra*) can be found below:

- Blocks (gravity),
  Rock blocks, with or without joining, are sensitive to dislocation.
- Concrete and mortar
  Concrete is used for the construction of gravity dams. Note that even if not absolutely required, steel reinforcement elements like welded wire meshes often are placed in this type of structure.
  The problems to be considered with this material are :
  - Abrasion: when exposed to run-off with loaded flows
  - Quality of the water for the concrete processing.

  Specific formulations allow using this type of material in zones prone to abrasion (concrete ‘alag’, aluminous cement, and special mortar). These blends are specifically designed and generally resist to the occurring impacts. The problem with these products is their processing that requires skilled staff and specific site conditions.
  Concrete is sensitive to physical and chemical evolution, mainly when in contact with water (cracking, oxidation, decalcification, alkali-aggregate reaction …). This phenomenon can lead to considerable damages.
  Dams made of concrete are sensitive to cracking when exposed to excess of tension within the structure.
- Reinforced concrete

Reinforced concrete is mainly used for the construction of free standing dams. The durability of reinforced concrete structures is confronted to the problem of the two components: steel and concrete.

- Steel
  Steel is used in different forms and for different purposes in check dams. Welded wire meshes and bars reinforce concrete. Sections can be used to protect concrete exposed to abrasion (U or L shaped).
  Steel is very sensitive to corrosion. In abrasion protection devices, the thickness is a key point as well as the problem of fixation on the structure.
- Wood
  Some dams are constructed assembling timbers. This type of structure is not really suitable in case of frequent debris/mud flows as it does not resist to strong abrasion or impacts. On the other hand, the advantages can be seen in the costs (construction and maintenance) when adequate tree species are available.
  Wood can also be used as abrasion surface. Timbers placed longitudinally to the flood in the weir offers a shock resistant protection against abrasion. It requires regular but rather cheap maintenance but it is not suitable for torrents with frequent debris/mud flows.
- Gabions and wire netting
  Sometimes, gabions are used for the construction of gravity dams, whereas wire nettings are used to build net barriers in gullies.
  Durability depends on the same phenomena as those mentioned for steel.

Software available
Both geotechnical and hydraulic designs are specific to torrential conditions. Commonly, available software is not appropriate for their design and specialized tools are necessary. In France, some automatic design tools are used.

BARTO – Design of gravity and free standing check dams. 2006. Developed by Cemagref and property of ONF-RTM. (in French)

Photo gallery

Figure 26: Series of free standing check dams (Cemagref)

Figure 27: Series of free standing check dams (Cemagref)

Figure 28: Series of gravity check dams (Cemagref)	**Figure 29: Series of gravity check dams (Cemagref)**
 **Figure 30: Rock masonry gravity dam (Cemagref)**	 **Figure 31: Wooden structure (Cemagref)**
 **Figure 32: Gravity dams (Cemagref)**	 **Figure 33: Gravity dams (Cemagref)**
 **Figure 34: Free standing dam with stilling basin (Cemagref)**	 **Figure 35: Geotextile reinforced backfill dam (Cemagref)**

3.1.3 Transformation of process

3.1.3.1 Debris flow breaker

Description and purpose
Within a mitigation measure concept considering debris flows, the debris flow breaker will be the first upstream measure of a series of structures. Its function is to decrease the energy level of the debris flow. Downstream, the debris flow breaker is followed by several structures controlling the sediment management.

The main goal is the reduction of the energy of debris flows to a lower level and thus to decrease the dynamic impacts of structures. Moreover, the debris flow masses can be deposited at an intended location in a more or less controlled way (Kettl, 1984). Thus, both downstream reaches of the stream channel as well as settlement areas are exposed to considerably lower dynamic impacts.
In special cases, debris flow breakers can operate as an avalanche breaker.

Specific design criteria
Debris flow breaker can be designed either as independent structures or as bifunctional check dams with a combination of filtering and dosing as well as splitting debris flow masses.
The classical design of a debris flow breaker includes a central section out of three to five longitudinal walls (fins), which are inclined to the retention area. Usually these fins get designed at least to the seven- to eleven fold hydrostatic water pressure (Armanini, 1997, Hübl et al., 2003). As liquid mudflows and stony debris flows show distinct flow dynamics, the flow behavior is an important criterion of debris flow breakers.
The shape of the fins can be buckled twice to approximate the structure to the shape of a circle, which is especially advantageous for the impact of the debris flow head. Therefore, the upper completion of the spillway is totally vertical, to avoid an overtopping of the structure. The distance between the fins is according to the grain size of the transported material and the shape of the woody debris, the bigger the grain size, the higher the distances of the fins. Usually, the upstream part of the fins is armored with a steel plate to avoid abrasion of the concrete.
At bifunctional check dams, the fin splitting the debris flow, is located in front of the central section, which is designed for filtering or dosing. This fin is designed similar to the single standing debris flow breaker, protects the check dam to extreme dynamical impacts and keeps the spillway clear from blogging (Setznagel, 1989).

Debris flow breakers can be combined with check dams for stabilizing and consolidation in one single structure. Thus, the intermittent retention capacity of the check dams can be used in the case of an extreme event.

Materials
- Reinforced concrete
- Steel plates for hard facing to avoid abrasion
- Granite plates for the spillway

Software available
Unknown, no software available.

Examples
Debris flow breakers in Austria have been affected by numerous debris flow events and are proven to be an essential element in any torrential training system (Hübl & Fiebiger, 2005). The deposition area upstream the structure has to be excavated after each debris flow, which makes a road access to the breaker essential.

Luggauerbach, Salzburg, Austria

Photo gallery

Figure 36: Debris flow breaker (IAN-BOKU)

Figure 37: Debris flow breaker (IAN-BOKU)

Figure 38: Debris flow breaker; the special design ("christmas-tree") should force the self emptying of the retention basin by concentrating the discharge at the constriction of the spillway (IAN-BOKU)

Figure 39: Debris flow breaker ("christmas-tree") filled completely after an event (IAN-BOKU)

Figure 40: Debris flow breaker; the special (rounded) shape of the fins should avoid the clamping of big boulders (die.wildbach, 1996)

3.1.3.2 Drop structure

Description and purpose
Drop structures are transverse structures, which are completely backfilled. They are especially qualified for steep fans by being built in series. Velocity and energy of debris flows are decreased and dissipated respectively by crashing down on a more ore less horizontal surface, so called “crash dam”.
The structure itself is not exposed to any direct forces caused by the debris flow but will only have to sustain the earth thrust.

Experience showed, that if there is a sediment over plus in a torrential catchment, the transported sediment will form fans at the base of natural terrain steps and waterfalls. These fans are removed continuously by regular or higher runoff. Thus, the terrain steps show the dynamic of usual fans.
Debris flows loose most of their dynamic forces if they fall down over a certain height and crash on to a horizontal surface. In this way, the transport process is changed from debris flow to runoff with bedload transport. In series of check dams, the same development could be regarded.

Specific design criteria (Jenni & Reiterer, 2002)
Characteristics of drop structures are:

- Transverse, vertical slim plates, which are made out of reinforced concrete
- Completely backfilled
- Slots for draining the backfilling
- The airside is rested on longitudinal fins, which stabilize the transverse toe slopes
- Level of the crest corresponds with the upstream bedlevel
- Spillway is designed for debris flows (no trapeze shaped spillway)
- Protection against scouring necessary

Functions:

- Annihilation of the debris flow head and dissipation of energy
- Deposition of sediments.
  Even on steep fans several thousand cubic meters of solids can be deposited. The small grain sizes and the fines will be cleared away, so there is less danger of erosion in the downstream channel. There is no unwanted water retention possible. Even woody debris cannot interfere with this.

Advantages:

- On steep fans, there is often less space for other structures like retention basins.
- After completion, the structure itself is not exposed to any direct forces caused by debris flows and avalanches.
- Structures have to be dimensioned only to the earth thrust behind. So the drop structures can be designed slim and cheap.
- Longitudinal fins on airside have not only static function but also protect the banks against scouring.
- There is no outlet structure, which can be blocked with woody debris. So a self-acting cleaning of the retention area is possible, which can reduce the costs for artificial cleaning. The structure will be fully functional again very fast.
- Artificial cleaning is possible from the airside.
- Bedlevel downstream the drop structure will be lowered, so that:
  - The channelbed upstream the structure will be kept clear from debris flow deposits and you can find retrogressive erosion with a fixed erosion base.
  - There is no interfering with avalanches. Dense snow avalanches are deposited, powder avalanches are not influenced.
  - If the catchment gets renaturated to its origin status, the structures can be filled natural or artificial almost without any costs.
  - If there are several events in series and the retention areas are filled completely, there is no increased danger, because then the status matches with the unspoilt channel.

Disadvantages:

- Especially in steep fans one will have enormous excavation. Therefore, the slopes have to be stabilized very carefully.
- As drop structures are dimensioned only to earth thrust, they react very sensitive to flood events or debris flows during the phase of construction, as long as they are not completely backfilled.
- The volume of the retention area depends on the excavation during the construction. It’s useful to use this material for building dams in the surrounding area.
- Drop structures disrupt the flow continuum for aquatic fauna.

Materials

- Reinforced concrete

Software available

Unknown, no software available.

Examples

Vorarlberg, Austria: Maurentobel
Wassertobel

Practical experiences:

In Vorarlberg, Austria, numerous drop structures have been built. None of these constructions have been damaged, though they have been infected by events near the design event.

During the events there was a quite good effect in filtering and dosing, but due to the small catchment area and the low discharge there was no self-acting cleaning possible after the event. Each single structure should be accessible by excavator and truck.

A chain of drop structures in series is very effective. In such a manner, the total retention volume can be increased significantly (single structure volume about 10.000 m³). In such series one can recognize a strong effect of sorting. In the upstream retention areas one will have a higher aggradation slope then in the downstream ones, so the length of these sections should be higher.

Woody debris had no bad influence to the effectivity, as it was held back in the first retention area.

Photo gallery

Figure 41: Artificial emptying of a drop structure (die.wildbach, 1994)

Figure 42: Series of drop structures in combination with a deflection wall (die.wildbach, 1989)

	
Figure 43: Series of drop structures (IAN-BOKU, 2006)	**Figure 44: Series of drop structures (die.wildbach, 1985)**

3.1.4 Organic debris filtration – Open check dam (rake)

Description and purpose
Woody debris rakes are facilities for separating large woody debris from mineral debris and always are realized in combination with other sediment management measures. They can be constructed as independent structures or integrated into a structure for filtering or dosing sediments.

As the woody debris tends to block the functional openings of open check dams it has to be filtered out in a way, which allows undisturbed transport of water and mineral sediments.

Organic material can be filtered out at three locations (SETZNAGEL, 1989):

- Upstream the structure with
  - Rope barriers
  - Net barriers
- Close to the structure with
  - Vertical rakes
  - Inclined rakes (see chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**)
- Downstream the structure (after overtopping it) with
  - nets and rakes (Zollinger, 1983)

Specific design criteria
Independent constructed rakes are realized only rare. If they fulfill their function to filter out the woody debris well, usually the structure gets partly ore totally blocked, so that the sediment is deposited in front of the debris rake. One consequence could be the breakage of the clogging, which can lead to another debris flow. Through the development of new designs of independent filters on the one hand and the integration of measures for organic filtering into other structures on the other hand, this danger can be avoided.

Rimböck & Strobl (2001) tried to find out the ideal arrangement of V-shaped rakes for retaining organic material with model experiments. Version “V” was favored, because of

- only low forces, which impact the banks
- consistent discharge
- stable woody debris layer even in light bends

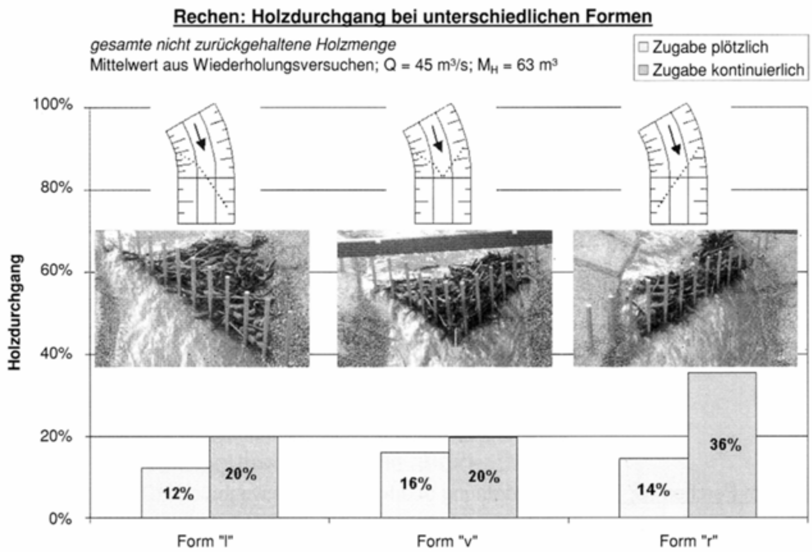

Figure 45: Effect of different rake designs in bends; passed woody debris in % by sudden (white color) and continuous addition (grey color) (Rimböck & Strobl, 2001)

V-shaped rakes are recommended for torrents with a longitudinal slope below 5 %. The clogging close to the structure is not to dense, so that the water can still pass the structure. The organic material causes only little backwater, so that below the surfacial woody debris layer the sediment transport is still possible.

Due to their easy construction, LOIPERSBERGER et al. (2000) recommend net barriers for filtering organic material. For a span width from 5 to 20 m, this measure is suitable for narrow valleys and steep slopes. The net barrier should be installed at flat and wide locations for causing only little backwater and keeping the forces to the net little.
Important specifications are

- the height of the net
- the distance to the stream bed
- the distance to the mean water level
- the longitudinal slope of the torrent
- the roughness
- the discharge
- amount and shape of the woody debris

If there are structures with limited cross sections like bridges, Bezzola (2001) recommends the installation of structures with exactly this limited cross sectional area upstream these bridges. He proposes to construct a series of left-right shifted steel frames with this limited discharge cross section over half of the stream bed width to force the blockings at these structures. The woody debris can be retained in a controlled way and the critical structures will not get blocked.

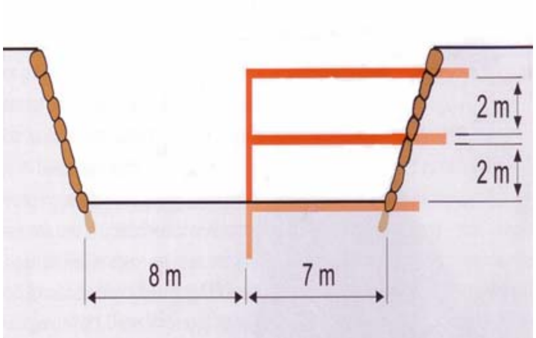

Figure 46: Steel frames for selective retention of woody debris upstream of critical (limited) cross sections (Bezzola, 2001)

Figure 47: Arrangement of steel frames for selective retention of woody debris upstream of critical (limited) cross sections in the model experiment (Bezzola, 2001)

Materials

- Steel
- Reinforced concrete
- Concrete

Software available
Unknown, no software available.

Photo gallery

Figure 48: Woody debris rake; spillway on the right hand side if rake is blocked (IAN-BOKU, 2006)

Figure 49: Woody debris rake (IAN-BOKU, 2002)

Figure 50: V-shaped woody debris rake (IAN-BOKU, 2002)

3.1.5 Permanent debris deposition

3.1.5.1 Open Check dam

Description and purpose
A check dam is a structure placed transversally to the torrent, from one bank to the other and presenting openings for draining the deposition area. It aims at controlling the solid discharge by retaining transported solids. This type of check dam can be used as a outlet structure of a permanent deposition basin, which means that the backfill increases progressively up to the top of the dam by alluvial accumulation.

Check dams usually are designed with several openings between two wings, a strong foundation and a weir and are mainly free standing structures.

Due to the limited cross section offered to the discharge, the flow velocity is reduced upstream the dam. Moreover, the size of the openings through the check dam is designed to retain solids. The transported particles are stopped progressively, large ones first being stopped by the openings, which, in turn, stop smaller ones.

Specific design criteria
The functional design first takes into consideration the openings. The dimension of the openings must be small enough to stop at least the biggest particles and large enough to allow the water flow. The dimensions and quantity of openings depends on the peak discharge and the size of the solids to retained.
At the beginning of its service life, the dam can be considered as an open check dam for temporary deposition. Once the retention basin is filled, the dam can be considered as a closed check dam.

Materials

- Blocks (gravity),
- Concrete and mortar
- Reinforced concrete
- Steel
- Wood
- Gabions and wire netting

Check dams are mainly made of concrete, steel (section or reinforcement) and rock. Gabions, wire nettings, geo textiles and timber may also be used for part or whole structure.
The weir is generally protected from abrasion using a specific material (steel section, granite or steel section mainly)
All these materials are exposed to abrasion, oxidation and site specific ageing effects (moisture, freeze/thaw cycles..). In some cases the torrential chemical water quality may affect the dam.

Software available
Both geotechnical and hydraulic designs are specific to torrents. Common available software is not appropriate for their design and specialized tools are necessary. In France, some automatic design tools are used.

BARTO – Design of gravity and free standing check dams. 2006. Developed by Cemagref and property of ONF-RTM. (in French)

Photo gallery

Figure 51: A 12 meters high open check dam, just after construction (Cemagref)

Figure 52: Small open check dam totally backfilled (Cemagref)

Figure 53: Small open check dam partly backfilled (Cemagref)

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3.1.5.2 Deposition basin

DEBRIS FLOW CONTROL STRUCTURES ON DEBRIS FANS

The type of debris flow control structure that is used on a debris fan must be site specifically adapted to the character of the canalized debris flow, the character of the debris fan and the purpose of the mitigation. Sometimes, several different types of debris flow control structures are used in conjunction with one another.
In general, debris flow control structures can be divided into two basic types: open and closed ones. Open control structures are designed primarily to *constrain* the flow of a canalized debris flow; closed control structures are designed primarily to *contain* a canalized debris flow. Sediment control structures, are often associated with both open and closed debris flow control structures.

OPEN DEBRIS-FLOW CONTROL STRUCTURES

Open debris flow control structures include:

- unconfined deposition areas
- impediments to flow (baffles)
- check dams
- lateral walls
- deflection walls
- terminal walls or barriers

Unconfined deposition areas, located on the debris fan, are designed and prepared to retain a portion or all of the debris flow material from a canalized debris flow. To encourage the coarse-grained solids to deposit, the gradient of the fan is reduced or the debris is allowed to spread out and lose its confinement).

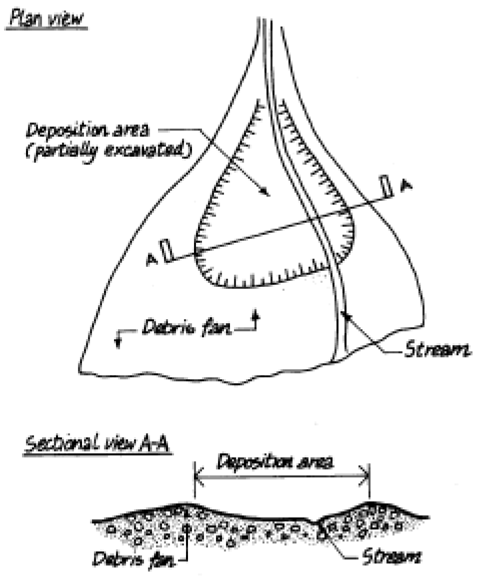


Figure 54: Plan and sectional view of an unconfined deposition area

Design considerations include the design magnitude or volume of the debris flow; the likely flow paths, including length to width ratio of the flow on the fan; the potential run out distance (see Rickenmann (2005) for details) and the probable storage angle.
This method of debris control is best suited to larger debris fans that have relatively low gradients and only few artificial structures. The geometry and morphology of the debris fan can be used to optimize the location of the area.
An excavated, or partially excavated, deposition area can be prepared and shaped to further decrease the gradient and thereby decrease the potential run out distance and increase the potential storage volume. This form of control can be accompanied by some form of flow impediment within the deposition area or by a terminal berm or barrier at the downstream end. Some methods of canalizing the fine-grained

sediment and water from the debris flow, and from subsequent stream flows downstream of the area, may be required. After a debris flow has occurred, the coarse-grained debris that has been retained in the deposition area must be cleaned out in preparation for subsequent flows.

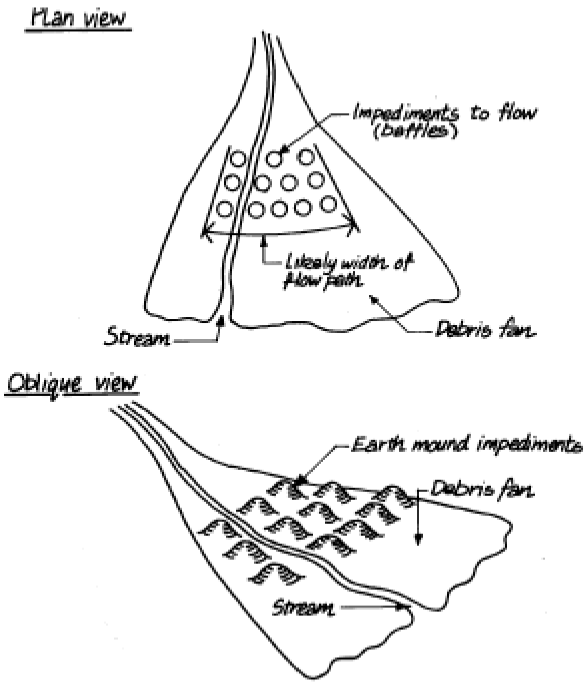


Figure 55: Plan and oblique view of impediments to flow (baffles)

Impediments to flow, or baffles, are used primarily to slow down a debris flow and thereby encourage it to deposit. In some instances they are used to deflect the flow.
Impediments can be either natural or artificial. When trees are used, they have been referred to as “debris flow dispersing forest zones”.
Artificial impediments can be constructed of earth berms, timber, or steel, and function in more or less the same way as snow avalanche retarding structures. They can be placed as single units, in lines or staggered. Although they can be used as independent structures, they are more commonly used in combination with other forms of control, often unconfined deposition areas. Impediments to flow should not be confused with debris-straining structures (discussed below).
Design considerations include the design magnitude or volume of the debris flow, the flow path, the potential runout distance and impact forces. Although they are often designed to be sacrificial and replaced or rebuilt after use, they should be designed in such a manner, that they can not be entrained by the masses of the debris flow.

Deflection walls are similar to lateral berms in the way that they are usually built immediately down slope from the apex of the debris fan, and parallel to the desired path of the debris flow whose lateral movement they are used to constrain. They differ from lateral walls or berms in a manner that they deflect the flow path and prevent it from going straight. They can be used to protect a structure, deflect the flow to another area of the fan or increase the length of the flow path, thereby decreasing the overall gradient and encouraging deposition. Walls are usually constructed of reinforced concrete, berms are usually constructed from local materials, but it can be a composite.
As for lateral walls or berms, the main design consideration for deflection structures is the maximum discharge and flow depth of the debris flow past the location of the structure. In addition, because of the curvature of the stream, potential impact forces, run-up and super elevation must be considered. To take these into account, the front face of the structure is designed for stability and with an appropriate slope and height. The freeboard heights discussed for lateral walls or berms can be used as well, but an additional height for super elevation is required. Some form of erosion protection or armoring must also be included in the design of these structures to minimize the addition of material from the structure to the debris flow mass.

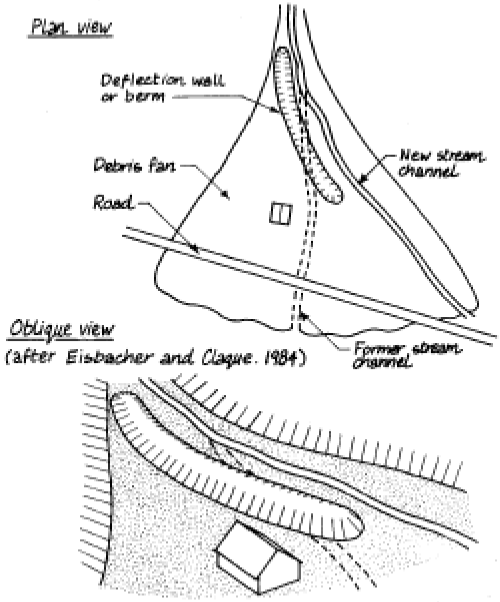


Figure 56: Plan and oblique view of deflection wall or berm.

Where deposition is encouraged, the flow path of the fine-grained sediment, water from the debris flow, and subsequent water flows must be considered. If deposition does occur, the coarse-grained debris must be removed from the stream channel.

Terminal walls, berms, or barriers are constructed across the path of a debris flow to encourage deposition by presenting a physical obstruction to flow. They do this by increasing the length of the flow path. They are built with a finite length so that normal water flows and fine-grained sediment and water from the debris flow can find their way around either end of the berm. Once a debris flow has been deposited upstream of a terminal structure, the coarse-grained debris must be removed from the area.
Design considerations include the design magnitude or volume of the debris flow, the likely flow paths, potential run out distance, impact forces, run-up, and probable storage angle.
Terminal walls, berms, or barriers are usually located as far as possible downstream from the apex of the fan to maximize the run out distance and deposition area, and to minimize the impact forces and run-up. These structures are often built with a deposition area or partial deposition area upstream. The excavated deposition area artificially lowers the gradient, increases storage capacity, and decreases run out distances, impact forces, and run-up.
Terminal structures have usually been constructed as massive gravity earth structures, so as to withstand the impact forces and the external forces of sliding and overturning. Impact forces and run-up can be reduced by decreasing the slope angle of the front face and by installing a sand cushion in front of the structure. For smaller magnitude debris flows, terminal walls, built as concrete walls, soldier pile walls, and soil and rock gravity walls, including gabions, can be used.

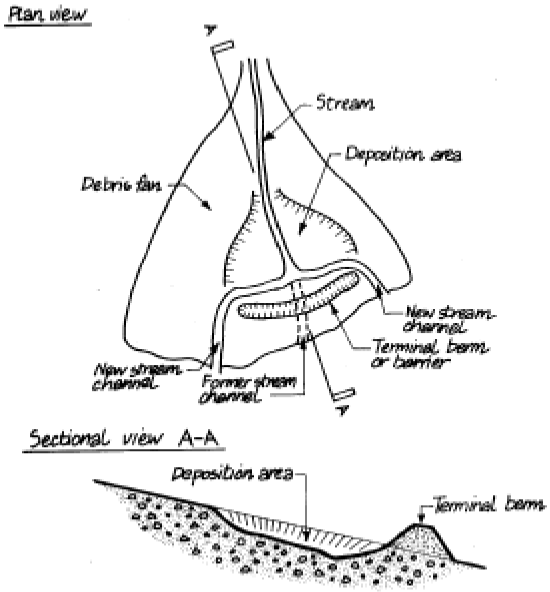


Figure 57: Plan and section of a terminal berm or barrier.

CLOSED DEBRIS FLOW CONTROL STRUCTURES

Examples of closed control structures include:

- debris racks, slit dams, or some other form of debris-straining structure located in the channel
- debris barriers and storage basins with some form of debris-straining structure incorporated into the barrier

Debris racks, slit dams, or other forms of debris-straining structures are used to separate the coarse-grained debris from the fine-grained debris and water of the debris flow, thus encouraging the coarse-grained portion to be deposited.

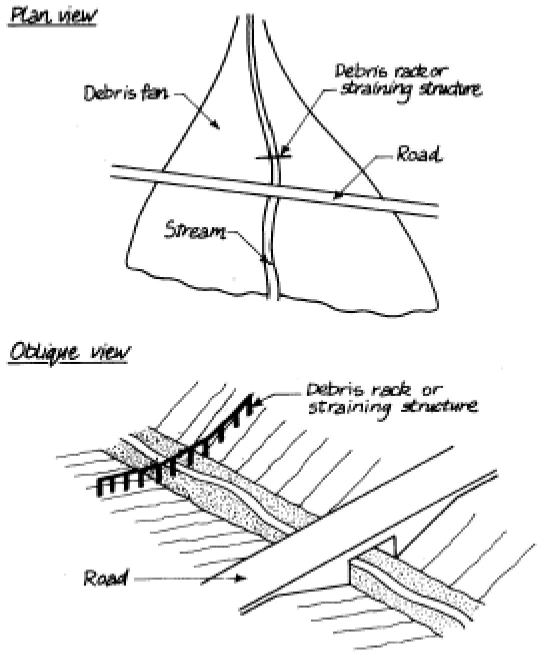


Figure 58: Plan and oblique view of a debris rack or straining structure.

Often used to prevent culvert openings and bridge clearances from becoming blocked with debris, debris racks are also often used as an integral component of debris barriers. To remain effective, the coarse grained debris must be removed from behind the straining structure on a regular basis.

Design considerations include the design magnitude or volume of the debris flow, the likely flow path so that the debris flow remains in the channel until it reaches the structure, the size and gradation of the debris, potential impact forces, and probable storage angle.
When located within a stream channel (with its storage volume constraints), this system of control is limited to small volumes of debris. Debris-straining structures located within a channel must be designed to allow the normal water flows and stream bedload to pass at all times, and should redirect fine-grained sediment flows and water from the debris mass back into the channel after the coarse-grained debris has been stopped. For this purpose, a weir is often incorporated into the design of the straining structure.
As a rule of thumb, Austrian practitioners design the slit interval at about 3 times the maximum diameter of the boulders.

Debris racks can be constructed of a wide variety of materials:

- railroad rails
- structural steel sections, such as I-beams
- timbers
- pre-cast concrete beams
- cables
- culvert pipes
- fencing materials

Zollinger (1985) found that when the structural elements were placed vertically rather than horizontally, inorganic coarse-grained debris jammed more easily. Organic debris was found to jam more easily with structural members placed horizontally rather than vertically. Numerous examples of debris-straining structures are included in Hübl & Fiebiger (2005).

Figure 59: Example of debris rack with horizontal steel beams, used as impediment to the flow, inside a retention basin

Debris barriers and storage basins, with some form of debris-straining structure incorporated into the barrier, are also referred to as retention basins.
This system of debris flow control is similar to that achieved by a terminal berm or barrier, in that both are located across the debris flow path and designed to encourage deposition. Unlike terminal berms or barriers, however, debris barriers are designed as a closed barrier, or "dam" so that all the coarse-grained debris is contained within the storage basin located upslope of the barrier. The debris-straining structure

must be designed so that during normal conditions, stream water and bedload can travel through the structure and, after a debris flow, the water that was in the flow and some of the fine-grained sediment can run off.
As for a terminal berm or barrier, the area upstream of the debris barrier can be excavated to reduce the gradient and to increase storage capacity. Depending on the site, an inlet structure may be constructed upstream of the storage basin to minimize erosion of the streambed. Different types of impediments (stacks, teeth, racks…) can also be used inside the basin to optimize lateral spreading of the flow, deposition, and energy dissipation. After a debris flow has occurred, the coarse-grained debris trapped behind the debris barrier must be removed.

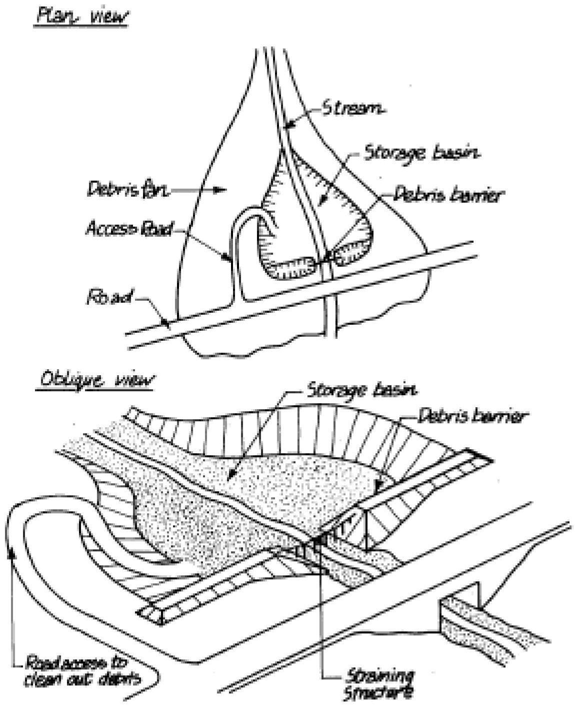


Figure 60: Plan and oblique view of typical components of a debris barrier and storage basin

This form of debris flow control is generally considered to be the most sophisticated and generally the most costly. Design considerations include design magnitude or volume of a debris flow, size and gradation of the coarse-grained debris (pertinent to designing the straining structure), potential run out distance, impact forces, run-up and probable storage angle. Properly located, designed, and constructed, a debris barrier and storage basin, with an appropriate form of debris-straining structure incorporated into the barrier, is probably the most positive form of debris flow control. As well, this form of control structure is best suited to a larger debris fan with a relatively low gradient. The geometry and morphology of the debris fan can be used to optimize design and minimize construction costs.
Most of the storage basins have been built as variations of earth berms or earth dams. Concrete and reinforced concrete gravity and arch-dam type structures have also been used. Unlike traditionally designed water-retaining structures, debris barriers are usually designed with the curve downstream to maximize the volume of debris storage. It is better to incorporate a weir or spillway into the structure to allow debris, fine-grained sediment, and water to safely overtop the structure should the storage basin be filled when a subsequent debris flow occurs. Other design considerations include external forces such as sliding, overturning uplift, and foundation and abutment loadings.

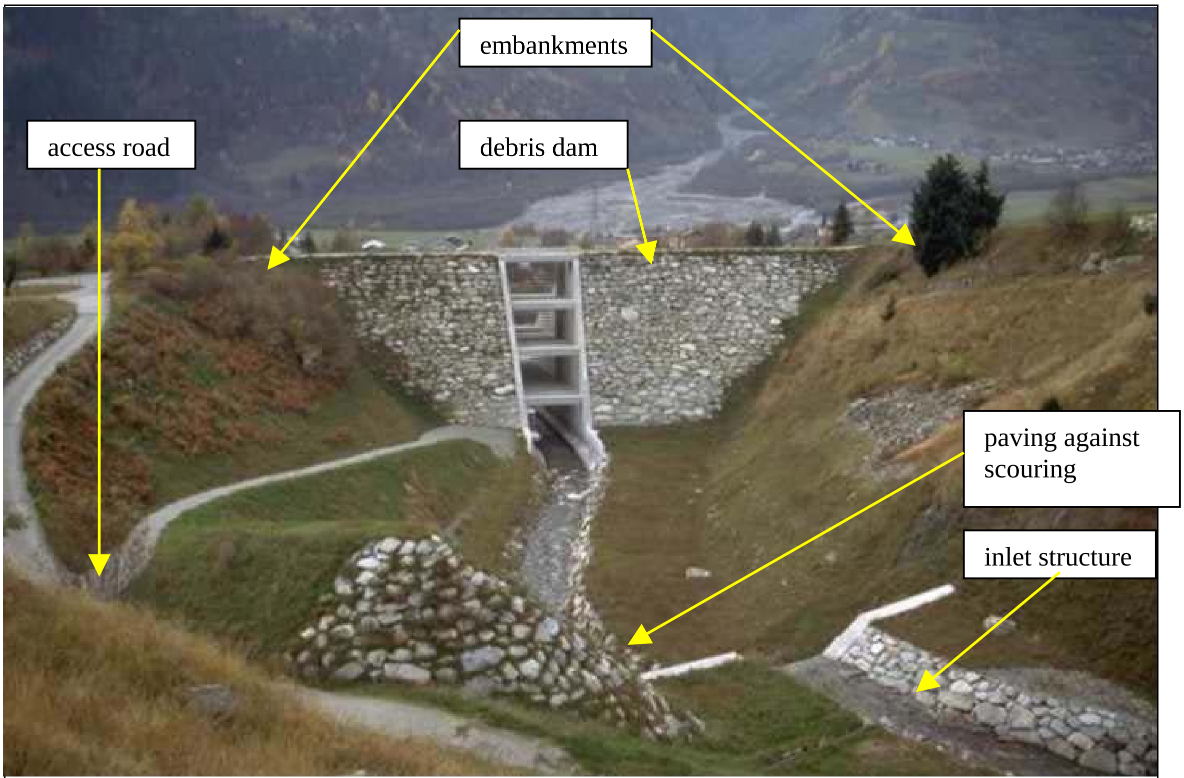


Figure 61: overview from upstream of a retention basin

To avoid erosion of the channel downstream of the retention basin, it is interesting to facilitate self-cleaning. This is possible when the outlet structure presents a slit down to the basin bottom and the downstream channel can receive the solid transport without damage.
Self-cleaning requires the following conditions:

- adequate water flow compared to the debris volume
- the deposited masses present a large fraction of fine but non-cohesive material
- retention basin is narrow and with a steep slope
- absence (or removal) of woody debris blocking the exit

Self-cleaning is difficult to achieve. However, experience showed a self-cleaning efficiency of 30 to 60%. Most of the time, artificial cleaning is required and is costly.

Shape of the retention basin

- angular shapes are not convenient because corners are not adapted to water and sediment flows
- extremely long or wide shapes do not optimize the sediment storage
- shape can be optimized for sediment retention or self-cleaning but it is difficult to achieve both objectives at the same time
- when self-cleaning is privileged, the pear-shape with the narrow extremity upstream will be preferred
- when sediment storage is privileged, the longitudinal slope of the retention basin has to be designed as low as possible, the deposition slope of debris flows being generally more difficult to assess and more gentle than the one for bed-load transport.

Below, one can find a selection of methods of volume assessment. Given the large uncertainty associated to each of them, it is better to combine the results of these approaches:

- assessment of erosion rate
- assessment on the basis of the alluvial fan volume
- historical data on floods
- assessment of volumes of debris flow prone areas of the basin
- empirical formula based upon global geomorphic parameters

As self-cleaning usually is limited, scouring very often takes place in the channel downstream the retention basin. It is therefore necessary to protect this channel by the use of check dams, lateral walls or armoring of the channel bed.

Sediment control structures are used by themselves or in combination with debris control structures to control the movement of fine-grained material across a debris fan or alluvial fan, thereby minimizing the amount of fine-grained sediment entering a neighboring body of water. In general, their design can be divided into two types:

- energy dissipation or settling basins
- sediment control fences constructed of natural or artificial materials

The location of sediment control structures is very important. Located too close to the apex of the debris fan, they are subject to a large volume of coarse-grained debris and large impact forces. When located at the distal end of a debris fan or on the alluvial fan, they must face the possibility of an avulsion of the stream channel and flow path farther up the fan, which might result in the structure being bypassed.

3.1.6 Temporary debris deposition – Open check dam

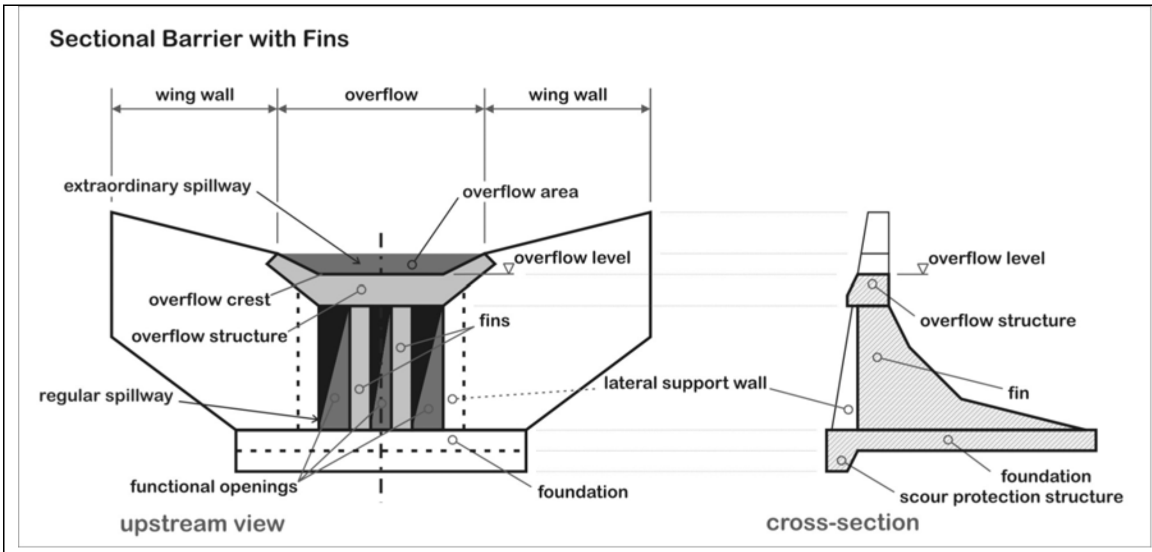


Figure 62: Functional elements of an open check dam

Description and purpose

Apparent problems with debris retention dams and the problems caused by bedload deficit downstream of these structures (erosion) initiated attempts to manage the bedload transport with temporary sediment deposition. The idea behind is to let the smaller grain sizes pass through and retain the larger ones to cut the peaks of discharge. With the abating flood discharge, this material will be washed out of the retention basin again and keeps the sediment balance stable.

During the 1970s, the concepts of "sorting" and "dosing" were established. Both concepts are based on a well dimensioned retention area, which is able to retain the full volume of bedload transport. Sediment sorting means particle segregation by grain size to allow only a given grain size to pass the structure. Dosing means the unsorted sedimentation by creating backwater at the structure. In both cases, sediment transport is only influenced by the occurrence of an event (Hübl & Fiebiger, 2005). As the woody debris usually causes a clogging of the drains, the self emptying of the retention area with the tail water does not work sufficient, so an artificial cleaning is necessary.

In modern debris flow mitigation, debris check dams are located downstream of debris flow breakers, followed by an array of check dams for stabilizing the channel. This concept can be described as a "functional chain" or a "torrential training system" (Kettl, 1984).

Specific design criteria

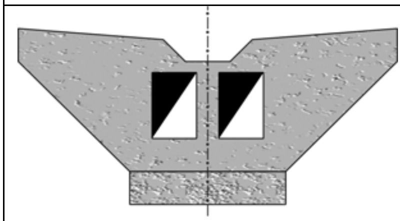
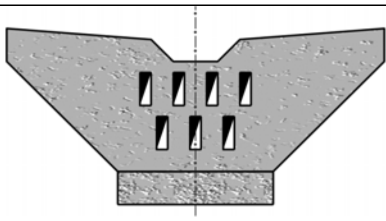
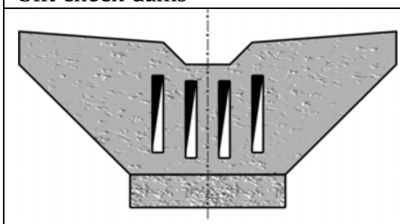
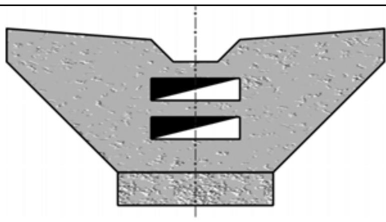
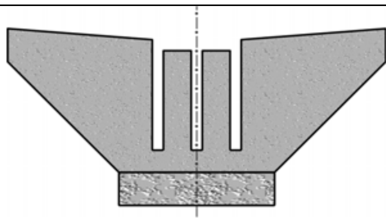
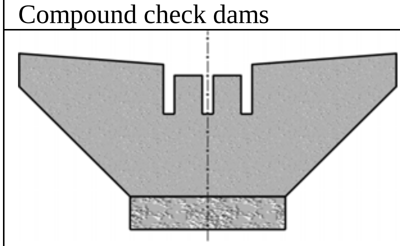
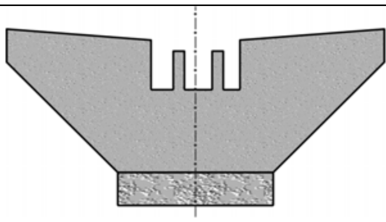
Within the last 30 years the open structures developed from closed check dams to those with small slots for draining, further those with large slots up to those with slits or compound and sectional check dams.

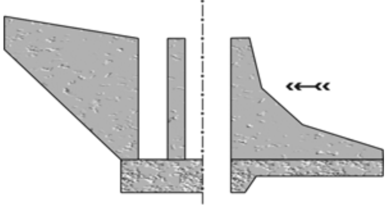
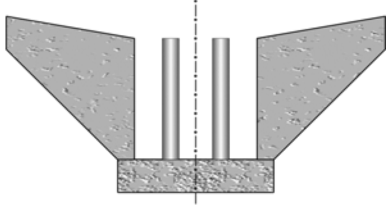
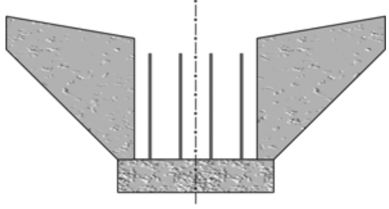
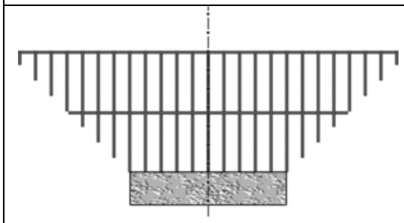
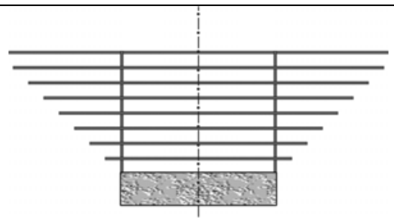
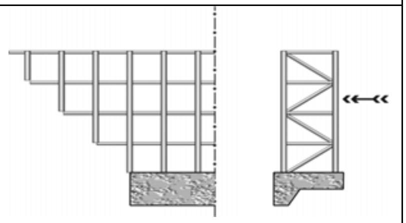
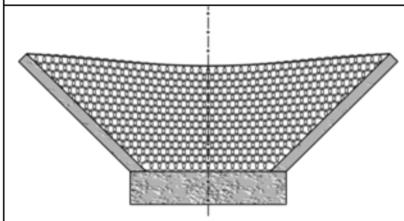
Figure 63: Classical closed check dam (IAN-BOKU)

Figure 64: Small slot check dam (IAN-BOKU, 2002)

 **Figure 65: Large slot check dam (IAN-BOKU, 2002)**	 **Figure 66: Slit beam check dam with clogging(IAN-BOKU, 2002)**

This development was based on experiences, so numerous types of open check dams exist today:

Slot check dams		
 Large slot check dam	 Small slot check dam	
Slit check dams		
 Slit check dam with vertical slits	 Slit check dam with horizontal slits	 Gap-crested slit check dam with vertical slits
Compound check dams		
 Compound check dam with openings	 Compound check dam with teeth	
Sectional check dams		

 Sectional check dam with fins	 Sectional check dam with piles	 Sectional check dam with braces
Lattice check dams		
 Rake check dam	 Beam check dam	 Frame check dam
Net barriers		
 Net check dam		

When designing an open check dam, the following considerations ought to be made (Hübl & Fiebiger, 2005):

- Assure sufficient drain width
- Drainage must reach the stream bed to permit automatic sediment transport under regular conditions
- Maintenance of a minimum discharge channel to assure survival of aquatic fauna
- Prevent clogging by woody debris by using a debris rake (see chapter 3.1.4)
- Determine variable beam-, rake- or grill widths for efficient debris flow retention
- Protection of wing walls by riprap or earth fill
- Maintenance access has to be located against the flow direction and should have variable elevations
- Small narrow basins with high gradient have higher self emptying potential

Different types of open check dams can fulfill different functions.

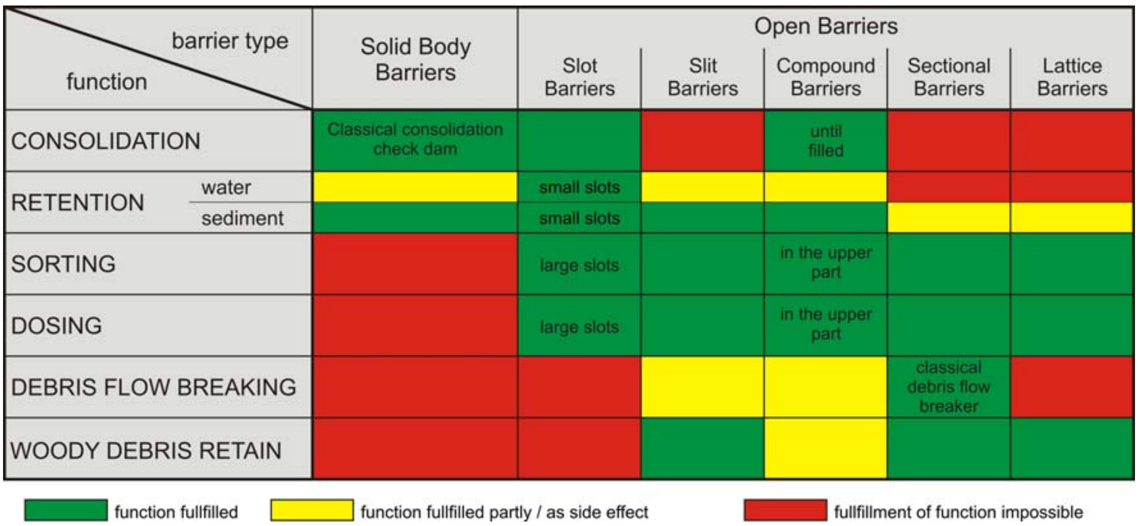


Figure 67: Functional design types of open check dams

Transverse elements of rakes and vertical rakes tend to encourage clogging. So inclined buckled rakes were developed to avoid clogging by organic material. The concept bases on the fact, that the woody debris will swim on the increasing water surface and slides up the inclined rake. Below the water surface with its woody debris layer, the sediment transport is not interfered.
Krimplstätter (1998) recommends the use of supporting lamella (discs), so in the first, almost horizontal field there is no need of transverse elements. Further, the effect of rinsing is increased by discharge concentration between the lamellas. Disadvantage of these lamellas are their high costs and the fact, that a future variation of the distance in between them is not possible. An alternative is the use of round beams, which allows different distances in different fields of the rake.

Figure 68: Rake is supported by lamellas and one round beam (KRIMPELSTÄTTER, 1998)

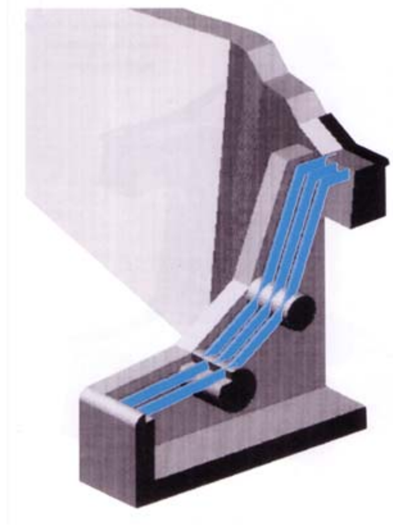


Figure 69: Rake is supported by round beams, which allows a variable rake width (KRIMPEL-STÄTTER, 1998)

Experience showed, that a twice buckled rake with inclinations of 1:10 – 2:3 – 5:2 and a horizontal section as upper termination works best (Skolaut, 1998). The more the buckles of the rake approximate a circle, the better the woody debris will swim up (Bitterlich, 1998).
If there is a horizontal element with a length of about 2 to 3 m as an upper termination, there is no danger of overtopping the structure.

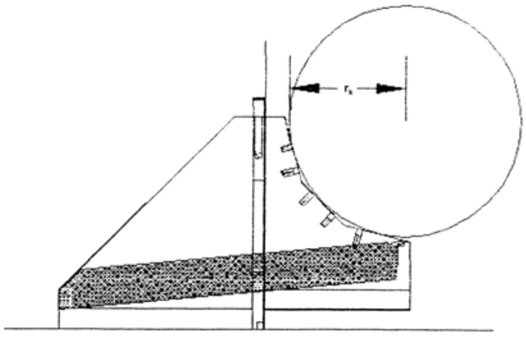


Figure 70: Twice buckled rake as approximation to a circle (HÜBL & MAYERL, 1996)

Materials

- Reinforced concrete
- Steel for the rakes
- Steel plates for hard facing to avoid abrasion

- Granite plates for the spillway

Software available
Unknown, no software available.

Photo gallery

Figure 71: Sectional beam check dam with fins (IAN-BOKU, 2002)

Figure 72: Sectional check dam with fins (IAN-BOKU, 2002)

Figure 73: Slit check dam with vertical slit (IAN-BOKU)

Figure 74: Compound check dam with teeth (IAN-BOKU)

Figure 75: Frame check dam (IAN-BOKU)

Figure 76: Gap-crested slit check dam with vertical slits (IAN-BOKU)

3.1.7 Protection and deflection walls / dams

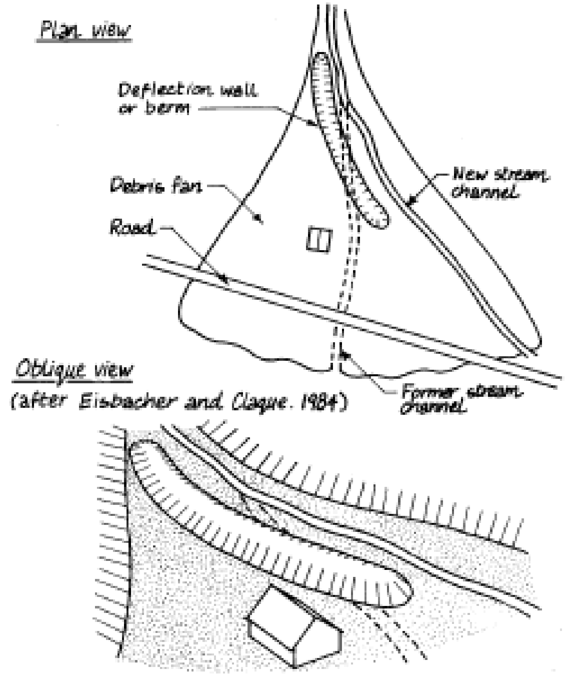


Figure 77: Plan and oblique view of deflection wall or berm.

Description and purpose
Deflection structures are installed to redirect debris flows away from high endangered areas towards areas with low vulnerability. In a series of protection measures, deflection structures usually are situated as last chain link at the fan to diminish any remaining risk.
Commonly used deflection structures are dams, walls, dikes but also groynes and usually constructed of concrete, reinforced concrete, boulder revetments and gabions.

Deflection walls are similar to lateral berms in the way that they are usually built immediately down slope from the apex of the debris fan, and parallel to the desired path of the debris flow whose lateral movement they are used to constrain. They differ from lateral walls or berms in that they deflect the flow path and prevent it from going straight. They can be used to protect a structure, deflect the flow to another area of the fan, or increase the length of the flow path, thereby decreasing the overall gradient and encouraging deposition.
Walls are usually constructed of reinforced concrete; berms are usually constructed from local materials, but can be a composite.
As for lateral walls or berms, the main design consideration for deflection structures is the maximum discharge and flow depth of the debris flow past the location of the structure. In addition, because of the curvature of the stream, potential impact forces, run-up and super elevation must be considered. To take these into account, the front face of the structure is designed for stability and with an appropriate slope and height. The freeboard heights discussed for lateral walls or berms can be used as well, but an additional height for super elevation is required. Some form of erosion protection or armoring must also be included in the design of these structures to minimize the addition of material from the structure to the debris flow mass.
Where deposition is encouraged, the likely flow path of the fine-grained sediment, water from the debris flow, and subsequent water flows must be considered. If deposition does occur, the coarse-grained debris must be removed from the stream channel.

These works can have problems about bend super elevation, dynamic impact of the debris flow in the normal direction to the wall and tangent stress transmit by debris flow in the parallel direction to the wall.

Materials

- Concrete
- Reinforced concrete
- boulder revetments
- gabions
- local materials (berms)

Software available

Unknown, no software available.

Photo gallery

Figure 78: Deflection dam in combination with series of drop structures (die.wildbach, 1989)

Figure 79: Deflection dam (IAN-BOKU, 2003)

3.1.8 Discharge control – Transport channel

Description and purpose
Transport channels are generally installed on the alluvial fans of torrents, to ensure the correct transit of torrential floods across urbanized zones. They are canalized reaches, more or less consolidated to limit erosion of the banks or of the bed . A crucial point is the size of their cross section, which will determine their hydraulic capacity (depending on the slope and nature of the flow). They are often built between sediment traps upstream and the confluence with the main river downstream.

The main purpose of transport channel is to ensure the flowing of a given discharge without flooding or divagations in the surrounding zones. A secondary purpose is to avoid excessive erosion in that calibrated reach, especially in the case that the transport channel is built downstream of a sediment trap that will catch the main part of the sediment load and deliver "clear" erosive water. They are "passive" countermeasures in the sense that their purpose is not to reduce the flow but to limit the possible negative effect of the flows on exposed areas.

Specific design criteria
The main aspect for the design of transport channels is to ensure some hydraulic capacity corresponding to the nature of the flow and the expected level of protection. When they are built downstream of a sediment trap, they are mainly concerned by water flows, eventually transporting sediments by suspension and/or bedload transport. If there is no sediment trap upstream or if the capacity of this is limited, it is necessary to consider the eventuality of debris flow transit in the channel.

Basically, a transport channel is a channel offering a certain cross section to the liquid flow. Depending on the situation, this section can be obtained digging on the natural soil or by constructing lateral dykes. Lateral banks of the channel are often to be consolidated to resist erosion, by the use of rip-rap, gabions, and masonry or concrete walls. The protection against erosion is particularly necessary downstream of retention basins. Indeed, in this case, the flow has a high erosion potential, as it is free of transported sediments.
Different techniques are employed to limit the effect of erosion on the river bed. The most frequent consists in building series of weirs regularly spaced that fix the global longitudinal bed profile. However, erosion can occur in the reaches between the weirs.
Bed erosion control can also be achieved covering the torrential bed with rip-rap, masonry or concrete apron.

Materials
- Banks
  - natural soil
  - rip-rap
  - gabions
  - masonry
  - concrete walls
- Torrent bed
  - natural soil
- Weirs
  - rip-rap
  - masonry
  - reinforced concrete

Software available
Unknown, no software available.

Photo gallery

Figure 80: Rio San Julian –Caraballeda (Vargas - Venezuela) – sills and banks toe protection in reinforced concrete

Figure 81: Gran Valle Torrent –Saint-Vincent (Val d'Aoste – Italy) – Bank protection made of masonry

Figure 82: Bossons torrent – Les Houches (Haute-Savoie - France) – Partial protection of the left bank with reinforced concrete.

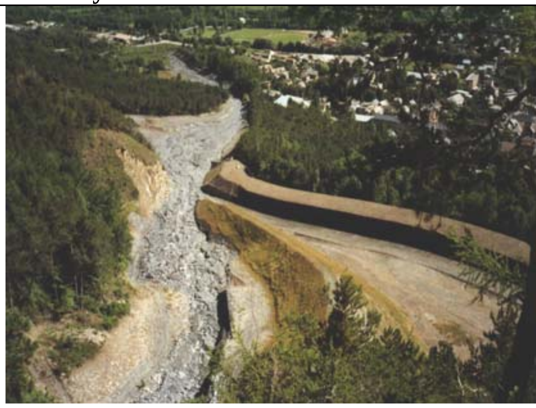


Figure 83: Saint-Antoine torrent –Bourg-d'Oisans (Isère - France) – left bank damming (and rockfall protection dyke in the rear)

3.1.9 Afforestation

Berm

Plate- or stepberm
Layer- or plowberm

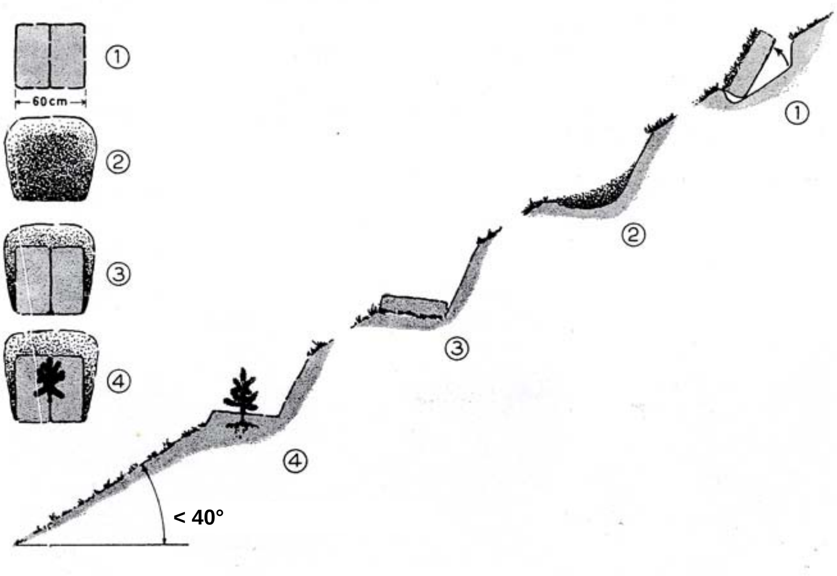


Figure 84: Details of constructing plate-berms

Description and purpose
Berm means a small horizontal area on steep slopes which serves as a basis for afforestation measures in alpine regions. As described in the picture above the seedling is planted nearby the center of this horizontal terrace.

Due to reduced friction forces between the different layers of the ground one often can observe mass movements at steep slopes in mountain areas. Furthermore, there is an additional phenomenon that can be observed on such slopes which is known as creeping. Both, sliding and creeping can be reduced by stabilizing the masses with afforestation by bushes and trees, whose roots consolidate the single layers of the ground. This goal can be achieved by digging horizontal terraces (berm), which provide better conditions for seedlings and other afforestation measures.
This measure is an additional action in the frame work of technical counter measures in order to develop a healthy forest and provide optimal natural hazard safety for alpine regions.
A horizontal area on steep and smooth slopes reduces the load of sliding snow masses on seedlings. In this way seedlings have a higher probability to reach a stable state in order to resist against biotic and abiotic factors.

Specific design criteria
Planting a seedling on a berm you have to take care to place it closer to its inner side than to the outer border of the horizontal area. Due to the stabilizing forces of the roots seedlings can ameliorate the position of the berm. The seedling should not be placed to close to the inner border of the horizontal area in order to avoid spilling of the small plants. The width of a berm varies between 70 and 80 cm, with a lateral distance of 1,0 to 1,5m.

When the seedling is planted, first of all one have to make a good choice considering the location. Adequate habitats are

- Areas with a short coverage of snow
- Locations close to a stump or lying trunks
- Ridges or small elevations

Inappropriate habitats are:

- Areas with a long lasting snow cover (mould)
- Depressions and holes
- Locations with a thick layer of duff
- Steep slopes with a sliding snow masses

Figure 85: Seedlings close to a stump

Figure 86: The high grass detains the growth of seedlings

The choice of the right origin of the seedlings is very important for the success of the afforestation measure. First of all the small plant has to be able grow up in high mountain areas near the timberline. Such seedlings can be larch (*Larix decidua*), Swiss Stone pine (*Pinus Cembra*) and spruce (*Picea Abies*). Further *Pinus sylvestris, Pinus mugo, Betulus pendula, Sorbus aucuparia, Acer pseudoplatanus* and *Abies alba* can be used for afforestation measures in alpine regions.

If it is not possible to make an adequate selection for the habitat one can use the ratio between the yearly precipitation and the altitude above sea level.

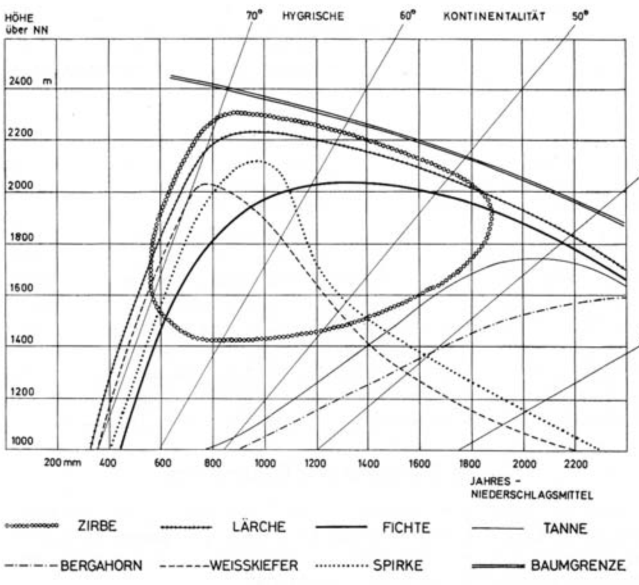


Figure 87: Choose the appropriate tree according to the precipitation and the location of the habitat

Zirbe = pinus cembra
Lärche = larix decidua
Fichte = picea abies
Tanne = abies alba
Bergahorn = acer pseudoplatanus
Weisskiefer = pinus sylvestris
Spirke = pinus mugo/rostrata

Baumgrenze = timber line

Höhe über NN = sea level

Jahresniederschlagsmittel = Mean annual precipitation

<u>Cluster afforestation</u>
Clusters are some individuals which are planted close together.

Figure 88: Cluster afforestation after 5-10 years. (from http://www.wsl.ch/forest/waldman/mfe/wasem/gebirgswaldverjuengung/rottenaufforstung2.ehtml)

Description and purpose
The cluster afforestation is carried out with a collective of seedlings with small lateral distances between them. The area between the clusters is free, without any afforestation measures.

The scope of the minor distance between the seedlings is to provide an optimal resistance against biotic and abiotic effects like snow pressure, wind, ice etc.
This measure is an additional action in the frame work of technical counter measures in order to develop a healthy forest and provide optimal natural hazard safety for alpine regions.

Compared to common afforestation measures with distances between seedlings of about 2 m, the cluster afforestation offers a better protection for the single individual. A main characteristic of the cluster afforestation is the vertical structure which can be found after 40 – 100 years. In this way the forest has an increased resistance against external effects like windfall or beetles.

Figure 89: Cluster afforestation after 40-80 years (from WLS.ch)

Figure 90: vertical structuring of cluster afforestation after 80-120 years (from WLS.ch)

3.2 Snow avalanches

3.2.1 Snow drift regulation

3.2.1.1 Snow fence

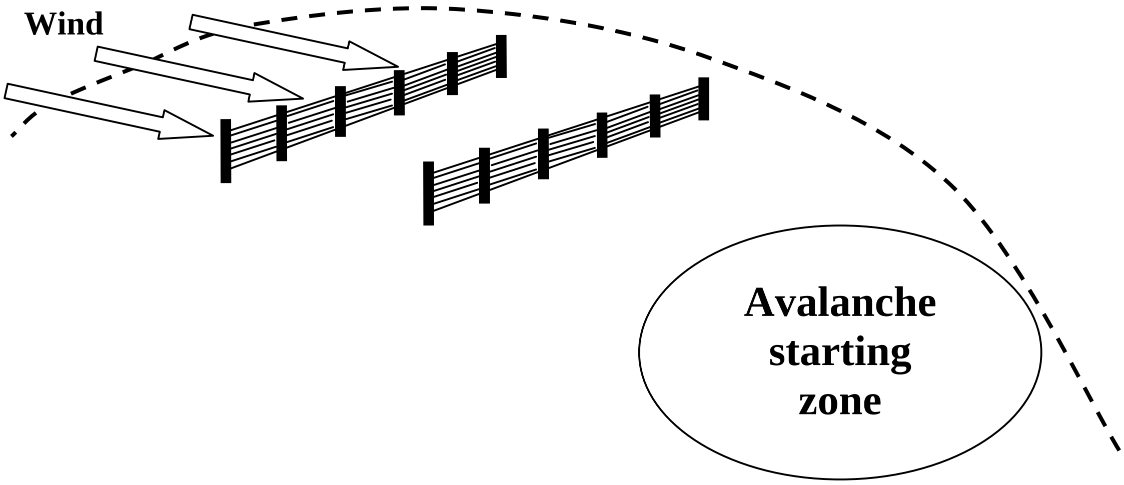
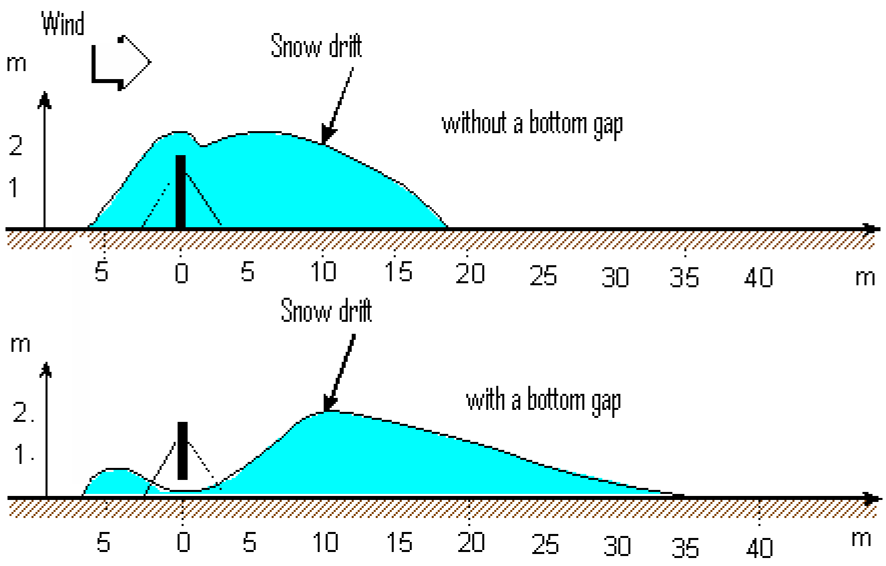


Figure 91: Snow fences

Description and purpose
A snow fence is a linear system that is designed to accumulate or hold snow at a certain location while acting on the wind flow. It consists of a panel and posts ensuring its anchorage in the ground.

Control of wind-transported snow to prevent avalanche formation in leeward zones.
A snow fence may be designed upstream of avalanche starting areas to limit cornices formation and to supplement snow supporting structures.
Note that snow fences are generally used to fight against snowdrifts formation on roads (“plateau” context). Here we only describe snow fences that are used in avalanche defense engineering (“high mountain” context).

Specific design criteria
- location: upstream of an avalanche release area
- collector fences are used on open windward slopes of low inclination (typically less than 15°). In steep terrain they are less effective
- typical mesh size: between 5 and 20 cm
- fence should consist of about 50% solid surface and 50% opening surface
- the distance from the ridgeline should be about 20 to 30 times the height *H* (*H* ranges generally from 3 to 4 meters)
- the fence should have a gap at base ranging from *0.15H* to *0.25H* where *H* is the height of the fence).



The main characteristics of a snow fence are the following ones:

- *Length*: the length is the distance between the two ends of the fence.
- *Porosity*: the porosity is defined as the percentage of the board's voids.
- *Bottom gap*: the bottom gap is the distance between the lower side of the board and the ground.
- *Height*: the fence height is the distance between the top of the fence and the ground (perpendicular to the ground).
- *Inclination*: the inclination is the angle (expressed in degrees from vertical direction) that the fence tilts upwind. This angle generally ranges from 0 to +15°, the sign "+" indicating that the inclination is in the wind direction.

Detailed design criteria and efficiency

- The *length* has to be sufficient in order to limit ends effects. It should reach at least 20 times the height of the fence.
- An increase up to 45-60% in the *porosity* of a fence lengthens the deposit, diminished its height and moves it away from the fence. Nevertheless, the increase has a general effect to raise the volume of the stored snow.
- The *bottom gap* produces wind acceleration at the bottom of the fence and leaves it clear. This voids the bottom of the fence being damaged by snow settlement, and also increases the intercepted snow volume. The bottom gap should be around 40 to 50 cm in mountainous areas (20 to 30 cm on a plateau). It is generally equal to 15 to 20% of the total fence height. Some kinds of fences have an adjustable bottom gap that can be increased when filled with snow.

The fence *height* determines the fence storage capacity that is the maximum snow quantity that the fence can accumulate.

Some kinds of fences can be made higher during the winter, which is very useful when snowdrifts have a tendency to reach the top of the fences at the end of the season (only along roads because maintenance is needed in this situation). The height ranges generally between 3 and 4 m in mountainous areas (whereas it ranges from 1 to 2 m on the roads)

- *Inclination*: the top of the fence can be inclined in the downwind direction up to 15° from vertical direction without affecting its performance adversely.

For optimal effectiveness:

- the fence should consist of about 50% solid surface and 50% opening surface
- fences should have a gap at base equal to *0.15-0.25H*, where *H* is the fence height
- the typical mesh size should be between 10 and 20 cm to avoid obstruction by rime ice

Location: collector fences are used on open windward slopes of low inclination (typically less than 15°). In steep terrain they are less effective. The main rules for location are the following ones:

- the storage capacity of a snow fence increases as the angle between the wind direction and the perpendicular axis to the fence decreases. Thus the snow fences should be orientated perpendicular to the prevailing wind direction. If the angle between the snow fence and the prevailing wind direction is higher than 45°, the snow stored by the barrier is negligible.
- the snow fences (porous and with a bottom gap) should be placed *25 H* away from the zone to be protected from snowdrift or from the next fence (where *H* is the fence height). When the amount of snow to be stored is high and therefore leads to the use of a fence higher than 4 meters, it is better to set up several fences. The value of *25 H* varies according to the characteristics of the fence and to the topography.
- fences should be as long as possible and without interruption. Furthermore, the base of the structure has to follow the slope line in order to make the bottom gap efficient.

Note that it is necessary to keep in mind that each site represents a specific case. The effectiveness of a snow fence depends on its location. It is therefore indispensable to have an accurate knowledge of how the site works in winter, acquired by local observations (main direction of the wind, typical value of the snow cover depth). These observations should continue after the structure has been set up to check that it has been correctly positioned. In fact, since the sites for the snow fences are marked out when there is no snow, the local topography may change when there is a snow deposit. That is the reason why it is important to be able to remove the snow fences easily, once that the project and the budget were drawn up. In a high mountain context, it is obviously very difficult (in comparison with a plateau context).

Materials
The first walls were made of stones but now they are mainly made of

- wood
- steel
- or aluminum

The choice of the material depends on the climatic conditions snow fences are exposed to. The easiness of maintenance is also important. Thus, steel and wood are mainly used in mountains (whereas synthetic materials can be used for temporary snow fences on plateaus or to manage the snow cover in ski resorts: these synthetic materials snow fences can be easily relocated).

Pressures due to wind exerted on snow fences can be calculated (see page 8 in *AFNOR Norme française NF P95-305 "Equipements de protection contre les avalanches : barrières à neige / spécifications de conception » 13 p.).*

Anchoring system solutions are described in *MEDD-DPPR / CEBTP Lyon / Cemagref Grenoble. 2004. Protection contre les risques naturels. Ancrages passifs en montagne : conception, réalisation, contrôle. Guide technique.*

Software available
Unknown, no software available.

Examples
A snow fence creates a disturbance in the wind flow, which decreases the local wind velocity. As a result a snow deposit appears mostly just behind the fence (a small deposit may also appear in front of the fence). Thus a snow deposit can be built at a chosen place according to the fence location. This counter-measure prevents snow from being transported elsewhere where it could be dangerous. The snow that is deposited in this way has a great cohesion. Therefore, it is very difficult for the wind to remove the snowdrift if the wind's direction changes.

Photo gallery

Figure 92: An example of a non porous snow fence without a bottom gap; the barrier is full with snow and the snowdrift exerts a pressure on the barrier (left side photo)

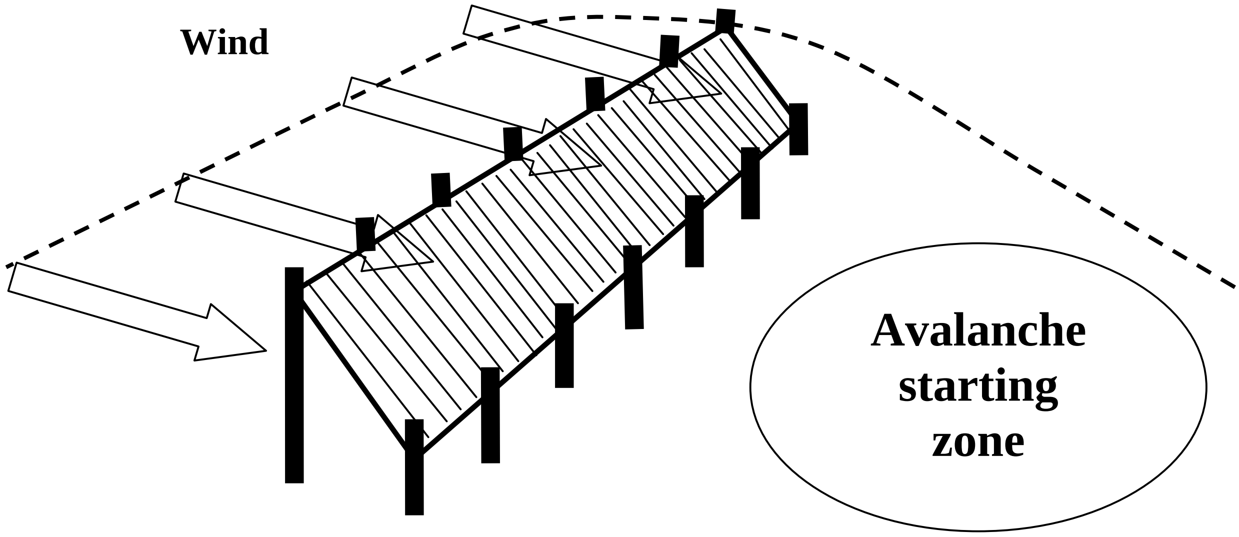
Figure 93: An example of a porous snow fence with a bottom gap; the barrier remains released from snow

Figure 94: Visualisation of the effects of the saltation layer near a snow fence in Le Chazelet (Alpes de Haute Provence, France)

Figure 95: Snow fence to prevent snow accumulation on the road. This image illustrates the base of the structure following the slope line. Col du Glandon (Savoie, France)

Figure 96: Snow fence to protect the road at Col du Lautaret (Alpes de Haute Provence, France)

3.2.1.2 Jet roof



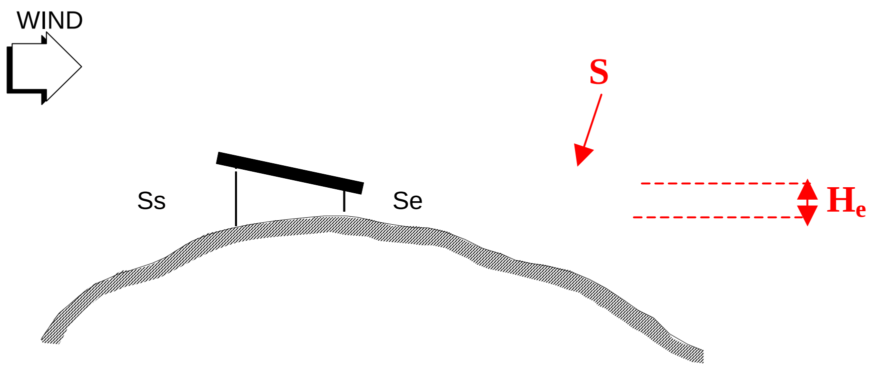
Description and purpose
A jet roof is a linear system used to prevent the formation of cornices and an undesirable accumulation of snow that appears immediately under the ridgelines. It consists of an inclined panel, held by several posts.

Control of wind-transported snow to prevent avalanche formation in leeward zones by removing cornices. Note that jet roofs have other applications, namely to protect buildings, ski lifts and roads. According to the principle of Venturi, a jet roof accelerates the wind: the wind coming out from the small opening under the inclined panel has a speed superior to the speed it had coming into the large opening. The result is a zone cleared from snow behind the jet roof but with a possible increase of snow accumulations in the starting zone! Jet roofs are often associated with downstream supporting structures to prevent avalanche formation.

Desk roofs can be also used to remove cornices. The purpose of such wind structures is identical to the purpose of jet roofs but they are differently designed.
A desk roof is a linear system, generally made of wood, which artificially prolongs the terrain preceding a ridge, a crest or a fall in slope. The desk roof is in contact with the ground on one side and is held by some posts on the other side.
Unlike the jet roof, a desk roof does not interfere with the wind but it prevents cornices formation by expanding the ground upstream of the drop in slope. The snow does not find any support at the end of the desk that is supported over the vacuum by posts.
Note that these structures are very rarely used (there is not special instruction about their technical characteristics and their efficiency is doubtful), that’s the reason why we chose not to describe in details this structure.

Specific design criteria
- location: avalanche starting zone
- the surface of a jet roof panel is equal to some square meters consisting of separate boards, inclined at about 40°
- the distance between the lower side of the panel and the ground, named the “small opening”, is about 1 m high
- a jet roof is usually made of wood

Characteristics:



Here we give the main characteristics of a jet roof:

- *Surface of a jet roof*: a jet roof panel has a surface (*S*) of some square meters consisting of separate boards, inclined at about 40°
- *Small opening*: the small opening (H_e) is the distance between the lower side of the panel and the ground. It is generally about 1 m.

Advantages: the jet roofs are the best efficient structures to fight against the formation of cornices.

Drawbacks: the cornice is often released out but the snow is transported further in the slope, which can increase the amount of snow in the starting zone! Therefore it's generally necessary to add, at least, a row of supporting structures to support downstream snow accumulations.

A jet roof should be placed on the ridgeline or at the top of a slope, before a cliff edge (or on the side of the zone to be protected, in case of snowdrifts on a road). This rule should take into account the local topography.

Its placement should take into account the wind direction since it uses the wind force. So the large opening would face the wind that would then flow out through the small opening.

Note that it's necessary to keep in mind that each site represents a specific case. The effectiveness of a jet roof depends on its location. It is therefore indispensable to have an accurate knowledge of how the site works in winter, acquired by local observations (main direction of the wind, typical value of the snow cover depth). These observations should continue after the structure has been set up to check that it has been correctly positioned. In fact, since the sites for the jet roofs are marked out when there is no snow, the local topography may change when there is a snow deposit. That is the reason why it is important to be able to remove the jet roofs easily, once that the project and the budget were drawn up.

Materials

- Jet roofs are generally made of wood (panel and posts).
- The posts are sometimes made of steel.

Anchoring system solutions are described in *MEDD-DPPR / CEBTP Lyon / Cemagref Grenoble. 2004. Protection contre les risques naturels. Ancrages passifs en montagne : conception, réalisation, contrôle. Guide technique.*

Software available

Unknown, no software available.

Examples

A jet roof is used to accelerate and deflect strong wind underneath. Thereby, deposition takes place away from the ridgeline (but in the avalanche staring zone).

Photo gallery

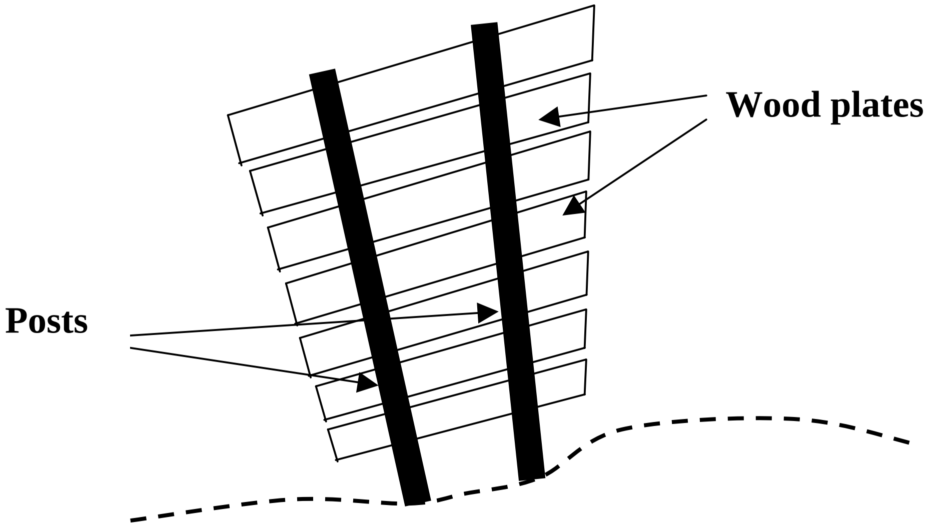
Figure 97: Jet roof associated with a downstream supporting structure (we can see a part of this supporting structure in the bottom right side corner). It illustrates the drawback of the method. The zone downstream of the jet roof is cleared from snow but snow accumulations are created further in the slope. Therefore, it's often necessary to associate some downstream supporting structures.

Figure 98: Small jet roofs in La Plagne (Savoie, France)

Figure 99: Jet roof in Le Chazelet (Hautes-Alpes, France)

Figure 100: Jet roof in Le Chazelet (Hautes-Alpes, France)

3.2.1.3 Wind baffle

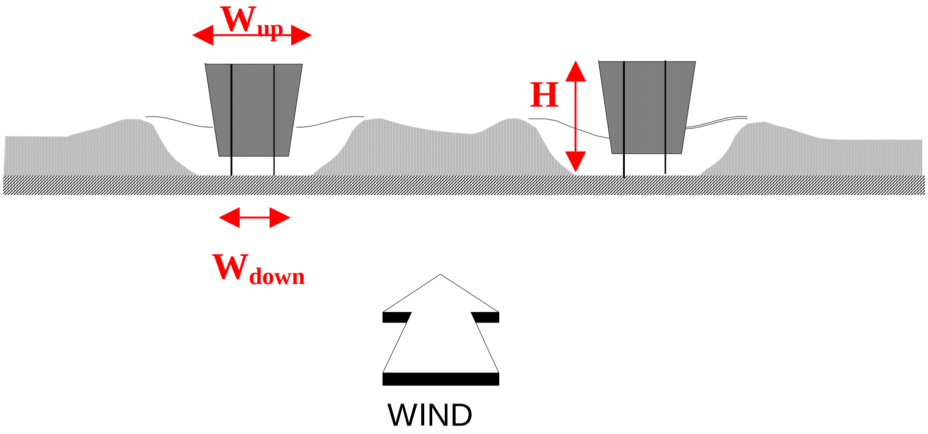


Description and purpose
A wind baffle is a discrete system consisting of one trapezoidal board held by one or two posts, and facing the prevailing wind direction. Cross-wind baffles are also used: they consist of two perpendicular boards that make their operation less dependent on the wind direction.

Control of wind-transported snow to prevent avalanche formation in leeward zones.
The wind baffle creates a disturbance in the wind stream which is accelerated in the vicinity of the wind baffle. Firstly the snow cannot settle around it and therefore prevents the creation of cornices. Secondly snow settling around the cleared zone acquires a great cohesion due to the modification in the snow crystals, creating a kind of crater. This crater constitutes a discontinuity and an anchoring for the surrounding snow cover and fights against the formation of great wind slabs.

Characteristics:
The wind baffles can have three purposes:

- *Stabilization of the slope*. In this case they are located under the drop in slope, inside the avalanche starting zone (case of Grimselboden in Switzerland where the wind baffles are located 20 m under the slope-line or Illhorn where they are located 60 m under the peak). The property of the wind baffle to modify locally the structure of the snow cover is used provided that the slope is not longitudinally too long; one "nails" the snow cover by the action of the snow cones or craters at the base of the wind-baffles. This system is rarely used and one does not have to use it to protect directly an inhabited zone located downstream. In the case of Grimselboden, this set-up was associated with downstream dams shortening the avalanche run-out.
- Wind baffles are more classically used to *prevent the formation of cornices* and more generally to avoid snow accumulations on supporting structures located downstream in the avalanche starting zone. In this case, the wind baffles are located at the top of the starting zone (examples: Mont-Gond and Mont-Cauille in Switzerland) so that the crater which form removes the appearance of cornices.
- A third way to use wind baffles is *to split the avalanche tracks into two* (case of Larche in France). In this case, the wind baffles are located on small transverse peaks that delimit the avalanche tracks between them. The wind baffles constitute a kind of discontinuity as a "prepunched" material. The possible release of one track will propagate until the transverse peak and will follow the weakness line without involving the close track.



- *Board shape*: a wind baffle has a trapezoidal shape turned up side down. It is therefore wider on the top than on the bottom.
- *Board Size*: the board is generally 1.5 m wide at the bottom (W_{down}) and 3 m wide at the top (W_{up}).
- *Height*: the height *H* of a wind baffle is often about 3 or 3.5 m.
- *Porosity*: the porosity is defined as the percentage of the board's voids.
- *Bottom gap*: the bottom gap is the distance between the lower side of the board and the ground.

Specific design criteria

- location: avalanche starting zone
- the larger the wind baffle is, the larger and longer the zone of influence is (the height *H* of a wind baffle is typically about 3 or 3.5 m)
- an increase of the porosity and of the bottom gap up to a certain limit seems to increase the area of the snow cover submitted to the effect of the wind

- The height *H* of a wind baffle is typically about 3 or 3.5 m but its size varies, given that the larger the wind baffle is, the larger and longer the zone of influence is.
- Concerning the porosity and the bottom gap of a wind baffle, there exist no comparative investigations of their influence on the wind. However, an increase of these two parameters up to a certain limit seems to increase the area of the snow cover submitted to the effect of the wind.
- As an example, for the typical following values $H = 3\ m$, $W_{down}=1.5\ m$ and $W_{up}=3\ m$ (see above Characteristics), with a porosity of 23 % and a bottom gap of 50 cm, the wind crater can measure up to 8 m in diameter and 30 m long (in cases of favourable local topography)

It has been noticed that wind baffles with low porosity (10 %) and low bottom gap (20 cm) worked very well. The zone devoid of snow was smaller, but clearer.

The objective of a wind baffle is to clear a given zone where the amount of snow, due to snow transport by wind, is too great. Therefore, it is very important to place the baffle as close to this zone as possible (a drop in a slope, avalanche defense structure…)
Nevertheless, this rule should take into account the local topography. Actually, a wind baffle should not be located in a wind protected zone. Because in this case, the wind baffle would be quickly covered by snow and thus would loose its effectiveness. It would therefore be necessary to setup the wind baffle further away from the wind protected zone, in a zone with more wind, and replace the wind baffle with a larger one, to compensate for the increased distance from the top.

If the wind baffle consists of one board only, this board should be orientated perpendicular to the wind direction that causes snow accumulation.

Note that it's necessary to keep in mind that each site represents a specific case. The effectiveness of a wind baffle depends on its location. It is therefore indispensable to have an accurate knowledge of how the site works in winter, acquired by local observations (main direction of the wind, typical value of the snow cover depth). These observations should continue after the structure has been set up to check that it has been correctly positioned. In fact, since the sites for the wind baffles are marked out when there is no snow, the local topography may change when there is a snow deposit. That is the reason why it is important to be able to remove the wind baffles easily, once that the project and the budget were drawn up.

Materials

- The board a wind baffle is generally made of wood plates.
- The posts are made of steel, but they also exist in aluminum.

Anchoring system solutions are described in *MEDD-DPPR / CEBTP Lyon / Cemagref Grenoble. 2004. Protection contre les risques naturels. Ancrages passifs en montagne : conception, réalisation, contrôle. Guide technique.*

Software available

Unknown, no software available.

Examples

The wind baffle is particularly adapted to fight against the formation of cornices. It is also used to limit any local overload on traditional avalanche structures. It can sometimes be used to prevent the development of avalanches from wind slabs, by generating a heterogeneous structure in the snow cover.

Photo gallery

Figure 101: A porous cross-wind baffle with two panels

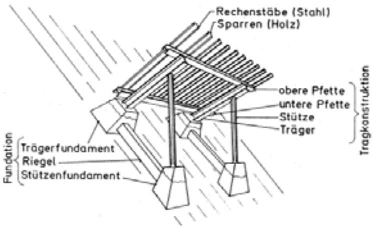
Figure 102: A row of porous wind baffles with one trapezoidal panel (Photo F. Rapin) in La Plagne (Savoie France)

Figure 103: A row of non porous wind baffles with one trapezoidal panel.

3.2.2 Stabilizing constructions

3.2.2.1 Permanent supporting structures (PSS)

Figure 104: Snow rake: structure with upright crossbeams to support snow.



Fundation = foundation
Trägerfundament = truss foundation
Riegel = waler
Stützenfundament = bracket foundation
Rechenstäbe (Stahl) = rake poles (steel)
Sparren (Holz) = chevron (timber)
Tragkonstruktion = supporting structure
Obere Pfette = upper purlin
Untere Pfette = lower purlin
Stütze = bracket
Träger = truss

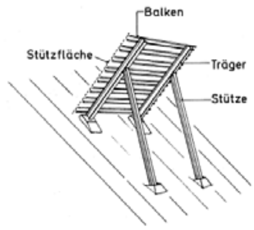


Figure 105: Snow bridge: structure with horizontal crossbeams to support snow.
Stützfläche = support surface
Balken = beam
Träger = truss
Stütze = bracket

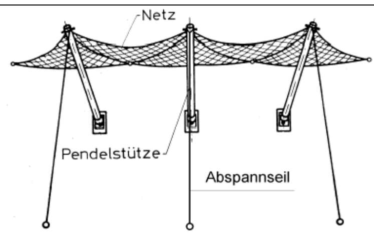


Figure 106: Snow net: rocking structure to support snow.
Netz = net
Pendelstütze = pendulum support
Abspannseil = tensioning rope

Description and purpose
Supporting structures comprise two major types of design: (1) rigid structures that sustain only small elastic deformation such as snow rakes (upright crossbeams, so-called rafters), and snow bridges (horizontal crossbeams, so-called bars); (2) rocking structures that are capable to support a limited deflection such as snow nets. Functionally, there are no differences between both designs. Both are erected more or less perpendicular to the slope and are well anchored in the ground. They act as barriers against creeping and gliding motions. A back-pressure zone extends uphill from the structure for a slope distance of at least three times the vertically measured snow height. This means that motions are diminished down-slope toward the obstacle. Within the back-pressure zone, additional pressure stresses are produced in the snow pack. These pressure stresses are parallel to the slope and depend primarily upon gliding. The supporting structure is able to withstand all such stresses. In this way the shear and tensile stresses that produced slab avalanches before the structures were built are reduced in the back-pressure zone of the structure.

Structures intended to support, sustain, or retain the snow cover in place and to prevent it from sliding downhill (photo gallery). Supporting structures have to bear mainly static loading resulting from the creeping, gliding, and settling snow pack. They are built in the starting zone of the avalanche (release area). Snow masses already in motion cannot be stopped by supporting structures as they are to weak to withstand large dynamic forces. However, they are designed to withstand slides and sluffs.

Advantages:
- Large experience with design criteria of avalanche supporting structures (see Margreth, in preparation)
- Large field experience with implementation under different conditions
- Low maintenance and no operating costs

Drawbacks:
- Limited appropriateness for very large release areas -> uncertain effectiveness

- expensive when applied to large release areas
- negative impact on the beauty of scenery (external costs of supporting structures)

Scopes

- As shown by Margreth & Romang (2006), one major scope in the field of permanent supporting structure is the determination of their effectiveness and the implications on hazard mapping deriving thereof.
- Namely discussed is the determinability of the effectiveness, which so far has been assumed by using a default value. This might not be justified as site and project specific conditions greatly impact the effectiveness of PSS.
- Also controversially is the question, if the construction of PSS should be reflected in the hazard map. Conditionally, that risk mitigation is included into hazard mapping, there arise a bench of questions concerning the financing of mitigation (e.g., PSS might lead to a downgrade of the hazard zone attributed to a specific land. This land would yield higher prices, and thus the private benefitor should contribute proportionally to his gain to the financing of PSS.

Specific design criteria

Type of structure: the choice between rigid and rocking structures depends on the site specific conditions of snow, terrain, and foundation. Generally, snow nets are less damageable by creeping and gliding motions and rock fall. However, their anchoring on loose ground is more difficult than that of rigid structures.

Height of structures:
depends on the expected maximal snow depth at the site of the structure.

Foundation of structures:
in general, two separate foundations are used for this type of structure. One is an upper or uphill foundation (so-called beam/ground foundation), the other is a lower or downhill foundation (so-called support foundation).

Arrangement of structures:
depends on the release area, the slope angle, and the distance between rows of structures (which again depend on the average and the maximal snow cover).

Height of structures:
The vertical height of the structure H_K is defined as the mean vertical distance between the upper border of the supporting plane and the ground. The vertical height of the structures H_K must correspond to the expected extreme snow depth H_{ext} at the location of the structure: $H_K \geq H_{ext}$ [m]. this fundamental requisite must be recognized for effective protection against avalanches during catastrophic events and for the design of the structures. It should be noted that the structures, depending on their features and on site-specific wind conditions, may themselves considerably influence snow depositions.

The slant height of the structure B_K is defined as the mean height of the supporting plane measured parallel to the supporting plane of the structure. The lower limit is formed by the ground .
The effective height of the structure D_K is defined as the mean distance between the upper border of the supporting plane and the ground measured perpendicular to the slope, which is analogous to the thickness of the snow.

Foundation of structures:
One task of the project manager is to thoroughly analyze the ground conditions for foundations (SIA 260: 2003). Thereby, he has to consider:

- Geological ground conditions (thickness of ground, nature and joint density of the ground, nature of overlap, humidity and frost conditions, solifluction, soil chemistry)
- Determination of the ground resistance (e.g. by anchor pulling test)
- Choice of the structure type: as they have different requirements for the foundation, foundation conditions have to be analyzed before this choice (e.g. by tentative anchor)
- Type of foundation

There are two types of foundation normally used on solid soil. Depending on the type of loadings described above, ground anchors, micro piles, base plates, and/or concrete fundaments are used to fix the structures on the soil. In general, two separate foundations are used for this type of structure. One is an upper or uphill foundation (so-called beam/ground foundation), the other is a lower or downhill foundation (so-called support foundation). In case of unstable or phreatic ground, it is advisable to connect the upper and lower foundations by a member called a pressure bar, which accepts tensile and compression stress. In these special cases SIA norm 267 should be consulted (SIA 267: 2003).

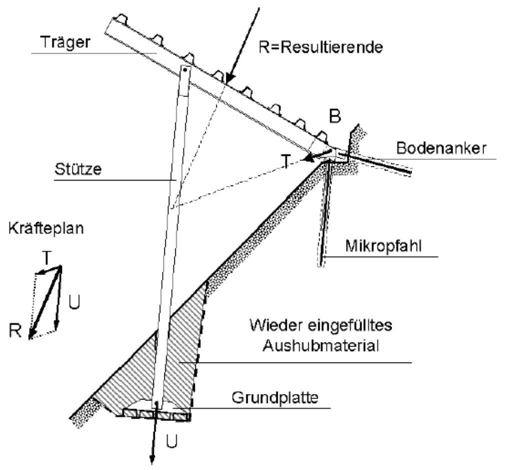


Figure 107: Structure with separated foundations. The forces impacting the structures are represented assuming a post jointed on both sides and girder pivotable in B. The supporting foundation consists of a base plate, while the bearing foundation is based on a combination of a horizontal soil anchor and a vertical micro pile.
Kräfteplan = force diagram
Stütze = bracket
Träger = truss
Resultierende = resulting force
Bodenanker = ground anchor
Mikropfahl = micro pile
Wieder eingefülltes Aushubmaterial = refilled excavation material
Grundplatte = bedplate

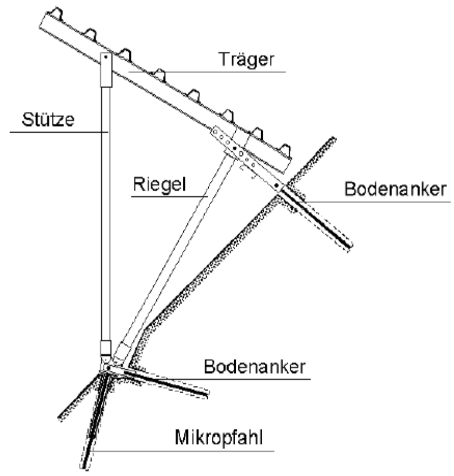


Figure 108: Structure with waling, where the down-slope foundation bases on a combination of a horizontal soil anchor and a vertical micro pile, while the up-slope foundation is based only on a soil anchor perpendicular to the slope.
Stütze = bracket
Träger = truss
Riegel = waler
Bodenanker = ground anchor
Mikropfahl = micro pile

Arrangement of structures:
Additionally to the overall requirements of supporting structures, the slope distance between structures and lines of structures has to be designed fulfilling three conditions: (1) the structures must not be damaged by maximal snow load; (2) dynamic stress by snow creeping and drift has to be accepted; (3) the velocity of snow creeping and drift in between the structures must not exceed a defined threshold.

Static design criteria of supporting structures have to warrant the withstand against snow loading. Supporting structures are not designed to withstand large dynamic forces. Thus, only slides and sluffs have to be considered for dynamic design criteria.

Materials

Snow fences and snow bridges are constructed in steel. The anchoring of the structures requires concrete fillings. For the foundation of the structures on regular soil anchors, micro piles, base plates, and concrete fundaments are in use.

Software available
Unknown, no software available.

Examples
Defining optimal countermeasures:
1. Hazard analysis
- Estimation of the expected maximum snow depth H_{ext} for hazard scenarios *H30*, *H100*, and *H300* with recurrence periods of 30, 100, and 300 years
- Estimation of the avalanche run-out area for each hazard scenario using a numerical avalanche modeling program such as AVAL-1D (Christen et al. 2002).

2. Risk analysis
- Statistical calculation of the recurrence of the expected extreme snow depth Hext
- Estimation of potential damage (identification of endangered values; vulnerability analysis; temporal and spatial coincidence of avalanche event and presence of mobile values)
- Calculation of the initial risk R0
- Analysis of potential protection scenarios and ex-ante calculation of the residual risk R1

3. Risk evaluation
- Determination of a cost-risk function for each protection scenario
- Determination of a benefit-risk function for each protection scenario
- Calculation of the net benefit for each scenario
- Selection of the maximum net benefit scenario

Implementation of the selected protection scenario:
4. Identification of the main design criteria
- Determination of the effective height of the structure DK
- Determination of the number and arrangement of supporting structures
- Determination of the distance between the rows of supporting structures
- Determination of the anchoring type

5. Detailed cost and time calculation

6. Detailed construction plan
- Detailed pegging out of supporting structures at the site
- Commencement of work at building site

7. Construction phase
- Site engineering
- control of achievements

Photo gallery

Rigid Supporting Structures	Rocking Supporting Structures
 **Figure 109: Hill slope covered by supporting structures.**	 **Figure 111: Unloaded snow net. Restraints allow for deflecting the net when loaded.**
 **Figure 110: Supporting structures are placed row-wise.**	 **Figure 112: Filled snow net. The snow load causes deflection of the net.**

3.2.2.2 Temporary supporting structures

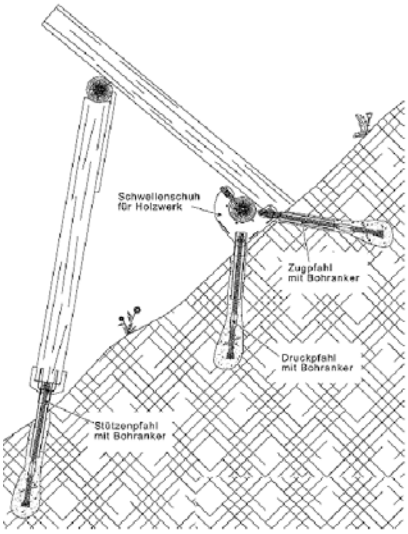


Figure 113: Cross-section of a Timber rake
Stützenpfahl mit Bohranker = bracket pile with drilled anchor
Zugpfahl mit Bohranker = tension pile with drilled anchor
Druckpfahl mir Bohranker = compression pile with drilled anchor

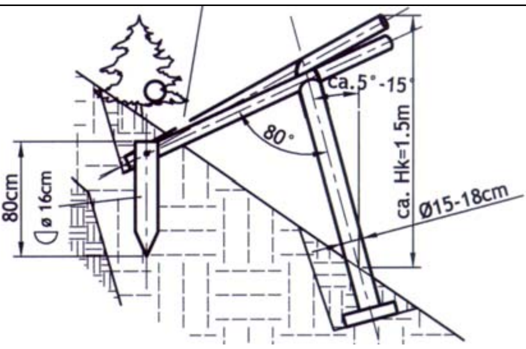


Figure 114: Cross-section of a tripod

Description and purpose
Temporary supporting structures have the same functionality as permanent supporting structures. They are erected more or less perpendicular to the slope and are well anchored in the ground and act as barriers against creeping and gliding motions. Under the term *temporary supporting structures*, we subsume timber rakes and tripods. While timber rakes are connectively built in a row, tripods are spaced at uniform distances.

Temporary supporting structures are used to stabilize the snow cover and reduce avalanche release in areas of reforestation. Within the lifespan of temporary supporting structures, the regenerating forest will become able to provide this protection function, as soon as the planted trees exceed in average the height of the maximal snow cover at the site. To serve this purpose, temporary supporting structures are designed for a lifetime of roughly 50 years depending on the wood used for construction.

Advantages:
- Timber structures are in general much less expansive than steel structures.
- Good experience with reforestation on different sites.
- In general, protection forest is one of the most cost-effective mitigation measures against snow avalanches.

Drawbacks:
- Success of temporary supporting structures depends on the success of reforestation, which is impacted by other factors such as ungulate browsing, choice of plants, vegetation period, snow height, light conditions (see Ott 1997).

Specific design criteria
Height of temporary structures:

depends on the observed maximal snow depth at the site of application. In general, timber rakes are between 2.5 m and 3.5 m in height, while tripods are 1.5 m in height.

Foundation of temporary structures:
in general, there are three types of foundations in use for this type of structure. 1st variant: waling anchored by a wire rope used on solid rock; 2nd variant: steel pedestal to avoid ground striking of wood used on bedrock; 3rd variant: waling anchored with micro piles used on dense soil (clay).

Arrangement of timber rakes:
depends on the release area, the slope angle, and the distance between rows of structures (which again depend on the average and the maximal snow cover).

Arrangement of tripods:
The number of tripods depends on the slope angle and the area to reforest (in steep slopes, up to 1000 tripods per hectare are used); the arrangement and distance between tripods depend on the reforestation goal. In practice, groups of 9 (75 sqm), 6 (50 sqm), 4 (35 sqm), 3 (25 sqm) tripods are built.

Foundation of structures:

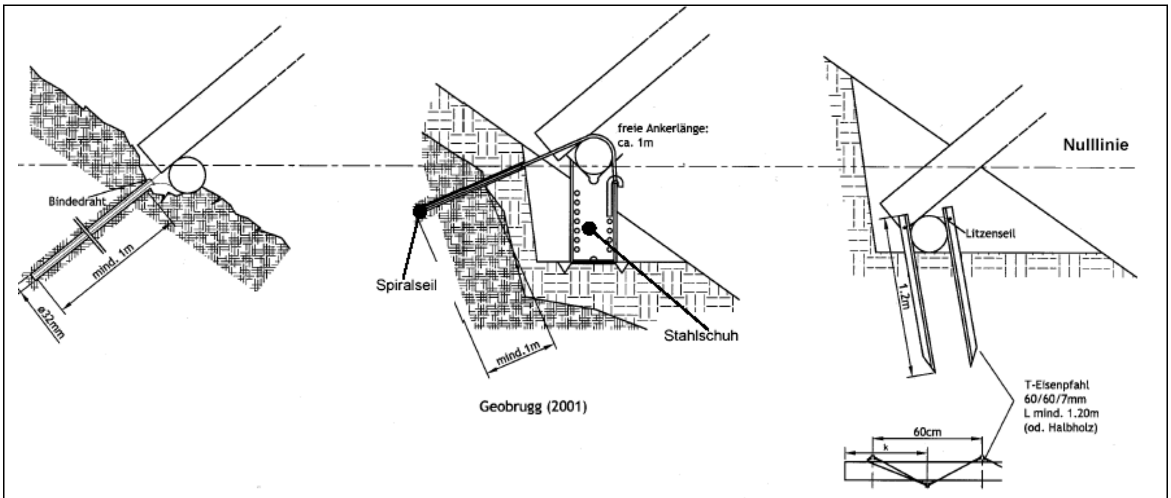


Figure 115: 1st variant: waling anchored by a wire rope used on solid rock; borehole filled with mortar; 2nd variant: steel pedestal to avoid ground striking of timber (-> extension of life experience); used on bedrock; minimal need of excavation; 3rd variant: waling anchored with micro piles used on dense soil (clay). In loose soil a timber pile can be used (never on eroding soil).

Arrangement of structures:

- Additionally to the overall requirements of supporting structures, the slope distance between structures and lines of structures has to be designed fulfilling three conditions: (1) the structures must not be damaged by maximal snow load; (2) dynamic stress by snow creeping and drift has to be accepted; (3) the velocity of snow creeping and drift in between the structures must not exceed a defined threshold. In that way, the momentum responsible for damages below the structures is limited to moderate scale.

Arrangement of tripods:

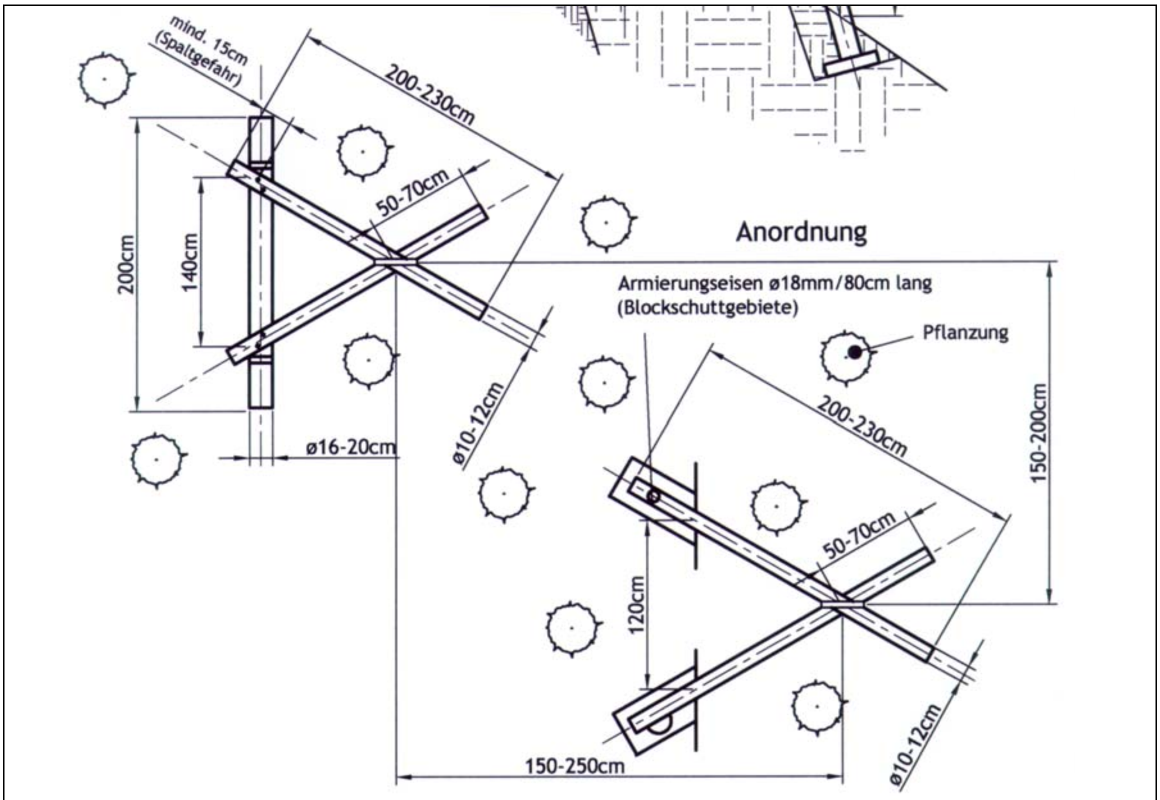


Figure 116: Distance between single tripods and the arrangement of the seedlings around the tripods.

Static design criteria of supporting structures have to warrant the withstand against snow loading. Supporting structures are not designed to withstand large dynamic forces. Thus, only slides and sluffs have to be considered for dynamic design criteria.

Materials

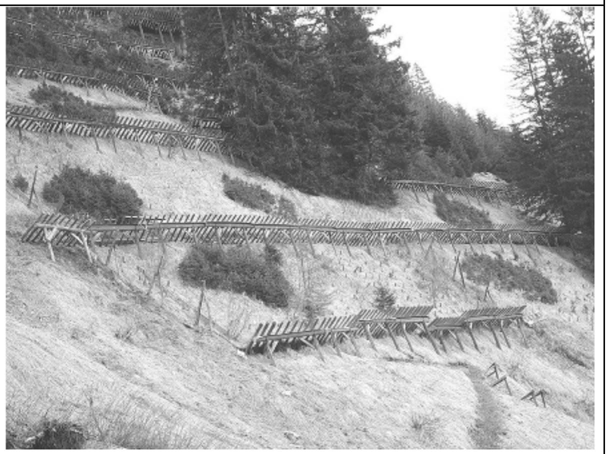
Temporary supporting structures are made of timber. For the foundation of the structures rope wire anchors, micro piles, and steel pedestals are in use. Each timber species shows a different vulnerability towards decomposition. Therefore, the choice of timber should be according to SIA norm 265/1:2003, Sect. 5. General experience with different timber species show lifespan (Leuenberger 2003) of:

- 10-20 years for Larix deciduas (untreated)
- 10-25 years for soaked wood (e.g., Picea abies, Abies alba, Pinus sylvestris)
- 25-40 years for Castanea sativa, Pseudorobinia acazia, Quercus ssp. (untreated).

Software available

Unknown, no software available.

Photo gallery

Tripods	Timber rakes
 **Figure 117: Tripods are used group wise to allow structured afforestations.**	 **Figure 120: Timber rakes are constructed to slow or avoid snow creeping in order to allow tree growth.**
 **Figure 118: Particularly on steep slopes it is wise to cover the whole slope by tripods in order to prevent gliding or creeping of snow.**	 **Figure 121: Once a tree is above a threshold point of approximately 1.5 m sustaining of snow creeping isn’t a problem anymore.**
 **Figure 119: Seedlings are placed around the single tripod.**	 **Figure 122: Old structures do hardly hinder the trees to growth and can be left in the field without problems.**

Examples

Tripods

Step 1. A gauge is used to position the girders and the column of the tripod.

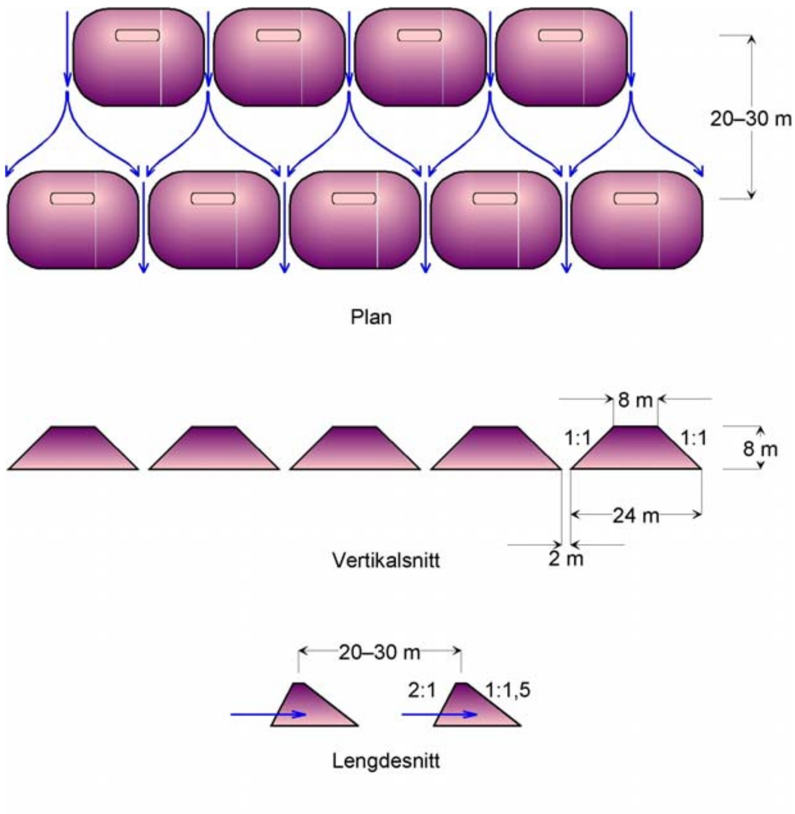
Step 2. Excavation for the foundation of the girders and the column using a foundation slab.

Step 3. Wooden elements are incorporated and the column is shaped.

Step 4. The tension anchor is adapted to the soil conditions using either concrete reinforcement, scantlings or cables.

Step 5. Finally, the anchoring is completely recovered.

3.2.3 Braking constructions – Avalanche breaker



Description and purpose
The measure usually consists of several rows of mounds or cones constructed in the run-out zone. They are mostly used to protect roads to reduce the velocity of avalanches reaching the road. For housing areas they are mainly used in combination with a catching dam down slope of the mounds, because they are less effective than catching dams to stop avalanches.
Braking structures are intended to reduce the run-out distance by dissipating the cinematic energy of the avalanche. This will slow the motion of the snow. They will increase the width of avalanche flow and thus result in reduced flow depth and greater contact with the ground.

Specific design criteria
The height of the mounds depends on the velocity and flowing height of the design avalanche. Large and dry avalanches flowing at high speed will hardly be affected by braking constructions. They are most effective against wet snow avalanches running at low speed and limited size. The effectiveness of braking constructions is therefore dependent upon a location near the end of the run-out zone of the avalanches.

Materials
Many different types of materials are used for braking constructions, depending on what is found to be the most cost/effective solution in each case. The construction materials normally consist of:

- loose deposits: rocks, gravel, sand
- reinforced earth
- concrete

Software available
Unknown, no software available.

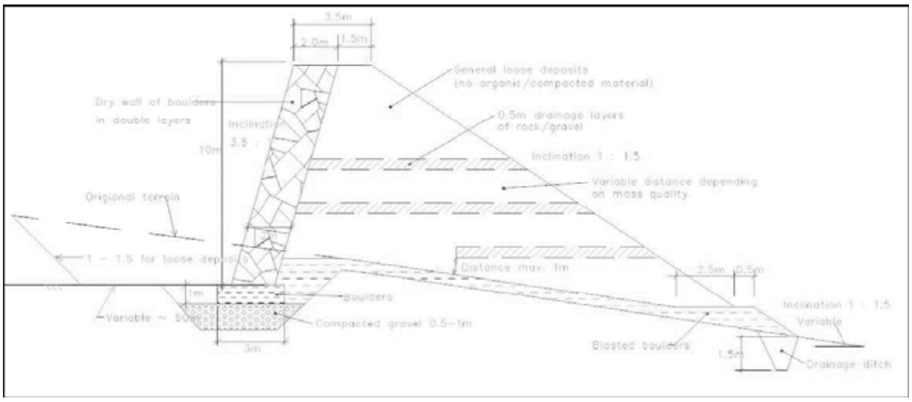
Photo gallery

Figure 123: Earth mounds used to protect a highway in Norway

Figure 124: Earth mounds used to protect a town in Iceland

3.2.4 Deflecting and catching constructions

3.2.4.1 Catching and deflecting dam



Description and purpose
Catching dam:
Transversal structure designed to stop or to initiate the stopping of flowing snow .
It is a dam or structure, built transversally to the flow direction of an avalanche.

Deflecting dam:
Structure designed to deviate flowing snow out of an endangered area. The structure is inclined to the flow direction by a certain deflection angle.

Catching dams are intended to stop avalanches completely before they can reach objects at risk. These dams are typically used for extended areas along the foot of a slope where there is insufficient space for deflecting dams.

If there is sufficient space in the run-out zone and if the endangered area is suitably located with respect to the direction of the avalanches, deflecting dams may be used to divert avalanches away from objects at risk. Deflecting dams are often a cost-effective solution and several examples of successful deflections of medium sized avalanches have been documented.

Specific design criteria

Design dam height depends on the velocity and flowing height of the design avalanche.

Large avalanches flowing at high speed can hardly be stopped by catching dams and there are many examples of avalanches overtopping such dams. The effectiveness of catching dams is therefore dependent upon a location near the end of the run-out zone of the avalanches.

Catching dam:
It is assumed that the upstream velocity u_1 and the flow height h_1 is known (employing e.g. numerical avalanche models). Also the design snow depth, h_s, (avalanche deposit or snow cover) in front is assumed to be known. Then, two dynamic requirements for determination of the minimum dam height above snow cover needs to be met:

Global stability: translation, rotation, material resistance, foundations.

Dynamic impact:
For earth dams stability against avalanche impact is usually not an issue. However, for special construction build of concrete or steel impact force need to be regarded.

The construction of a building or wall-like structure in an avalanche prone area requires an assessment of reasonable design loads, i.e., estimates of the total maximum force, F_m, and moment, M, due to an avalanche. In general, three flow regimes should be distinguished for the determination of the impact force on a wall-like structure.

- dense flow
- fluidized flow (also referred to as saltation layer)
- suspension flow (powder part)

Materials
Many different types of materials are used for avalanche deflecting and retaining dams or walls, depending on what is found to be the most cost/effective solution in each case. The construction materials normally consist of:

- loose deposits: rocks, gravel, sand
- reinforced earth
- concrete

When dealing with earth fill dams, and especially with dams where fine grained materials are used, the following points must be assessed:

- quality of the earth materials
- treatment of organic material in the ground
- design of the dam
- design of the excavation area
- water, drainage and erosion protection

Software available
Unknown, no software available.

Photo gallery

Catching dams

Figure 125: Catching dam made of earth fill and gabion nets on the top

Figure 126: Catching dam with avalanche brakers in front to reduce the velocity

Figure 127: Catching dam has stopped a wet snow avalanche at the Ryggfonn full scale experimental site in Norway

Figure 128: Catching dam made of concrete formed as half cylindrical shells

Deflecting dams

Figure 129: Deflecting dam in steeply inclined terrain has worked effeciently

Figure 130: Deflecting wedge construction above the settlement of Flateyri in Iceland

Figure 131: Deflection dam protecting a settlement

Figure 132: Concrete wall protecting houses

3.2.4.2 Avalanche shed - Gallery

Figure 133: Avalanche shed used for highway protection

Description and purpose
Avalanche sheds (also called galleries) are designed to protect roads and railroads by allowing avalanches to pass over the object. A typical shed is a concrete structure with a thick inner wall and roof, and either with columns or a solid outer wall. Backfilling behind the inner wall should give a smooth transition between the terrain and the roof.

Avalanche sheds are constructed to let avalanches pass over without causing damage to the object.

Specific design criteria
General considerations:
The size and frequency of the design avalanche has to be decided. In Norway the road authorities normally design for avalanches with a 20 year return period. Swiss Guidelines normally consider avalanches with a 30 year return period, but more extreme events are also evaluated in the design.

An avalanche shed will change the driving conditions on a road and this should not reduce general traffic safety. Therefore both avalanche issues and traffic safety must be considered in the planning. Traffic safety is affected primarily by road alignment, in addition to lighting, drainage- and temperature conditions inside the shed.

It is important to have a natural road alignment where the shed is built to reduce surprises and hazards to a minimum. Natural lighting in the shed is best with a column outer wall. However, columns should only be used when the terrain below the shed is steep, as in less steep down slope terrain avalanche debris may build up outside and enter the shed. Furthermore dry avalanches passing over an open shed will create an under pressure reducing visibility due to suspended snow particles. All this should be considered when making the decision for a solid outer wall or columns.

On cold sunny winter days the road inside a shed may be icy, while the road is dry outside. Animals inside a shed may also represent a problem. Traffic safety may be increased by water gratings and cattle grids near the entrance to prevent water and animals from entering the shed.

Combined with the other traffic safety considerations mentioned above, the overall safety situation regarding probability for accidents caused by an avalanche in absence of a shed should be compared with the probability of accidents because of reduced traffic safety due to the shed.

Terrain adaptation:
Placement should be optimized to reduce both shed length and design loads. Road alignment should be considered to reduce potential traffic hazards.

Deflecting dams are often built to narrow the width of the avalanche by canalizing the flow. This reduces the required shed length. Avalanche sheds are expensive to build, and it is therefore often economical to spend money on effective deflecting dams to shorten a shed. Deflecting dams are normally built of in situ earth and rock. Shed roofs normally have a deflecting wall made of concrete or a dry rock wall. There are several examples where sheds have been shortened too much. This may create accidents by avalanches blocking the road after overrunning the deflecting dam. Deflecting dams in the avalanche path must be designed with care, and might be more challenging to design than dams in the run-out area.

Terrain adaptation should give a smooth transition between the terrain and the roof of the shed. The avalanche will then flow easily over the shed and not create large transition avalanche loads.

The avalanche track should be as even and straight as possible. Small ridges, large stones etc should be removed to prevent accumulation of avalanche debris and consequently laterally spreading of the avalanche. Even small irregularities may influence the avalanche flow and cause laterally spreading, i.e. extra effort should be made to smooth the avalanche track. Stones, trees etc transported by the avalanche may also damage the shed, or they could create irregularities in the track.

There should be a maintenance road to the inside of the deflecting dam and to the top of the shed to enable removal of debris to maintain proper function of the deflecting dam and drainage.

Drainage:
Avalanches normally occur in terrain depressions where water flows naturally, hence adequate drainage is important. The possibility of a debris flow should also be considered.

Surface water is normally drained by building open concrete channels over the roof of the shed. Drainage pipes under the shed are also used but normally only when it is difficult to collect the surface water, or when directing the water over the shed results in major erosion problems.

Water carried over the roof has a strong erosion potential and should be directed to an area specially protected against erosion. A water channel on a shed roof should be sufficiently low so that debris is not collected. In Norway the height of these channels is normally recommended to be less than 20-35 cm.

Gratings, pipes and drains must be designed such that debris can be removed mechanically to enable proper functioning.

Culvert design:
Earth fill around a culvert is necessary to achieve sufficient load bearing capability of the relatively thin steel or concrete structure. Therefore culverts are normally placed in gently sloping terrain where it is possible to build a sufficiently large earth fill.

Figure 134: Culvert of corrugated steel pipe under construction.

Figure 135: Single lane culvert with deflecting dams. Note dry masonry retaining walls at the portal.

Culverts of steel or concrete completely covered with earth might also be regarded as a type of avalanche shed. Culverts are cut and cover tunnels, and have different design criteria than sheds.

Deflecting dams are also used when building culverts. However, it is difficult to build a concrete deflecting wall as used at the end of shed roofs. Therefore culverts are often made 10-15 m longer than a solution with a shed would be. This makes culverts more economical when long stretches are to be protected.

Design loads are determined from decisions on size and frequency of the design avalanche. Design loads depend on velocity, density, flow height, and transition of flow direction of a design avalanche. A shed must be designed for:

- Static load by the snow and earth lying on the shed.
- Dynamic load as the avalanche passes over the roof including transition loads due to change in flow direction at the roof.
- Earth pressure from the surroundings and possible point pressure load from impact from rocks or traffic.

There are different guidelines in Europe for calculation of design loads and use of load cases and load factors. Norwegian guidelines require design for 4 different load cases. The Swiss guidelines are currently under revision and new guidelines are to be completed early 2007. It is recommended that the applicable regulations are applied when establishing design loads for a given avalanche shed.

It is possible for a shed to be hit by an extreme event that it is not designed for. The designer of the shed should therefore ensure that such events do not cause a collapse of the entire shed.

Materials
Construction materials for an avalanche shed normally consist of:

- Concrete
- Local backfill material (soil, rocks etc).
- Steel (corrugated steel pipes in culverts)

A typical avalanche shed is a concrete structure with a thick inner wall and roof, and either with columns or a solid outer wall. Backfilling behind the inner wall should give a smooth transition between the terrain and the roof. The backfilling is normally local soil or rocks. Sheds can also be made of steel or wood.

Culverts of steel or concrete completely covered with earth might also be regarded as a type of shed. Steel solutions are corrugated steel pipes for single or double lane roads. Concrete solutions are either prefabricated concrete elements or cast in situ.

Hence the construction materials for a shed normally consist of:
• Concrete
• Local backfill material (soil, rocks etc).
• Steel (corrugated steel pipes in culverts)

Software available
Unknown, no software available.

Photo gallery

Figure 136: Two lane avalanche shed with columns.

Figure 137: Single lane avalanche shed with solid outer wall. Note the concrete deflecting wall at the roof.

Figure 138: Rodger Pass, BC, Canada.

Figure 139: Mt. Stephen Avalanche Shed, Field, BC, Canada

3.2.4.3 Tunnel

Description and purpose
This measure is used to protect roads. Because they are expensive, they are only used when other measures are not feasible because of topographic conditions, or when there are a great number of avalanches crossing the road.
Tunnels are used to avoid that traffic enters into avalanche prone area.

Specific design criteria
The design of the tunnel is based on traffic density, type of traffic and the quality of bedrock. On stretches with low traffic density and if the tunnel is short, one lane tunnels can be considered.
It is important that the tunnel entrances are placed in safe areas. There are many examples of bad planning where the entrances have been put in tracks with frequent avalanches, because the planner has tried to minimise the length of the tunnel.

Materials
Tunnels are mainly built in bedrock, but can also be constructed in loose deposits using steel lining.

Software available
Tunnel design is widely described in the discipline of engineering geology and several software programs are available.

Photo gallery

Figure 140: Tunnel in loose deposit used to protect a highway in Norway

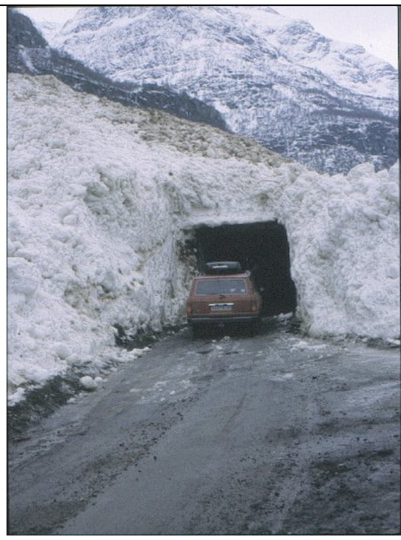
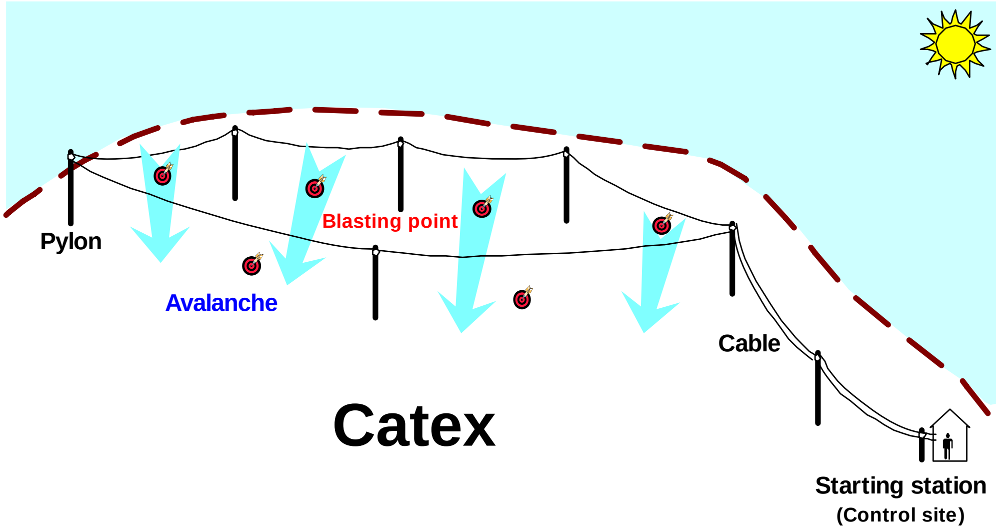


Figure 141: Tunnel entrance exposed to avalanches in Norway

3.2.5 Artificial release

3.2.5.1 Aerial cableways



Description and purpose
System of artificial release of the avalanches allowing the explosion by a cable which moves an explosive charge above the snow cover. The installation is composed of an aerial cable, few pylons, a starting station and, very often, a control device.
Preventive measure (recommended only for inhabitant area): to release few neighboring avalanche starting zones with aerial explosions using explosive, usually dynamites, often without anybody nearby the starting point, as soon as a snow fall height reaches 20 to 30 cm within 3 days.

Advantages
- Allow to release just down a crest many neighbor blasting points, even on the 2 faces of the mountain;
- Management far away from the dangerous sites, if the access of the station is safe; (with radio control),
- Good safety level for the staff (control from the starting station);
- Good efficiency (explosion few meters above the snow cover);
- Working in bad weathers conditions (except with a hard wind), also in the night;

Drawbacks
- Long duration of the effective release work ;
- Expensive;
- Use of explosives (regulations, constraints, safety);
- Difficulties to work with hard wind (possibility to loose / to disconnect a charge);
- Cable sensible to rime in some humid places; if yes need a special additional device (and electricity power for the engine);
- Aerial constraints: depends on national rules for the height of the cable, and also because nearby the crest, less wide cable and possible big angles between 2 neighbour pylons, the system is (very) dangerous for helicopter, plane, parachute / parapente (crash deaths); it needs "beacons";
- Need a safety location for the starting station and "not too bad" safety way to go;
- Sensible to lightning (electronics devices): must to be disconnected in summer times;
- Nature impact: cable nearby crests and paths (view, birds); towers along mountain;
- If necessary, difficult (not easy for safety conditions inside one avalanche starting zone) to repair during the winter season;
- Not easy "to see" the avalanche site just before the blast to be sure that there is nobody inside;
- Not easy to see the starting zone after the blast for to know if the avalanche occurs;
- Noise of the frequent blasts if the exploder is situated nearby buildings.

Specific design criteria
Location: cable over each (blasting point from each) starting zone; Station and pylons: outside of avalanche areas; pylons: with good anchors
•Distance between cable and ground (lengthwise profile): over than 5 m (explosive charge above the snow cover), less than 50 m (aerial constraint);
- Environmental conditions: temperature, wind, snow cover height;
- Use of radio control;

Complete design procedure:
- Interest of the artificial release in the site (avalanche protection for roads, ski runs, …);
- Possibilities of explosive management (official rules, qualification, storage, times, …);
- Interest of easy blast (staff, in the night, in bad weather conditions, …);
- To choice the blasting area / point (in a natural starting zone); to check the towers locations and the cable between, at few meters from the snow cover: topographic study is very often necessary, with a length profile; Take care with the wind effect on the charge (moved beside);
- To check the location of the possible station (safety access, avalanche protection, space to move around, how to escape urgently);
- To design the station to hang the charge on the cable, with 2 different levels if use of special device;
- To check for electricity power at the station (better if possible);
- To choice materials respecting the technical rules (standards, …) : steel, cable…;
- To evaluate the cost level;
- To use experienced companies for the works;

Materials
List of the possible material used to construct the structure or parts of the structure:
- Anchors (for rock or for “soft” ground)
- Concrete
- Steel
- Pylons
- Cable
- Motor

Software available
Unknown, no software available.

Examples
A ski resort knows safety difficulties with few hand charges points. Ski patrollers must walk along a steep crest. But it is easy and safe to reach nearby. Few blasting points are necessary, possible on the 2 ways from the crest. The rime seems not to be a problem in this location. It is also interesting to reduce the duration of the avalanche release. The explosive national rules are effective (management, storage, etc.) without hard difficulties. Cost is hardly in view. Cable ropeway system looks a good possibility.

An existing avalanche aerial cableway is always in use to protect a main road with only four blasting points. The users are pleased with, without hard maintenance work. The system needs an extension to protect more over avalanche paths. The technical possibility looks easy. To extend the aerial cableway looks a good possibility.

Photo gallery

Figure 142: CATEX - aerial cableways, explosive and control cabin.

Figure 143: CATEX - aerial cableways and explosive

Figure 144: CATEX - aerial cableways, explosive and control cabin.

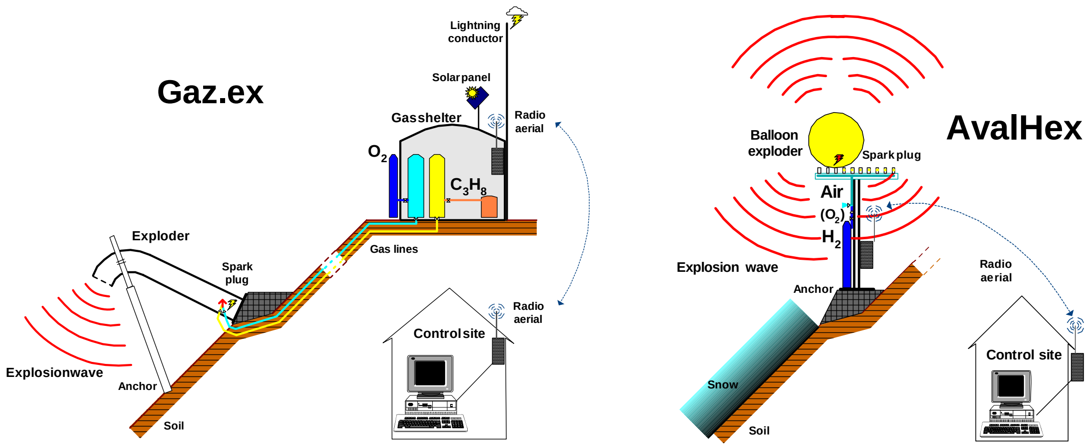
Figure 145: Radio transmission and control for CATEX

Figure 146: CATEX

Figure 147: CATEX control cabin

 **Figure 148: CATEX – aerial cableways**	

3.2.5.2 Gas exploders



Description and purpose
System of artificial release of the avalanches allowing the explosion of a mixture gas above the snow cover. The installation is composed of an enclosure of gas containment, a gas shelter and a control device.

Preventive measure (recommended only for inhabitant area): to release one avalanche starting zone with an aerial explosion but without any explosive, without anybody nearby the starting point, as soon as a snow fall height reaches 20 to 30 cm within 3 days.

Advantages

- -No use of explosives;
- Quick, easy management (with radio control, far away from the dangerous sites, in few minutes);
- Very good safety level for the staff (control from the office);
- Very good efficiency (explosion few meters above the snow cover, well oriented for the Gas.ex);
- Working in all weathers conditions (except with a hard wind for the Avalhex), also in the night;
- If designed for that, can be easily (helicopter) dismantled during the summer times (and re-installed in autumn): no special devices erected in the summer mountain (National park, etc…);
- Rather good for the nature impact (it is not so easy to see the exploders).

Drawbacks

- Only one avalanche track (blasting point in the starting zone) per tube / pylon ;
- Very expensive;
- Very hard cold weather (delay for the gas propane, electronic devices, battery);
- Sensible to lightning (electronics devices) : must to be disconnected in summer times;
- Regulations (gas tanks, artificial release);
- If necessary, difficult (not easy for safety conditions inside one avalanche starting zone) to repair during the winter season;
- Not easy “to see” the avalanche site just before the blast to be sure that there is nobody inside;
- Not easy to see the starting zone after the blast for to know if the avalanche occurs;
- Need very good anchors (Gas.ex);
- Noise of the frequent blasts if the exploder is situated nearby buildings.

Specific design criteria

- Location: exploder inside / just nearby each starting zone;
- Power of the explosion: more than 2kg of equivalent TNT;
- Distance between exploder and gas shelter: length, difference in height;
- Number of possible blast for a winter season;

- Environmental conditions: temperature, wind, snow cover height;
- Use of radio control;

Complete design procedure:

- Interest of the artificial release in the site (avalanche protection for roads, ski runs, …);
- Interest of no explosive management (official rules, qualification, storage, times, …);
- Interest of easy blast (staff, in the night, in bad weather conditions, …);
- To choice the blasting area / point (in a natural starting zone); to check the anchor possibility in this location (nature of the ground, length); To check the avalanche protection of the exploder;
- To check the location of the possible gas shelter (avalanche protection, for helicopter use, nearby a direct view for the radio control) and the distance with the exploder(s) (less than ~400 m in difference in height);
- To design the level of the detonation (with the starting zone wide, with the slope angle, with the efficiency in view); To choice the type of gas exploder;
- To choice the minimal number of winter blasts for the same point, and to design the necessary volume of the gas tanks;
- To choice materials respecting the technical rules (standards, …);
- To evaluate the cost level;
- To use experienced companies for the works;
- To take care of counter-slope for the gas lines (which produces condensation water deposit, fill up the tube in cold weather conditions);

Materials

- List of the possible material used to construct the structure or parts of the structure:
- Anchors (for rock or for “soft” ground)
- Concrete
- Steel
- Pipes

Software available

Unknown, no software available.

Examples

With a new ski-lift, a ski resort needs to protect against avalanches an other part of the mountain, which is difficult to access nearby the crest in realistic safety conditions. It exist only few blasting points (4 or 5). It uses an avalanche map with these paths and, during 2 winter seasons, they have observed the avalanches (starting zone / fractures lines, track and run-out zone (extents, look-out posts)). It wants to blast this sector very early in the morning, even in the night. The explosive national rules are restricting (management, storage, etc.). It wants to use a long effective material. It can provide the estimated investment cost. Gasex system looks a good possibility.

A twenty years old avalanche cable ropeway is always in use to protect a main road with only four blasting points. The system needs a large maintenance work. The road staff wants to reduce hardly the delay of operations (from 90 minutes to nearby 15-20 minutes for the release works, and if possible in the same direction, for the cleaning works). It also wants manage the blasting operations from the road. The financial aspect seems difficult. Gasex or Avalhex system looks a good possibility.

Photo gallery

Figure 149: GAZEX

Figure 150: AVALHEX

Figure 151: GAZEX

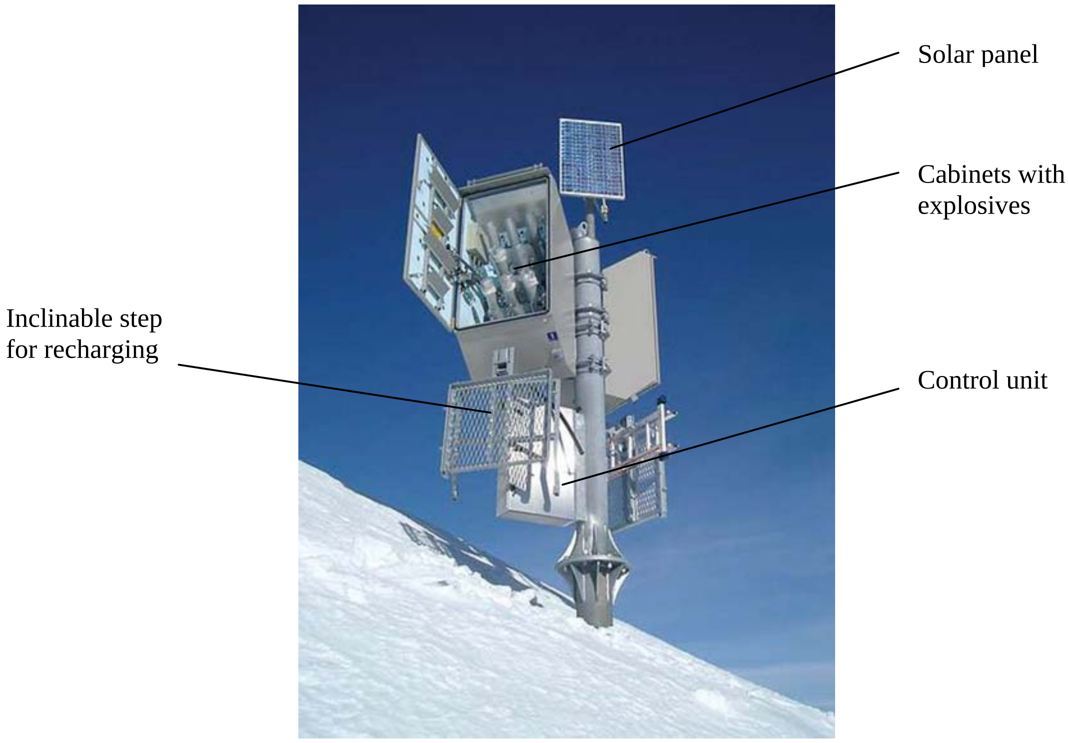
Figure 152: GAZEX control of release from office.

Figure 153: AVALHEX with the inflating ballon

Figure 154:

 **Figure 155: bottled gaz for GAZEX (Lautaret, France): general view of the cabin.**	 **Figure 156: bottled gaz for GAZEX (Lautaret, France): zoom on the cabin.**

3.2.5.3 Avalanche guard



Description and purpose
System of artificial release of the avalanches allowing the explosion of an explosive charge in the snow cover. The installation is composed of a pylon with a cabinet containing the explosive charge and a control device.
Preventive measure to trigger an avalanche in the starting zone with explosive material whereby the whole device is installed outside the avalanche prone area.
Costs: Investment: 70.000€ / blasting point (two cabinets) plus 8.000€ for control unit. 40€ per shot.
Efficiency is very good, whereby each shot is registered by a geophone and therefore duds can easily be recovered by the avalanche safety team.

Advantages
- Device can be installed outside the avalanche prone area
- Several avalanche starting zones close to the triggering device can be reached.
- Weather independence: Each remote explosives tower can be deployed by coded radio signal at any time
- Remote control allows fast interaction by the avalanche control headquarters. The avalanche can be triggered with powerful charges without mobilization delay
- Avalanche control staff remains outside danger area
- Effective avalanche release with minimum number personnel results in cost savings
- Relatively low investment and installation costs
- Secure magazine locations: the cabinet’s door opens automatically for each shot and gets closed after launching the explosive.
- The successful detonation is detected by the geophone and confirmed at the PC
- Minimal intervention in the natural environment
- Absence of duds, shrapnel or other debris
- Energy supply through solar cells, with no external and susceptible supply lines needed

Drawbacks
- The launching distance depends on the propelling charge. Therefore the numbers of shots for different starting zones in one cabinet are limited.
- Strong wind can influence the launching distance and direction.

Specific design criteria

- Location: close to the starting zone;
- Power of the explosion: about 2.8kg of equivalent TNT;
- Distance between explosion and triggering device: The explosive material is fired to the target points in the starting zone. Launching rates vary from 50 to 150m;
- Number of possible blast for a winter season: one charge magazine contains 10 explosive charges. Can be recharged by the avalanche safety team without helicopter support.
- Environmental conditions: temperature, wind, snow cover height;
- Use of radio control for triggering;

Complete design procedure:

- Interest of the artificial release in the site (avalanche protection for roads, ski runs, …);
- Interest of no explosive management (official rules, qualification, storage, times, …);
- Interest of easy blast (staff, in the night, in bad weather conditions, …);
- To choice the blasting area / point (in a natural starting zone); to check the anchor possibility in this location (nature of the ground, length); To check the avalanche protection of the exploder;
- To choice materials respecting the technical rules (standards, …);
- To evaluate the cost level;
- To use experienced companies for the works;

Materials

- Anchors (for rock or for “soft” ground)
- Concrete
- Steel
- Pipes

Software available

Unknown, no software available.

Photo gallery

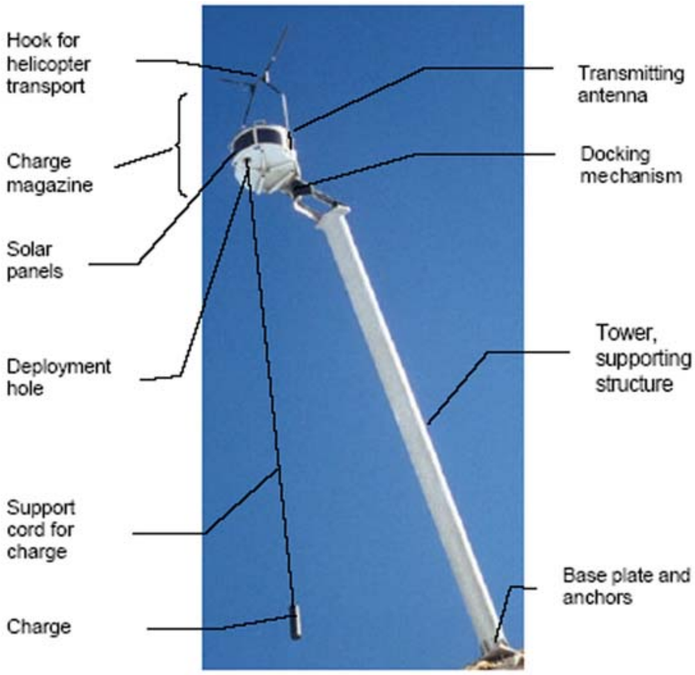

Figure 157: Charging the launching tubes

Figure 158: Propelling charge


Figure 159: Opened door of cabinet


Figure 160: Avalanche guard close to a starting zone in Lech (AUT)

3.2.5.4 Avalanche tower



Description and purpose
System of artificial release of the avalanches allowing the explosion of an explosive charge above the snow cover. The installation is composed of tower, a charge magazine and a control device. Preventive measure to trigger one avalanche in the starting zone with an aerial explosion, without anybody nearby the starting point, as soon as a snow fall height reaches 20 to 30 cm within 3 days.
Costs: Investment (level without taxes): between 30 000 and 50 000 € per exploder (in France); Running costs (level per year without taxes) only for materials: between 15 and 25 € per blast; Maintenance costs: between 2 and 3 % of the investment cost.
Efficiency is very good, usually more than 2 kg of dynamite.

Advantages:
- Explosion takes place above the snow, which is known to produce the most effective explosive action
- Weather independence: Each remote explosives tower can be deployed by coded radio signal at any time
- Remote control allows fast interaction by the avalanche control headquarters. The avalanche can be triggered with powerful charges without mobilization delay
- Avalanche control staff remains outside danger area
- Effective avalanche release with minimum number personnel results in cost savings
- Relatively low investment and installation costs
- Secure magazine locations: on top of remote towers during winter, removed and stored in a safe place off-season
- Minimal intervention in the natural environment
- Absence of duds, shrapnel or other debris
- Energy supply through solar cells, with no external and susceptible supply lines needed
- System integration with snow and avalanche measurements, as well as routine information gathering can reduce overall helicopter flight cost

Drawbacks:
- Only one avalanche track (blasting point in the starting zone) per pylon

- Recharge by helicopter may be dangerous if strong wind is present in the starting zone
- Delay of recharge if meteorological conditions are not good

Specific design criteria

- Location: exploder outside / just nearby the starting zone;
- Power of the explosion: more than 2kg of equivalent TNT;
- Distance between exploder and charge magazine: 8m (tower) plus the difference in height according to the inclination of the starting zone;
- Number of possible blast for a winter season: one charge magazine contains 12 explosive charges. Can be recharged by helicopter
- Environmental conditions: temperature, wind, snow cover height;
- Use of radio control;

Complete design procedure:

- Interest of the artificial release in the site (avalanche protection for roads, ski runs, …);
- Interest of no explosive management (official rules, qualification, storage, times, …);
- Interest of easy blast (staff, in the night, in bad weather conditions, …);
- To choice the blasting area / point (in a natural starting zone); to check the anchor possibility in this location (nature of the ground, length); To check the avalanche protection of the exploder;
- To choice materials respecting the technical rules (standards, …);
- To evaluate the cost level;
- To use experienced companies for the works;

Materials

- Anchors (for rock or for “soft” ground)
- Concrete
- Steel
- Pipes

Software available

Unknown, no software available.

Photo gallery

Figure 161: Avalanche tower

Figure 162: Charge magazine of an avalanche tower

Figure 163: Installation of an avalanche tower

3.2.6 Afforestation

See chapter 3.1.9

3.3 Rock avalanches

3.3.1 Introduction

There exist few examples of countermeasures for rock avalanches. The main reason for this is that the frequency of this hazard is low leading to that planning of mitigation measures has not been prioritized. Moreover, the triggering mechanisms have not yet been fully understood making it difficult to know how countermeasures best could be implemented. The large volume and great forces involved in rock avalanches makes it difficult to implement traditional physical measures used for smaller rock falls, e.g. anchors, rock bolts, nets and concrete ribs.

Experience on countermeasures for rock avalanches are mainly based on monitoring systems including early warning and evacuation of endangered zones. Experience on physical measures are sparse, hence main focus in the following description will be on description of non-physical measures.

3.3.2 Physical countermeasures

Two possible physical measures most relevant for rock avalanches will be described:
1. Blasting
2. Drainage systems

3.3.2.1 Removing unstable rock mass by blasting

There exist reports on rock avalanches that have been triggered by explosives both from Soviet and China. Nuclear underground tests on Novaya Zemlaya during Soviet times triggered a large rock avalanche/rock avalanche, which subsequently blocked a river. There are also several accounts of artificially triggered rock avalanches that served as artificial dams for hydropower generation and debris flow protection on the territory of the former Soviet Union. However, there exist no examples where use of explosives has been used with primary objective to reduce risk of rock avalanches.

As the consequences of the blasting operation can be hard to predict such measures should be carried through with great caution. Especially, the controlling of how great volumes that will be involved can be hard to predict. If the volumes are greater than expected, unforeseen and undesirable consequences can occur.

Moreover, the planning of location of the charges can be complicated as the geometry of the fractures is not always known. Therefore, careful mapping of the fractures should be a prerequisite before such measures are carried through. Also the magnitude of the charges can be hard to design. Consequently, use of explosives is only a possible measure, but presumably the use in most cases will not be recommendable, because of the uncertainties in the consequences of the blasting.

3.3.2.2 Drainage

Many of the rock avalanches are presumably triggered by building up of cleft water pressure. Measures reducing the possibilities of water to be stored in the unstable rock mass will in such cases improve the stability and reduce the rock avalanche hazard. Such measures are widely used for the smaller rock slides where joint geometry affecting the water flow is better known. However, for big rock avalanches such measures have only been exceptionally used.

The prerequisite for use of drainage measures is that water pressure is the governing triggering factor. Another important factor is that the flow pattern and that the critical locations for build-up of water pressure can be identified. In many cases with complicated fracture geometry this can be hard to foresee. Moreover, the stability of the rock mass is governed by many processes, whereof water pressure can be of only minor importance.

There are two main ways to control water drainage:

- Diversion of surface water
- Control of underground water drainage

3.3.2.3 Diversion of surface water

I cases where surface water is concentrated along major stream channels, the diversion of the water to avoid infiltration into the unstable rock mass can counteract storage or pressure build-up of water in the fracture systems.

This measure may not be effective if the surface water is more dispersed and there also are indications that surface water infiltrates the ground above the unstable rock mass. In such cases the critical water supply to the fractures may be controlled by underground water flow.

3.3.2.4 Underground water drainage

Building of tunnels or drilling of bore holes to control the underground drainage can be used separately or in combination with surface water diversion. Before such systems are established careful mapping of the drainage system must be performed. The identification of the major drainage channels is challenging, especially if the bedrock is heavily jointed. To examine the effectiveness of the drainage, discharge recordings must be carried through. Such measures seem inadequate if the underground water flow is scattered along several minor fractures.

4 Description of non-structural countermeasures

4.1 Administrative and organizational methods

4.1.1 Introduction

Administrative methods include all political and administrative/organizational measures to reduce risk for natural hazards:

- Land use planning by use of hazard maps
- Information and education
- Preparedness/emergency planning
- Insurance

Such methods are normally invoked for two main reasons:

- To reduce the consequences of possible rapid mass movements to existing buildings and infrastructure
- To avoid that new buildings and infrastructure are established in exposed areas

On the contrary to physical measures which are aimed at preventing a disaster from occurring, administrative methods are targeted on preparing activities to be taken to reduce the consequences of a disaster.

4.1.2 Land use planning based on hazard maps

In the long-term perspective careful land use planning taking into account natural hazards is the most cost-effective measure to reduce risk. Empirically, the cost to implement safety measures is high, and in most cases far more expensive than the value of the building.

Land use planning with respect to natural hazards should have to main purposes:

- Where to put new developments in safe places
- Where to establish new infrastructure according to hazard level

The planning must be based on inventory maps showing historical documented mass movements or even better on hazard maps. Normally, building regulations require different hazard levels for different types of buildings or infrastructure, and the planning should therefore preferentially be based on hazard maps including all these hazard levels.

Hazard maps are closer described in Work package 3.

4.1.3 Information and education

During emergency periods information is of vital importance to ensure correct and uniform information to avoid misunderstanding. Information must be included as one of the major components in the preparedness planning described later. Information is also of vital importance during accidents and when people have been evacuated to reduce the psychic strain and uncertainty. To ensure that significant information is disseminated to relevant people (public and media), use of common public meetings, telephone and radio/television can be suitable sources. One person should be assigned to be press spokesman during emergency operations. The press is always an important source to spread information, and consistent and correct information to the journalists will normally improve the quality of this information. Empirically, the importance of good information management is many times neglected.

Education to improve the competence related to understanding of natural hazard processes can be relevant for many people and purposes:

- Specialists performing hazard evaluation to improve their capability to evaluate the hazard properly
- Teaching staff in schools and universities needs to be updated to strengthen the education of technical experts
- Governmental employees dealing with natural hazards should know the needs and challenges

- Land use planners should have knowledge about natural hazards to ensure that natural hazards are properly allowed for at an early stage in the planning process.
- Technical staff in the municipalities responsible for building licenses should have adequate basic information
- Consulting engineers/companies should know about hazard elements to ensure they are included in the planning process early enough.
- Contractors/builders should also have basic information to avoid that natural hazards are forgotten in the planning phase.

Empirically, wrong decisions leading to misplacement of new developments in exposed areas, can usually be attributed to the lack of knowledge about natural hazards somewhere in the planning process.

4.1.4 Preparedness and emergency plans

Preparedness and emergency plans include measures implemented mainly to reduce the consequences of natural disasters mainly to reduce the personal risk. They will normally not reduce the risk for structural damage to buildings, roads and infrastructure. Usually they are used when the costs for physical measures are too high compared to the economical risk, or they can be used as temporary measure until permanent physical measures are in place.

Preparedness plans include two main parts:

- Plan for activities depending on the hazard level
- Organizational plan to define who is the responsible persons to effectuate the activities

Emergency plans (or disaster management) involve preparing, supporting, and rebuilding society when disasters occur. Usually the emergency plans constitute a major part of the preparedness plans.

4.1.4.1 Evaluation of danger level

The activity plan usually describes what actions that must be implemented at different danger levels. Hence, recording of relevant meteorological factors, snow cover stability and observation of avalanches in the local environment to perform hazard evaluation should always be the basis for the activity plan. One therefore has to make sure that the quality of the data and the frequency of the recordings are good enough to detect the variability in the current danger level. Moreover, careful planning to define the criteria for danger evaluation needs to be defined. These criteria should preferably be based on empirical data.

The danger levels should preferentially follow the international danger

The danger evaluation should preferably be performed by specialists. In many cases the municipalities have the responsibility to perform the daily danger evaluation based on objective criteria. When critical conditions occur and risk becomes high, specialists should be involved.

A detailed description of avalanche forecasting is described in the next chapter.

4.1.4.2 Identification of exposed areas

The next basic input to the activity plan should be hazard maps, preferably including several zones with different probability of avalanche to occur. In such cases necessary actions would normally be extended to larger areas as the hazard level increases. Based on the hazard map one should define all elements at risk, including buildings both public and private, roads, infrastructure and possibly areas used for recreation. For each of these elements one should then define acceptable hazard levels before actions should be effectuated. The higher the risk the lower hazard level should be accepted.

4.1.4.3 Detailed activity plan

The different activities for the different hazard levels should be described with clear recommendations what to do for the different elements at risk and with reference to the zones on the hazard map. The activity plan could for example be structured by defining of activity lists for each danger level.

Table: Example of Activity list for danger level 4 (high hazard)

Element at risk	Activity
House 1	Staying overnight in basement and not stay in rooms with windows facing the slope
House 2	Evacuate people to hotel A
School A	Evacuate
Road I	Open for private cars, but public buses only under surveillance

Effective preparedness management relies on thorough integration of emergency plans at all levels of government and non-government involvement. Activities at each level (individual, group, community) affect the other levels and therefore needs careful planning.

Plans for how information and dissemination of all decisions to the public and the media must also be included. The importance of dissemination of information is often neglected in preparedness planning, but all experience demonstrates that this part should be given high priority in the planning.

4.1.4.4 Organizational plan

There is a strong need for detailed descriptions of which persons that have responsibility for the different actions in the activity plan. The persons included in the plan should cover all levels in the community and involve all agencies having responsibility for safety, e.g.:

- Representatives from the Police
- Mayor of the municipality
- Technical manager of the municipality
- Representatives from the Civil Defense
- Representatives from the inhabitants
- Professionals delaying with danger evaluation
- Representatives from rescue parties
- Representatives from health personal
- Person responsible for information dissimination

The number of persons to be included in the organization should be reflected by the risk level and how large areas that are affected by the plan, the higher the risk and the larger the area the more people should be involved.
The plans must also take into consideration whether it must be treated on a local, regional or national scale. Sometimes the key staff coordinating the activities must involve personnel from different levels in the administration according to the aerial extent and seriousness in the situation.

To implement the plans to all relevant persons, effective use of good visual aids like GIS is important.

There is a strong need for regular exercises to make sure that the plans work according to the intentions. Such exercises will demonstrate shortcomings and need for improvements in the planning both in the activity and organizational parts.

4.1.5 Conditions of insurance

To reduce the economical risk, insurance schemes can be used that will ensure that economical loss for the public is minimized. The psychic strain connected to accidents is high, especially if lives are lost. If economic concern comes in addition, this strain will be further worsened.

Such schemes can be arranged in many ways. To ensure that most people have insurance against natural hazards, the insurance should be included in the standard conditions. For example in Norway this insurance is included in the standard conditions for fire insurance policies. This insurance includes full compensation for all material losses due to natural disasters. For other subjects like for example farming land, private roads and forest that can not be included in this insurance, the National Fund for Natural Disaster Assistance can compensate for part of the loss of value caused by the disaster, typically between 50 and 80%.

4.2 Forecasting and operational methods

General definitions

Monitoring	Continuous observation of a system or measurement of characteristic parameters of a system over days, month and years.
Early warning	Warning against dangerous natural hazard events 72 to 36 hours in advance. An early warning is targeted to safety services and professionals and is distributed via specific, mostly protected communication channels.
Warning	Warning against dangerous natural hazard events more than 36 to 6 hours in advance. A warning is targeted to safety services and professionals and is distributed via specific, mostly protected communication channels.
Forecasting	A prediction several hours or days in advance which describes the characteristic phenomena of an expected weather situation or weather related situation (e.g. avalanche situation). A forecasting is generally broadcasted to the public via many different communication channels
Alert/Alarm	An acoustic, optical or mechanical signal which informs about a dangerous event shortly before its occurrence. An alarm is targeted to the public.

4.2.1 Debris flows

4.2.1.1 Introduction

Debris flows are generally developing very rapidly due to some triggering factors (see explanations in WP 1). Since debris flows are generated in small catchments often as a consequence of local thunderstorms and local geomorphological conditions, the possibilities for forecasting and warning are limited, because of the following reasons:

- the time period for warning is very short, and the
- process knowledge is low and the prediction of the local weather pattern is highly uncertain.

Because of these limitations there is no general, national or regional forecasting for debris flows like for other hydrological processes e.g. for large scale floods. Local predictions for debris flows are only possible with good local expert knowledge. These predictions can only provide a rough estimation whether debris flow could occur.

In the following, the situation in Switzerland is presented.

4.2.1.2 Forecasting and warning systems

Description and purpose
As mentioned above operational forecasting services are not established in the way they exist for snow avalanches. In Switzerland mainly the cantonal authorities obtain data and warnings from the National Meteorological Office. Their task is to derive decisions about closure or evacuation in case a dangerous situation is imminent.

Specific design criteria and materials

A forecasting and warning service should ideally consist of the following components:

a. A team of experts, which analyses observations and meteorological data before and during periods with intense rainfall. These experts have to be on the state-of-the-art of knowledge and should rely on a long year experience.

b. Observations, measurements and models

- amount and location of erodable material
- water content of erodable material
- discharge
- slope angle and morphology of the terrain
- local precipitation intensity
- air temperature (altitude of 0°C)

c. Information and communication facilities

d. Education and training programme

In Switzerland currently a measurement and observer network for forecasting of debris flow is developed in the project IFKIS-Hydro. Until 2007 the following data are used:

- Network of the Federal Meteorological Office MeteoSwiss.
- IMIS-Network, which has been established for national, regional and local avalanche forecasting. Some of these stations are equipped with precipitation sensors.
- Water depth gauges of the Federal Office for the Environment FOEN.
- Network for the measurement of debris of the working group for operational Hydrology (GHO).
- Several cantonal and local network for the measurement of precipitation.

In Switzerland there is no operational model which is able to predict debris flow.

The aim of IFKIS-Hydro is to fill this gap. The goal of this project is to build up a similar organization as it has been build up in the field of avalanche forecasting. First systems has been installed at several test sites in Switzerland. The main goal of this project can be summarized as follows:

- Establishment of a observer and measure network in several catchments,
- Definition of standards for measurements and observations,
- Coordination of existing networks for an optimal information of the safety services and fire brigades,
- Unified data storage and communication,
- Unified education courses,
- Additional research activities in the field of debris flow release.

Because most of the processes, which cause debris flows are not fully understood yet and the necessary data are not available, an operational forecasting system is not to be implemented within the next five to ten years.

Software available
The platform IFKIS-Hydro is under development in Switzerland at the moment.

4.2.1.3 Alarm systems

Since warning against debris flows is very difficult and uncertain, the timescale for safety measures is in the range „minutes to seconds“ which allows an alarm only. There are a number of alarm stations in use which release an alarm as soon as a debris flow has been triggered. These alarm stations are often combined with avalanche detection stations.

For debris flow detection there are sensors available which combine an acoustic, a seismic and a pressure sensor. This sensor is typically integrated in an alarm station and allows the detection of a debris flow event or in winter of an avalanche.
The sensor is most often installed at the edge of a debris flow or avalanche gully.
Like alarm stations used for avalanches, these systems are foremost used to protect traffic lines. An example for such an alarm station in Switzerland is the "Ritigraben" station, which protects the cantonal road from the village Visp up to the Matter valley in the canton of Valais. The station consists of two seismic sensors in the starting zone, hard- and software for controlling and data analysis as well as for alarm triggering. When an alarm is triggered, an electronic signal switches two traffic lights to red and a telephone alarm is transmitted to the police station in Visp. After 15 minutes the traffic lights switches to a blinking, yellow signal. During these 15 minutes the police checks whether the alarm was correct and conducts necessary measures. The station exists since summer 1995 and proved to be effective.

4.2.2 Snow avalanches

1. Introduction
Organisational measures, like closure of traffic links and evacuation, have become more and more in the management of avalanche hazards during the last years mainly because of improved technological facilties to forecast critical avalanche situations and to alarm potentially affected people. Two important components are forecasting / warning systems and alarm systems.

2. Forecasting and warning systems

Forecasting and warning for snow avalanches has become very important for mountain regions all over the world. Especially in the Alps it has a long tradition particularly because of the importance of the Alps for traffic and tourism. The foundation of civil avalanche forecasting services in the alpine countries started after the Second World War. Up to now it has reached a high standard in most countries. In Europe the national avalanche forecasting services are organised in a working group, which meet each other every two years. A website serves as a basis for the exchange of actual avalanche information (www.lawinen.org).
More detailed descriptions of the state-of-the-art regarding available data, danger scales and dissemination of the forecasting products and the setup and organisational aspects of European forecasting services are given in chapter 2 of deliverable 1.3 (NUMBER REFERENCE CORRECT?). In this section only a very general description of the components of a forecasting and warning system is presented.

Description and purpose

Forecasting services for snow avalanches normally exist on the national, regional and local level. In some countries avalanche forecasting is organised at the national level while in other countries they are organised at the regional level. Decisions concerning safety in villages and on traffic links are made at the local level.
The main task of avalanche forecasting services is to inform and to warn organisations and persons responsible for avalanche safety in villages, for infrastructures and for transportation links and the public about snow conditions and avalanche danger. Avalanche forecasting and warning build the fundament for decisions and actions aiming at improving the avalanche safety at the local level. Actions for reducing avalanche risk include closure of traffic links and endangered areas, evacuation of endangered areas and / or buildings. For persons moving outside controlled areas (e.g. ski pistes) measures consist of avoiding dangerous areas in the terrain or of the abandonment of an activity.

Specific design criteria and materials

The main components of a forecasting and warning system are:

a. A team of experts, which continuously analyses observations, meteorological and snow pack data from the terrain. These experts organised in a forecasting and warning service have to be on the state-of-the-art of knowledge and should rely on a long year experience.

b. Observations, measurements and models

- Manual or automatic measurement data in high temporal and spatial resolution: snow depth, new snow depth, air temperature, -humidity, global radiation, wind speed and wind direction, snow temperature. Additional data are: reflected short wave radiation, surface temperature snow, soil surface temperature.
- Field observations: observed avalanches, indications of avalanche danger in the terrain.
- Physical based models: modelling of parameters, which cannot be directly measured.
- Statistical models or expert systems: reference to actual situation, comparison with past situations.
- Electronic system for data, observation and information exchange between forecasting service and users in both directions (information system).

c. Information and communication facilities: Information system for data acquisition and transmission, software for data analysis and preparation of forecasting products, network for dissemination of forecasting and warning products (i.e. radio, TV, Internet, phone, fax etc.)

d. Education and training programme for forecasters and practitioners.

Software available

In most European avalanche forecasting and warning services there are software packages for data illustration and information exchange. In Switzerland the platform IFKIS (www.ifkis.ch) is accessible for those local and regional forecasting services, which registered to the software.
In France …
In Italy the avalanche services are organised in different regions.
In Austria …
In Norway the Norwegian Geotechnical Institute NGI establishes this platform.

Photo gallery

	
Figure 164: IMIS Wind Station Sarsura Pitschen, Canton of Grisons, Switzerland. Source: SLF	**Figure 165: IMIS Snow Station Madrisa, Canton of Grisons, Switzerland. Source: SLF**

3. Alarm systems

Description and purpose

Alarm systems are mainly in use to protect traffic links. They all work according to the same principle. When an avalanche is released, a detection system registers the process and a signal is transmitted by cable or radio to the alarm basis station at the endangered zone. A red light or a tocsin is put into operation and via a relay station an alert is transmitted to the alarm centre. The flow time from the detection site along the track to the endangered zone has to be larger than the evacuation time.

Specific design criteria and materials

The typical technical solutions, which are in use, are optical detection, mechanical detection, and seismic and acoustic detection. In the following some examples installed in Switzerland are presented.

Optical detection

Based on the principle of Doppler radar there are pulsed Doppler radar and continuous Doppler radar in use. The pulsed Doppler radar sends out short pulses in a certain time range. A pulsed Doppler radar system is e.g. used in Austria to detect and to measure artificially released avalanches but can be used as an avalanche alarm system as well. In continuous pulsed radar the signal is sent out continuously with multiple channels. It is e.g. used by the SLF at the international experimental test site „Vallée de la Sionne“ in the canton of Valais. At Vallée de la Sionne Doppler radar is applied for calculation of the avalanche velocity.

Mechanical detection

Most of the mechanical sensors are working with weighing cables, which are mounted on a cable crossover the avalanche gully. When an avalanche is moving downwards the gully, the snow touches the weighed cables causing an electrical signal, which is transmitted to the endangered area. There traffic lights are set to stop traffic on the road and/or rail and an acoustic signal is released. A further system works with gates, which are mounted on one side of the gully. The moving avalanche snow pushes the gates to the lateral side of the gully, which causes an interruption of an electrical circuit. The signal switches the traffic light to red and provides an acoustic signal.

Seismic and acoustic detection

The method is currently used both for research projects and for operational use. For seismic detection three-component geophones are used to record the avalanche activity in an area of several kilometres in diameter.

The acoustic system called „ARFANG“ which uses infra-sound microphones are either mounted on pylons in a horizontal cross shape or they are buried in the ground. They are also used to record the avalanche activity in an area.

Example of an avalanche detection and alarm system

At the alarm station Embd in the canton Valais, Switzerland avalanches from four starting zones are detected. The station is located at 2250 m a. s. l. and measures snow movements, forces on the detection cables (mechanical sensor) and concussions of the detection cables. When an avalanche is detected, alarm is released via radio and the traffic lights are switched on. In addition a message is transmitted to the head office in Sierre.

Software available

For each installed system specific software is in use. Because there are different systems in use, it is not possible to give an overview about the existing software.

Photo gallery

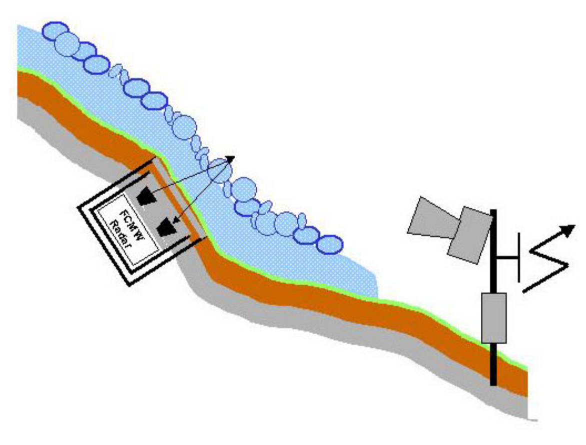


Figure 166: Schematic illustration of an optical alarm system. Source: SLF.

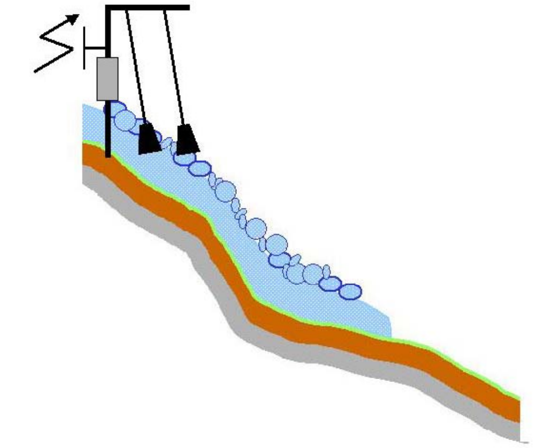


Figure 167: Schematic illustration of mechanical alarm system. Source: SLF

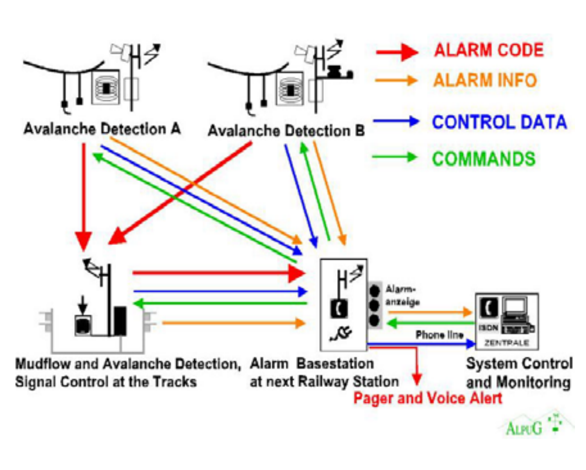


Figure 168: Illustration of the data flux in an alarm system. Source: AlpuG..

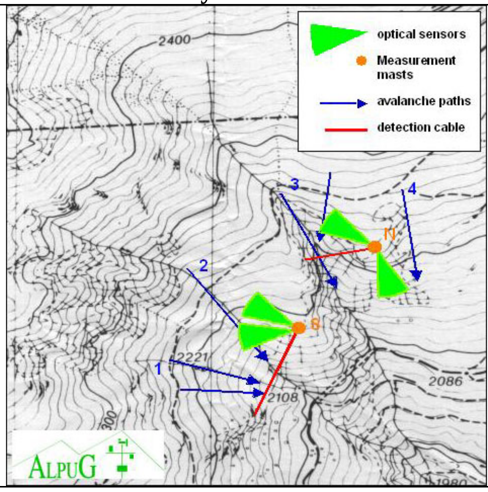


Figure 169: Alarm station Embd in the canton of Valais. Source: AlpuG.

4.2.3 Rock avalanches

4.2.3.1 Monitoring and early warning

Based on the nature of failures in rock slopes the most, and normally the only method of managing the risks associated with a rock slope movement, is the development of an effective warning system. As pointed out by Crosta and Agliardi (2003), remedial countermeasures are normally not useful when dealing with a large rock avalanche due to the extremely high kinetic energy involved. Suitable emergency planning is then the only effective tool to reduce the consequences by means of evacuation, road closure and other active measures. One of the most challenging tasks is therefore to develop realistic monitoring thresholds that are not too conservative resulting in excessive false alarms, but provides adequate warning should an event occur (e.g. Froese, 2006).

In order to establish a reliable continuous monitoring network, a series of methods needs to be used, both on the surface and in boreholes. The array of sensors needs to provide as complete information as possible in order to cover the entire slope and sectors of the unstable areas. However there are a series of practical limitations in terms of distance from measured points to the monitoring instrument, local slope conditions, rock fall and snow avalanche hazard and problematic atmospheric conditions.

The design of monitoring systems is largely controlled by the slide scenarios and the deformation pattern at the specific sites. This normally requires a detailed geological and movement investigation program. The possibility to do a forecast during an event is largely dependent on a good understanding of the 3D deformation pattern. This requires a series of different monitoring types which can detect both surface and subsurface deformation. In addition the monitoring should be able to distinguish between deformation both on a local scale (e.g. opening of small fractures) and on a larger scale (e.g. movement of larger blocks).

In the following a description of the monitoring system established at the Åknes rock avalanche location in Norway is presented. This system is presumable the most extensive instrumented rock masses in Europe and includes more or less all possible instruments available today to monitor rock avalanche initiation.

4.2.3.2 Surface monitoring

There are a series of available methods and sensors for measuring movement and deformation on the surface. These are both local measurements across fractures and clefts, and more global measurements detecting total displacements on the slope.

4.2.3.2.1 Crack meters/extensometers

The crack meters are instruments that measures the distance between open fractures, and is an easy to handle and inexpensive monitoring system. There are several types, but the most common is the vibration wire system. They can detect sub mm displacements. There are also special wire extensometers that can measure over longer distances.

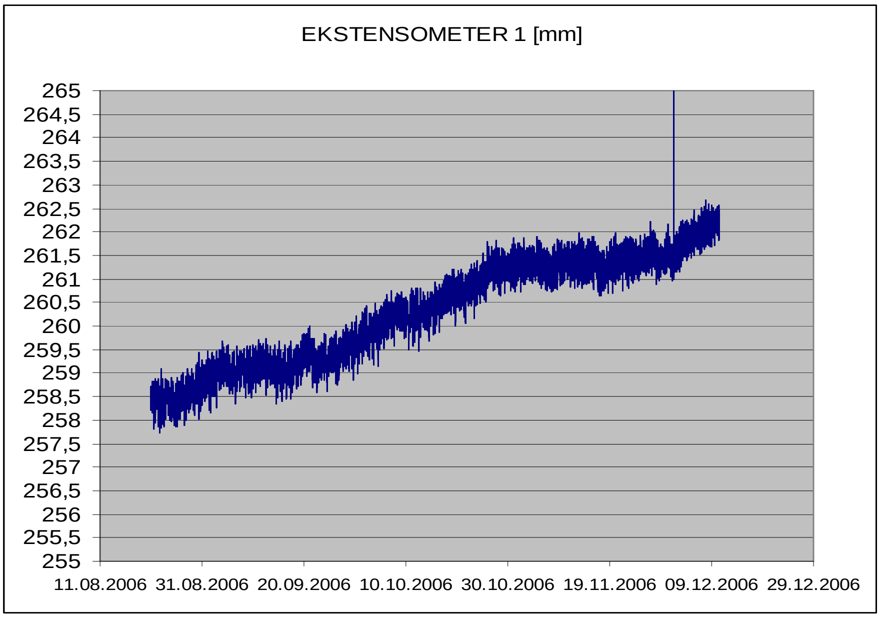


Figure 170: Pictures and example of data from an extensometer at the Åknes rock avalanche in the second half of 2006.

4.2.3.2.2 *Tilt meters*

A tilt meter measures very small changes from the horizontal level, either on the ground or in structures. The modern electronic tilt meter uses a simple bubble-level principle, as used in the common carpenter level. The arrangement of electrodes senses the exact position of the bubble in the electrolytic solution, to a high degree of precision. Any small changes in the level are recorded using a standard data logger. This arrangement is quite insensitive to temperature, and can be fully compensated, using built-in thermal electronics.

Tilt meter a relatively cheap monitoring system that can be important during stages of large displacements, and can also be used for the evaluation of the deformation mode, e.g. if the rockslide is rotating.

Figure 171: Modern electronic tilt meter

Figure 172: Traditional tilt meter

4.2.3.2.3 *Single laser*

Distance laser sensors measure the distance from the sensor to a target or reflector on the detached area. It can be particular important system in areas were you have a large distance between open cracks, and where extensometers or crack meters can not be used. The target can also be large reflector plates witch can be heated in order to avoid snow and ice on the target. The resolution can be better than 1 mm, but as all measurements through air, the data are changing due to atmospheric conditions, e.g. temperature and humidity.

Figure 173: Example of one of the single lasers that are established at the Åknes rock avalanche (the laser and web camera to the right and reflector plate to the right).

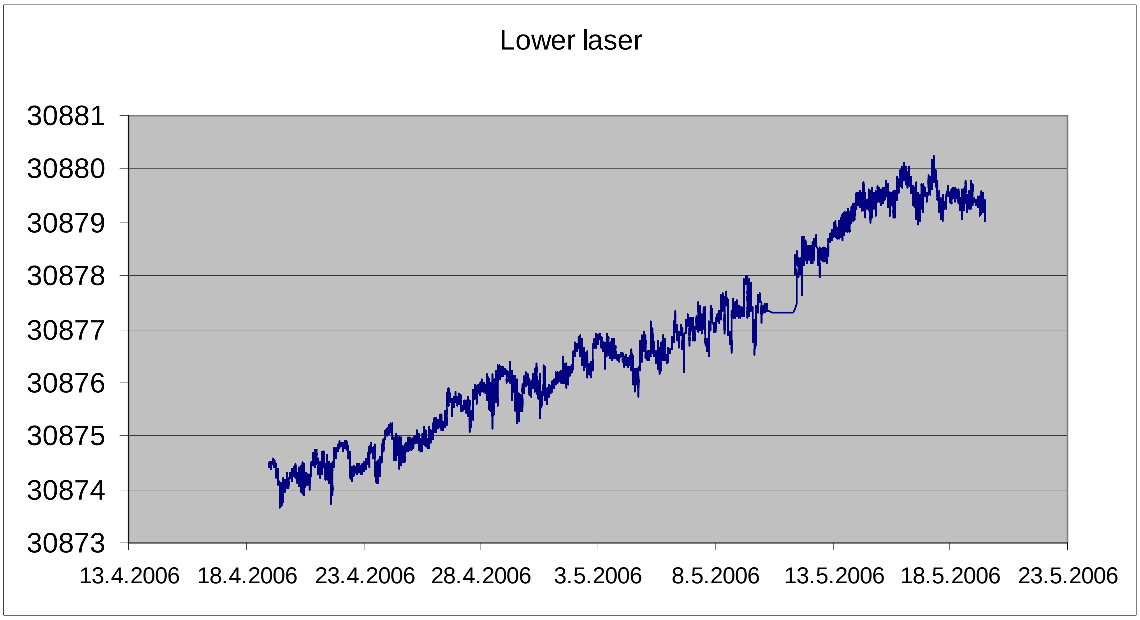


Figure 174: Example of data from single laser at the Åknes rock avalanche site.

4.2.3.2.4 Total station

A total station is a robotic optical survey system that can measure the distance to numerous prisms in the unstable area. The system is important in order to get an overview of displacements. The position on each prism can for example be performed every

Figure 175: Example of a total station

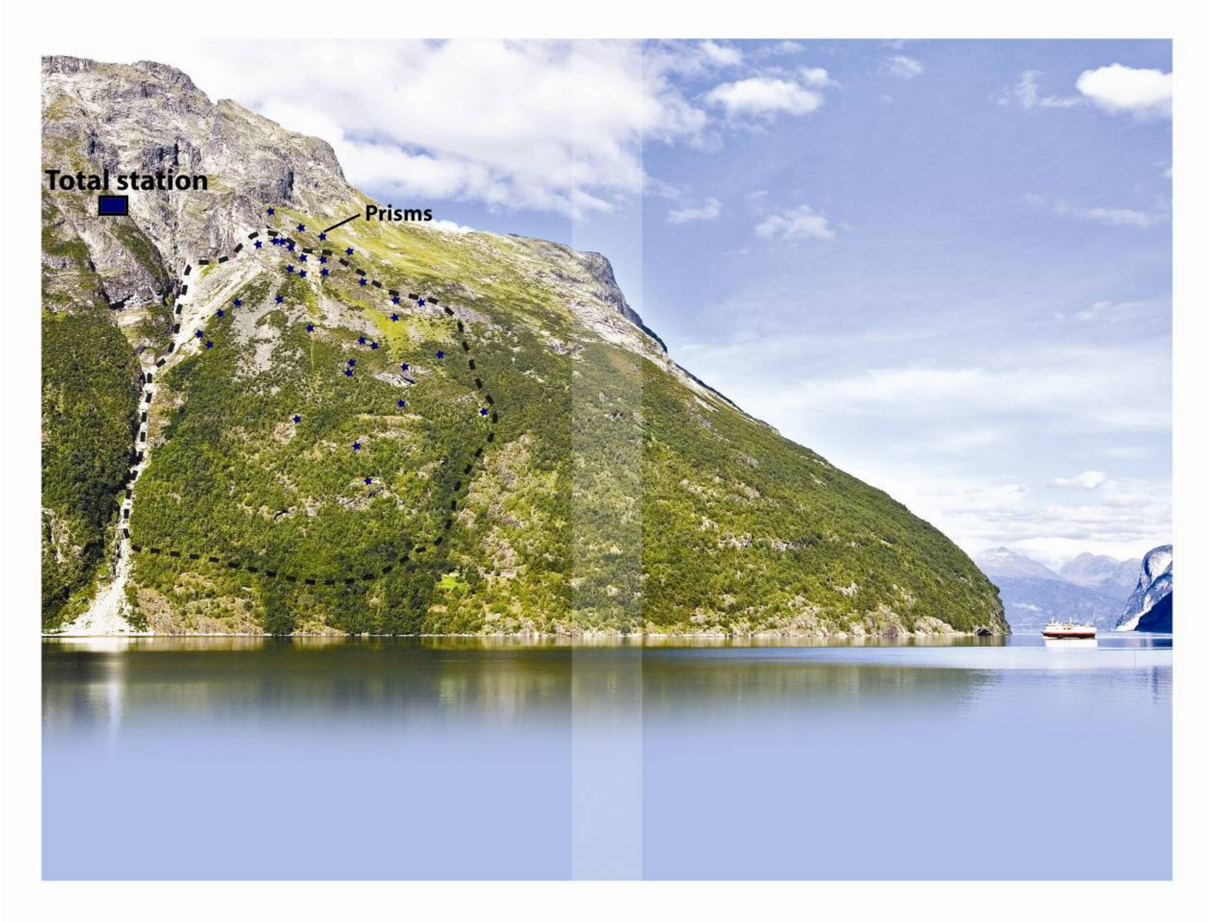


Figure 176: Overview of the location of total station and prisms at the Åknes rock avalanche.

4.2.3.2.5 Global positioning systems (GPS)

A GPS network was established to detect movement in areas where it is difficult to use Lidar scanning or ground radar owing to poor visibility. Two of the GPS are established in stable areas acting as reference points. The data are transformed by radio signals automatically to a PC. The GPS points are localized to areas assumed to be critical for the overall stability condition. The resolution can typically be down to 1 mm.

Figure 177: Stationary continious recording GPS at Åkneset

4.2.3.2.6 Lidar scanning

LIDAR (*Light Detection and Ranging*) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The prevalent method to determine distance to an object or surface is to use laser pulses by measuring the time delay between transmission of a pulse and detection of the reflected signal. Lidar scanning can be used to scan movement on larger surfaces. The instrument must be placed at a location with good view to the unstable rock mass. By comparing two images taken at a different time, relative movements can be estimated.

4.2.3.2.7 Ground-based radar

Radar is another technology with same purpose as the Lidar scanning, but using radio waves instead of light. As for the Lidar the accuracy of the technology largely depends on the existence of good reflectors on the surface.

Figure 178: Ground based radar sensor in use at Åkneset

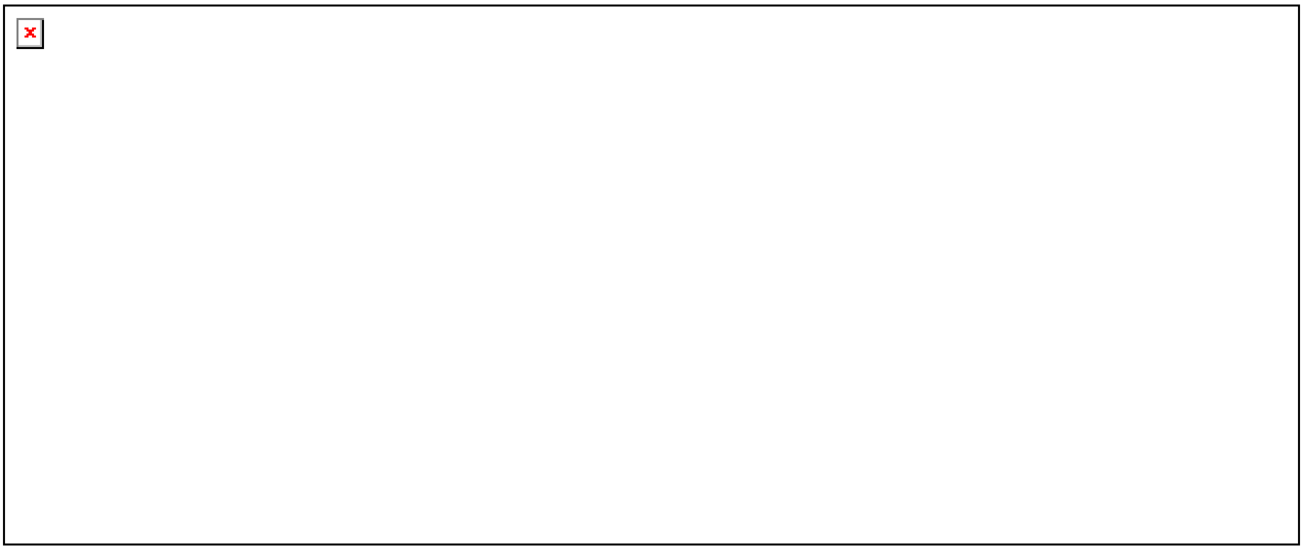


Figure 179: Surface movements detected by means of ground based radar

4.2.3.3 Seismic network

The objective of permanent passive seismic monitoring systems is to record seismic events that are related to deformations in the rock mass. The network at the Åknes rock avalanche consists of 8 3-component geophones (4.5 Hz). The geophones need to be oriented and solidly cemented to the rock. The individual instruments are then connected to a central acquisition system in a concrete bunker by up to 300 m long reinforced cables that are fixed with bolts to the ground in order to withstand snow creep. The acquisition system at the Åknes rock avalanche consists of a digitizer (Geode), an industrial computer (PIP6) with very low power consumption, a GPS-clock, an Ethernet hub and a GSM telephone relay that allows to switch on/off the individual components and sends an SMS-warning in case of power failure. An important task is to establish a reliable transfer of large amount of data. The current monitoring in continuous mode at Åknes with a sampling frequency of 125 Hz results in about 1Gbyte of data per day.

The rate of seismic activity may be indicative for the current state of the slope, and an increase in seismicity may indicate an acceleration of the movement.

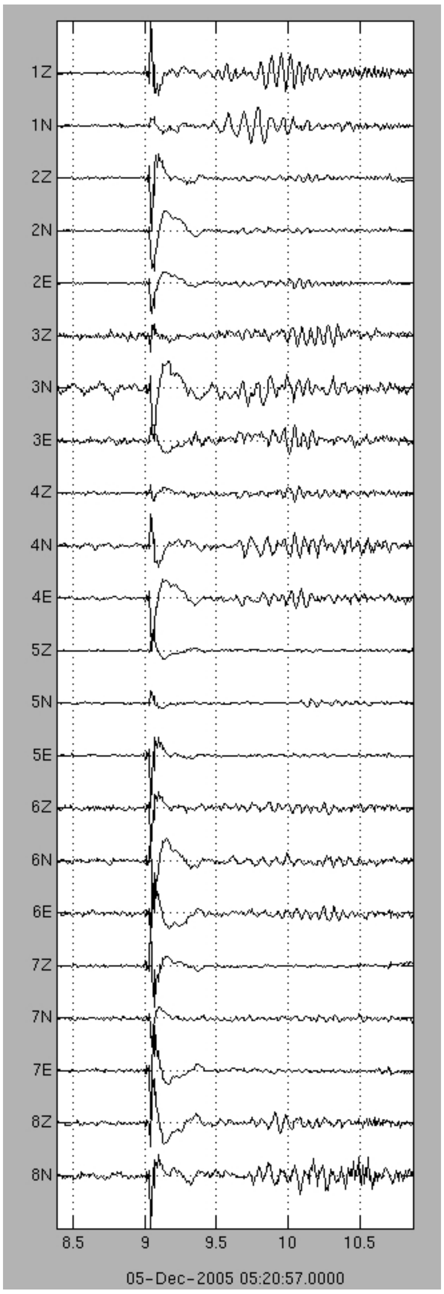


Figure 180: Figure: Seismic signals recorded at the Åknes rock avalanche, western Norway (Roth, 2006). A very strong seismic event that could be the result of a sudden movement in the uppermost part of the slope.

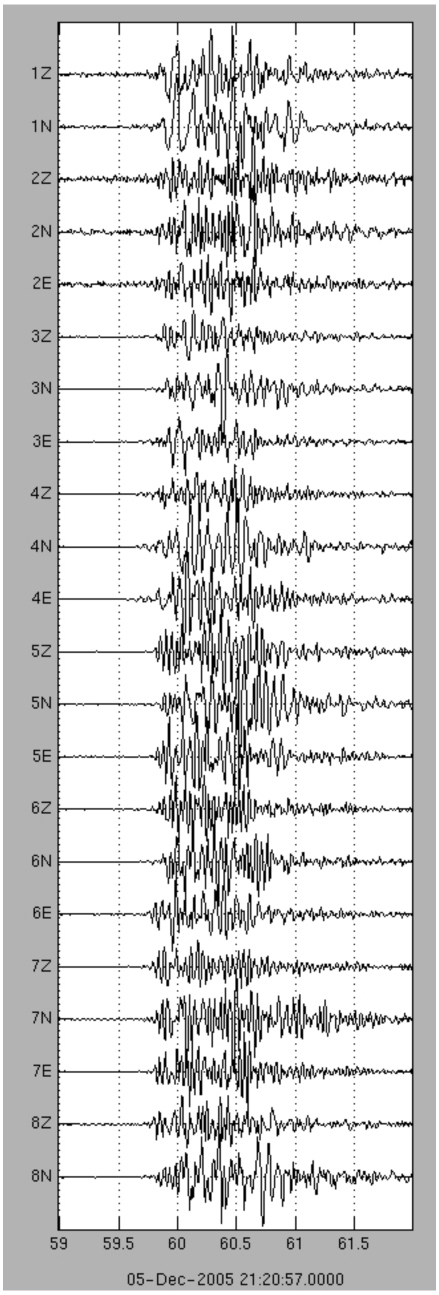


Figure 181: Figure: Seismic signals recorded at the Åknes rock avalanche, western Norway (Roth, 2006). A complex seismic signal that could be the result of a rockfall.

4.2.3.4 Subsurface monitoring

The choice of subsurface monitoring in boreholes is largely dependent on what type of deformation is going to be monitored. It is also normally possible to integrate several types of sensors in the same borehole (e.g. inclinometers and piezometers).

Figure 182: Drilling rig used to establish boreholes

4.2.3.4.1 Borehole inclinometer

Inclinometers detect small changes in the inclination of the borehole and can thus be transferred into horizontal displacements. There are now digital systems available that can configure a series of sensors in one column (Figure).

Figure 183: From the establishment of instrumentation of the DSM column at the upper borehole at Åknes. The 50 m long DMS column include 50 individual inclinometers, 50 temperature sensors and two piezometers.

4.2.3.4.2 Borehole extensometer

The borehole extensometers are well suited if you have extension in the subsurface, e.g compression and buckling that can give upward movements. Borehole extensometers can also be used in more horizontal boreholes in order to detect horizontal displacements.

4.2.3.4.3 Piezometer

Piezometers are measuring the pore pressure or the water level in the borehole. You can either use single piezometers in open piezometric pipes or solutions with multi piezometers if there are more complex hydrological conditions (e.g. perched water tables).

4.2.3.5 Supplementary monitoring

The displacements need often to be related to climate data, in particular precipitation and snowmelt. A meteorological station would normally include sensors giving temperature, precipitation, snow depth, wind speed, ground temperature and radiation.

Also measurements of discharge in springs in lower part of the rock avalanche can give valuable data about changes in the hydrological conditions, which is often critical for rock avalanche displacements

Figure 184: Automatic weather station at Åkneset

4.2.3.6 Integration of systems

The data handling and interpretation is an important aspect of all monitoring projects. It is thus of major importance that the data are processed, stored and visualized in an effective manner. In critical situation with increased displacements it is vital that the experts can get data fast with predefined visualization tools and with the possibility to do proper analysis.
The historical data is important for the analyses of movement behavior and velocity trends. This will be the basis for establishing site-specific threshold values for the different levels of warning.

4.2.3.7 Power and communication

One of the major challenges related to monitoring in remote areas is the power supply and data transfer. This is often crucial for the quality and reliability of the entire early-warning system.

4.2.3.8 Reliability

In order to optimize the reliability of the monitoring systems there are several important aspects that is needed to be taken into account:

- The need for several different monitoring systems in order to cope with problematic situations were one or several system may be out of order
- Large changes in weather and atmospheric conditions may occur that may affect the efficiency of the instrumentation
- Snow-avalanche and rock-fall hazard in the monitored slope may cause damage the instrumentation
- Optimal and reliable system for power and data transfer

The experience from some of the large international monitoring projects may indicate that the different systems can be grouped according to their importance and reliability in operational early-warning systems, which is often site-specific:

Primary sensors: Reliable and robust
- Surface crack meters/extensometers
- Surface tilt meters
- Single lasers (needs caution during bad weather)
- Borehole inclinometers
- Borehole extensometers

Secondary: Not yet reliable for full operational monitoring
- Laser Ranging (EDM),
- GPS
- Ground-based radar
- Microseismic sensors

Tertiary: Support/Information Sensors
- Meteorological station
- Piezometers
- Weir

4.2.3.9 Early-warning

A fully operational early-warning systems (monitoring centre) needs to include the following important aspects:
- Reliable monitoring network, including stable power supply and data transfer
- Full operational monitoring (technical and geoscientific)
- Warning procedures, including evacuation routes and implemented warning systems

In Åknes the early warning is based on the rate of movements. Five alert levels are used:

Alert level	**Rate of movement**	**Activity**
Green	• Small variations in movement	• Situation can be handled by staff at the emergency control centre • Technical maintenance
Blue	• Seasonal differences • Threshold-value 1	• Higher frequency of recordings • Geological expert group is informed
Yellow	• General increased movement • Threshold-value 2	• 24 hours continuous observations • Geological expert group is involved • Police and municipalities are informed
Orange	• Acceleration in movement • Threshold-value 3	• Emergency control centre continuously manned • All relevant personnel in emergency management are involved
Red	• Increased acceleration in movement • Threshold-value 4	• Evacuation is initiated

The alert levels are based on the velocity (mm/day) of the movement of joint opening.

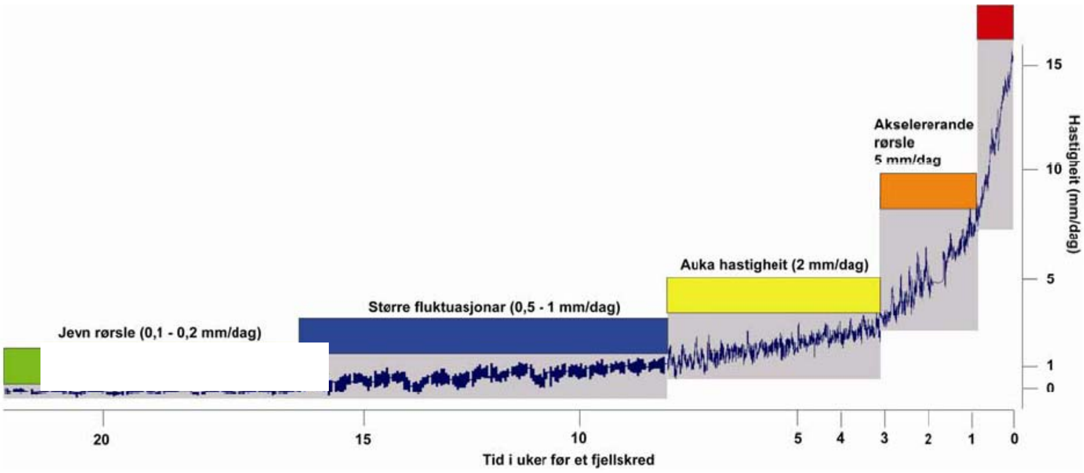


Figure 185: The alert levels depend on the rate of movement. Y-axis: Velocity of movement (mm/day). X-axis: Time (indicated by weeks before a possible rock avalanche)

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