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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

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PRIORITY VI
Sustainable Development, Global Change and Ecosystems

SPECIFIC TARGETED RESEARCH PROJECT

irasmos

INTEGRAL RISK MANAGEMENT OF EXTREMELY RAPID MASS MOVEMENTS

WORK PACKAGE 2:
HAZARD ASSESSMENT AND MAPPING OF RAPID MASS MOVEMENTS

DELIVERABLE D2.3

Recommendations and best practice

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Chapter 1

INTRODUCTION

Introduction	When countermeasures are planned it is important to distinguish between the different kinds of infrastructures that are subjected to the hazard of rapid mass movements, e.g.: • Housing areas • Roads, railways • Electrical power and communication lines • Alpine ski areas, tourist infrastructure • Others The reason is that different kind of infrastructures may have different demands concerning safety levels (social demand for protection, acceptability of risk), and because different protection methods are best applicable to certain kinds of infrastructures. In general, possibilities for reducing the risk must be discussed: 1. Relocation of the endangered infrastructure 2. Use of non-structural measures: establish preparedness plans, hazard forecasting, and temporal evacuation. Long term perspective: Land use planning and legislation 3. Use of structural measures In the discussion which of the three alternatives is preferable, one should seek the best solutions both for the people exposed to the hazard, and for the local and national society. It is to be kept in mind that the interest of these three groups is not always congruent The reduction of risk and the increased safety gained by each of the three methods must be compared to the total cost of the implementation of the methods by: Determination of cost/risk functions Determination of benefit/risk functions Calculation of the net benefit Selection of the maximum net benefit solution

	All direct and indirect costs and benefits must be taken into account in Cost-Benefit Analysis (CBA), however there might be other decision making methods such as Maintenance-Cost Analysis (MCA). Examples of direct cost are: • Planning of defence structures • Access roads for the constructions • Implementation of the chosen defence structure • Maintenance cost and running cost (e.g. excavation of retention basins; explosives for artificial release) of countermeasures Indirect cost could be: • Compulsory acquisition of the land needed for the defence structure • Relocation of houses, roads, drainage systems etc. because of the location of the defence structure • Human, socioeconomic factors and related costs • Time and energy used by unpaid people involved One must also bear in mind that natural hazards and risk reduction is often a matter of conflict between the expert, the political authorities and the people directly exposed to the hazard. The expert may regard the hazard differently than the local people exposed to the hazard and may therefore present solutions for risk reduction which are not acceptable to the people involved, or to the politicians.

Chapter 2

NON-STRUCTURAL MEASURES

2.1 Administrative methods

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

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

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 structural 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.

The cost of such measures can be low compared to the gain with respect to avoiding loss of lives and damage of property, for example by avoiding that new houses are established in exposed areas due to hazard maps.

	2.2 Forecasting and operational methods
	Forecasting and operational methods are dealt with in WP 1. Forecasting systems are most relevant for roads and other infrastructure. For housing areas however, forecasting and evacuation during acute weather conditions, should only be used as preliminary measure until permanent measures are in place. The exception is for rock avalanches where monitoring systems including forecasting and alert systems can be relevant. The reason for this is that the annual probability and frequency of rock slides are much lower than for the other hazard types, and that the efficiency of structural measures are uncertain and that the cost is high. On the other hand the consequences can be extremely high, often making the total risk unacceptably high.

Chapter 3

STRUCTURAL MEASURES

3.1 Analysis and planning

The national or local safety regulations for the different kinds of infrastructure types are the basis for the type and dimensions of the mitigation measures. Return period of the mass movements, in combination with impact forces are the most common basis for legislative regulations. Some countries like Iceland define the personal risk of death as the basis for the accepted risk level.

Acceptable risk level determines the design of the measure. The willingness of the society to pay for preventing a fatality is an important issue in this context. How much money should the society spend for safety of the people? This is a clear political issue, and for the politician to decide.

For buildings, safety levels are defined by national building codes decided by political authorities, where different kind of buildings may have different requirements related to risk. For roads and outdoor activities (e.g. downhill skiing), acceptable risk levels in many cases are not defined. Therefore it is important to reach an agreement to which safety level the measures should be designed for at an early stage in the planning process.

The choice of mitigation method will depend on the kind of infrastructure that is to be protected, type and magnitude of the structures, strength and localization in relation to other structures, how existing infrastructure will reduce the hazard for other structures farther down slope, etc.

3.1.1 Analysis

As a first step in the planning process an analysis of the release area must be performed:

Description of the hazard area:

	Catchment/release area: • Inclination, area, shape (cirque, depression, scar, brook), instable slopes, sediment sources, possibility of separate avalanche starting zones that can reach the same runout area • Avalanches: assessment of the possible magnitude of the starting area. Special emphasis should be given to non-typical slide terrain, as protruding areas, ridges, wind exposed areas, rugged starting zones with boulders, and partly vegetation covered starting zones. Such terrain formations are difficult to analyze with respect to release area and frequency, especially when no historic records of slides exist. • Lithology, geology, geomorphology • Vegetation cover, woodland, tree line • Drainage, area of water shed, water discharge • Type of mass movements which may occur • Historic events at the location and in the area • Geomorphic indications of mass movement activity • Mass wasting, soil creep, erosion, transport and sedimentation • Volume of sediment potential • Climatic conditions: Precipitation (long- and short term), temperature, snowfall, prevailing wind directions. Analysis of extreme weather situations. Return period of extreme weather conditions. • Return periods of snow heights, snow cover development, snow cover distribution • Ground investigations for defence structures • Magnitude and frequency of the design event • Human activity *Channel/track:* • Open slope, shallow depression, gully, brook, straight, curved • River bed and river banks: Loose deposits, bedrock, woody debris. Potential of erosion, transport and accumulation • Potential bottlenecks for clogging • Ground investigations for defence structures • Magnitude of entrainment • Human activity *Deposition area/runout zone* • River fan, open slope, river course, depression, gully • Area, length, inclination, lithology, geomorphology • Bedrock, type and amount of loose deposits • Drainage conditions • River bed and river banks: Loose deposits, bedrock. Potential of erosion, transport and accumulation • Ground investigations for defence structures • Type of infrastructure/buildings to be protected • Tenure (private or public land) • Process velocity, volume and frequency for a given location in the path of the mass movement
	3.1.2 Planning
	The planning of structural counter measures is usually performed in two steps: 1. Survey plan 2. Detailed plan The planning process must consider which kind of defence structure fits best for the

	project: Constructions in the • Catchment/starting zone • Channel/track • Deposition area/runout zone The plan should consider alternative solutions if possible. **Survey plan.** The survey plan should contain the conclusions from the sections mentioned above concerning the: • Terrain inspection; catchment/starting zone, channel/track, deposition area/runout-zone • Impact exposed to infrastructure/settllements • Calculation of initial risk • Discussion of alternatives for protection • Overall design of the defence structures: Location, design, length, height and strength of structures based on accepted dimensioning criteria • Description of uncertainty for the alternatives • Calculation of residual risk for the alternatives • Description of cost/benefit for the alternatives • Secondary impacts to the local area or society induced by the defence structures, e.g. ecological / economic consequences? **Detailed plan** The detailed plan must be based on the chosen alternative from the survey plan. The plan must contain drawings and descriptions of the defence structures in such a detail that a contractor or other kinds of construction companies are able to implement the defence structures in such a way, that the builder can verify and control the implementation. For the defence measures, the plan must describe location, design, heights, lengths, length profiles, cross sections, volumes of excavation and fill, detailed drawings of concrete structures, foundations, drainage etc. In short, all items which are needed to fulfil the project. The plan, with complete description and drawings, must be made to fit into a set of tender documents. The tender documents must be structured according to the national building codes and construction standards. A detailed electronic map with counter lines 1 m should cover the area for the location of the defence structures. All constructions must be shown on the map. The location of the structures must be surveyed in the terrain to establish the geographical coordinates for the constructions.
	3.1.3 Planning process
	The planning and design of the safety measures must be performed by experts with long experience in the field of natural hazards. Also during the constructional phase there is a need for experts to control that the plans are followed. In addition, a final control should be carried through to ensure that constructions are built as planned. When natural hazard mitigation works are planned, the clients are usually municipalities, other public institutions or authorities, building consultants, contractors,

architects or private persons. Few or none of these are experts in mitigation measures for natural hazards. It is therefore important that the expert informs the builder or client to ensure that they obtain a good overview and understanding of the plans. Cost estimations and any major secondary consequences of the plans must be clarified as early as possible in the process.

Very few people are aware of the magnitude of defence structures which normally is needed for protection against mass movements, and this point should be dealt with in detail. The responsible expert must first of all explain to the client about process behaviour. The expert must for instance illustrate which speeds, volumes and impact forces one need to consider and what this means with respect to heights, lengths and volumes of the protective constructions.

The preferred location of the defence structures should be discussed thoroughly. Many considerations must be taken into account in this respect. Seen from the expert's side, it is usually a clear advantage to locate for instance a retaining dam as far down in the path as possible, first of all to reduce speeds before the dam is hit. The client or landowner, on the other hand, could want to locate the dam higher up in the track, outside of the most economic valuable area, or far away from existing buildings, so that the dam does not disturb his view or reduce the exploitation of his land or excess to the area.

The expert must first of all present his preliminary plans to his client, for instance the administration of a municipality and discuss the basic layout and possible alternatives. If a housing area is the subject for protection, the residents must be informed about the planning and decision process as early as possible in the planning process. Public meetings for the involved people should be arranged. Here, both the experts and the political leadership should present the plans. If possible, more than one alternative should be worked out and presented.

Design criteria and the most important layouts should be presented. Advantages and drawbacks of the plans should be discussed; together with possible means of financing the defence structures.

3.1.4 Cost/efficiency aspects

Alternative measures should be evaluated to find the most cost effective measure. The efficiency should include both personal risk reduction and economical profits to land use and buildings. Maintenance costs and the effective life of the measure have to be taken into account.

The experts must be open and honest, explain in understandable terms what he or she does know about the effect of the proposed defence structure, and what is not known. The expert should inform about any uncertainties in the design criteria. Moreover, what is thought to be the design event with respect to magnitude and frequency. This last point must reflect the national safety demands and safety regulations concerning natural hazards.

There is always residual risk related to safety measures due to constraints in design criteria and physical understanding of the processes involved in the interaction between the measure and the sliding mass. The residual risk must be calculated or at least discussed, as no defence structure will in principle be able to guarantee a 100% safety.

The expert must be prepared to meet strong arguments, both in favour and disfavour of his plans. People often have good knowledge and clear views about how things should be in their own neighbourhood, and about the natural hazard, but sometimes also irrelevant arguments are brought forward. The expert must be patient and willing to listen to all kinds of arguments, because natural hazards involve strong feelings.

A hazard map is usually carried out previous to the planning of defence structures. In some cases natural hazards affect buildings, roads and other kinds of infrastructure unexpectedly, and in such cases no hazard zone existed before the event.

As a consequence of the planned defence structures, an updated or new hazard zone must be made for the area in question. The hazard zone must reflect the effect of the defence structures, as the endangered area will be altered. Whether the adjusted hazard zone should take into account the full expected effect of the defence structures, must be based on the calculated residual risk, other elements such as human factors (peoples feeling of safety), environmental conditions, and finally, political decisions. The determination of effectiveness is a critical issue that has to be based on expert judgement rather on general guidelines.

Possible restrictions with respect to land use in the original hazard zone after construction of safety measures should be decided.

3.1.5 Other aspects

Psychological factors:
The human factor has to be taken into account when safety measures are planned. People influenced by the measures have to rely on the efficiency of the measure. The people should therefore be involved in the planning process to have the possibility to have influence on the design. People also have great concern about how the measure influences on the landscape.

Landscape architecture:
Large building projects should include landscape architects to minimize the interference with the natural terrain conditions. Important factors are choice of material, biological remedies to make the measures less visible, rounding off of fills etc.

Land use:
Land use after the construction phase should be taken into consideration. What are the plans for the use of land in the future? Therefore the land owner and the public authorities have to be included in the planning process to evaluate how these requests can be included in the design phase.

Geotechnical/geological aspects:
The geotechnical and geological conditions will be of vital importance in the planning process to which kind of structure that can be built. Both the stability of the fill material for dams and walls and the foundation conditions both in loose material and in bedrock for the measures have to be taken into account, and they will give restriction to the design and the possible alternative measures.

Need to include all possible kinds of natural hazard:
In many cases several natural hazards are possible in the same mountain side, drainage basin or slide path. In the planning process there is a need to find optimal solutions taking into account all the relevant hazards. The height and strength of the measure should normally be based on the hazard with the widest deposition area and major impact.

3.2 Structural countermeasures against debris flows

3.2.1 Drainage

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 (hillside)
- Draining subsurface runoff to prevent the formation of shear surfaces

3.2.2 Soil bio-engineering

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 surface erosion, improve soil water conditions and control shallow land sliding.

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 made 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.

3.2.3 Afforestation

Berm afforestation 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 centre 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 framework 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.

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.

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.

3.2.4 Sill

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, the bed slope should not exceed 5 %.

A series of sills is able to reduce the flow velocity by permanent alteration of the hydraulic conditions from supercritical ($Fr>1$) to sub critical ($Fr<1$) 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 destabilise the banks and the sills themselves.

3.2.5 Ramp

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 nature-like 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 key factor for their stability.

3.2.6 Series of check dams

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 force of the discharge is reduced and the sedimentation is encouraged, 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.

3.2.7 Debris flow breaker

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 flux.

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. 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.

3.2.8 Drop structure

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 pressure.

Experience showed that if there is sediment abundancy 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.

3.2.9 Organic debris filtration – open check dam (rake)

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 sediments.

Organic material can be filtered out at three locations:

- Upstream the structure with
    - Rope barriers
    - Net barriers
- Close to the structure with
    - Vertical rakes
    - Inclined rakes
- Downstream the structure (after overtopping it) with
    - nets and rakes

3.2.10 Open check dam – permanent deposition

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 an 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.

3.2.11 Open check dam – temporary deposition

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 helps to maintain a balanced sediment flux.

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 a substantial 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. As the woody debris usually causes a clogging of the drains, the self-draining of the retention area with the tail water does often not work as intended, 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”.

3.2.12 Protection and deflection walls

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 they are 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 at the location of the structure. In addition, because of the curvature of the flow path, 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 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 armouring must also be included in the design of these structures to minimize the entrainment 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.

	3.2.13 Transport channel
	Transport channels are generally installed on the alluvial fans of torrents, to enhance the convergence capacity of torrential floods across urbanized zones. They are normally canalized, 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 channels is to ensure the flow of a given discharge without flooding or flow diversion into 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.

3.3 Structural countermeasures against snow avalanches

3.3.1 Snow fences

Snow fences are linear rows consisting of posts anchored to the ground combined with horizontal boards.

The purpose of the snow fences is to collect drifting snow and thereby reduce snow heights in the starting zones, and to prevent formation of cornices.

The fences are built on mountain plateaus and ridges above, and windward of the starting zones. Direction of the fences should ideally be normal to the prevailing wind direction. The width of the plateau windward to the starting zone should be at least 15 times the height of the fence to have enough area for the snow accumulation.

Snow fences are usually 2-4 m high. Construction material is steel and impregnated wood mainly. To collect maximum amounts of snow, and to prevent snow accumulation at the fence itself, the fences should consist of 50% openings and 50% solid material, plus a gap at the ground of 1/5-1/10 of the height of the fence.

Several rows of fences may be used if the plateau is wide enough, instead of increasing the height of the fences.

Higher fences will be subjected to strong wind forces. Because of high wind forces in mountainous areas in general, snow fences must be of solid construction. Strong anchoring to the ground is therefore necessary.

On inclined slopes, greater than about 15°, fences may be subjected to forces from snow creep and glide.

The effect of the fences must be regarded as a supplement to other countermeasures, as fences alone will not eliminate avalanche hazard.

It is anticipated that the fences may reduce snow depths about 100 m vertical into the starting zone. Therefore fences are more effective in small slopes with little vertical drop, compared to bigger starting zones.

Costs differ greatly, according to location, terrain, material and country. Prices range mainly between € 1000 – 6000 per running metre fence for European countries.

	3.3.2 Jet roofs (blower fences)
	Jet roofs are inclined panels that accelerate the wind and direct it into the slope below. The jet roofs are built at the edge of mountain plateaus and at ridges above-, and windward of the starting zones, to direct the snow drift downhill. The purpose of jet roofs is to prevent the formation of cornices. The jet roof should ideally face-, and be located perpendicular to the prevailing wind direction. The construction is made of an inclined roof, at about 40° to the horizontal, with an opening of 2-3 m height on the windward side. The opening on the leeward side is about 1 m. Design criteria for jet roofs are scarce or not existing, and the use of this kind of countermeasure is limited. The effect of the ret roofs must be regarded as a supplement to other countermeasures, as jet roofs alone will not eliminate avalanche hazard. The roofs may prevent the formation of cornices, but transport drifting snow down slope where snow heights will increase and thereby lead to avalanche hazard. Costs seem to be in the range of € 3500-5000 per running metre.

	3.3.3 Wind baffles
	A wind baffle consists of a trapezoidal board, turned upside down and fixed to one or two poles, which are anchored to the ground and facing the prevailing wind direction. The purpose of wind baffles is to create local zones of wind erosion of the snow cover. Thereby they can reduce or prevent avalanche release. The baffles are implemented at the top of the starting zone to prevent formation of cornices or to break up the snow cover by increased wind speed around the baffles. Wind baffles should be located in wind exposed areas to ensure high wind speeds around the construction. Areas with little wind and depressions in the terrain should be avoided, as the constructions will soon be covered by snow. Typical heights are 3 – 3,5 m, width is 1,5 m at the bottom and 3 m at the top. Ground clearance is about 50 cm. The baffles may have a mixture of openings and solid material like ordinary snow fences. The baffle may be built as one panel, which should be orientated perpendicular to the prevailing wind direction. The baffles may also consist of two panels, built as a cross. Wind craters in the snow around the baffles are reported to obtain sizes up to 8 m width and 30 m length. Higher baffles lead to greater areas of influence. Design criteria for wind baffles are scarce or none existing and the use of this kind of countermeasure are limited. Costs are uncertain and depend on local conditions

3.3.4 Permanent supporting structures

Permanent supporting constructions comprise two types: Rigid structures and flexible wire 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. The structures intend to support and retain the snow cover in place to prevent avalanches, and the snow heights should not exceed the height of the structures.

Supporting constructions are built in the starting zone of the avalanche (release area). The structures have to bear mainly static loading, resulting from the creeping, gliding, and settling of the snow cover. Snow masses already in motion cannot be stopped by supporting structures as they are too weak to withstand large dynamic forces. However, they are designed to withstand slides and sluffs.

The structures are built in parallel rows, where each row is following the contour line. The distance between the rows depends mainly on the snow height, inclination of the slope and the ground conditions.

The height of the structures must be dimensioned for the expected maximum snow heights for a specific return period. If the snow height exceeds the height of the structure, avalanches may release in the uppermost part of the snow cover. The dimensioning return period differs between countries. For Switzerland, for example, a 100 year return period for the snow heights is used. (30 year times a safety factor of 1,5). For Norway, the structures should be able to prevent snow heights with a return period of 1000 years for housing areas.

Supporting constructions are the most commonly used countermeasure, especially in the Alpine countries, where several km of constructions are implemented each year.

Advantages:

- Large experience with design criteria of avalanche supporting structures. (Swiss design criteria available on internet: http://www.bafu.admin.ch/php/modules/shop/files/pdf/phpUiQM8a.pdf
- Large field experience with implementation under different conditions
- Low maintenance costs (2-3% per year of investment)

Drawbacks:

- Limited appropriateness for very large release areas => uncertain effectiveness
- Expensive when applied to large release areas
- Negative environmental impact on the scenery

Costs are high to very high depending on local conditions and country. For example in Switzerland the cost for one meter of steel construction range between 1000 and 1600 €. For snow nets the cost is around 1700 €.

	3.3.5 Temporary supporting structures
	Temporary supporting structures have the same function as permanent supporting structures. The structures are erected more or less perpendicular to the slope and are well anchored in the ground, and act as barriers against creeping and gliding of the snow cover. The usual types are timber rakes and tripods. While timber rakes are connectively built in a row, tripods are spaced at uniform distances. The structures are used in areas of reforestation, as the regenerating forest will provide the protection, when trees are high enough. Temporary supporting structures are usually designed for a lifetime of roughly 50 years.
	Advantages: • Timber structures are less expansive than steel structures. • In general, good experience with reforestation. • In general, protection forest is one of the most cost-effective mitigation measures against snow avalanches in alpine countries. 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. • Reforestation as countermeasure is less effective in colder climates where the tree line is considerable lower than the starting zones Design criteria, foundation and arrangement of the constructions are based on long experience and practice. Specific design criteria are developed for the structures. Costs are moderate and range between 600 and 800 € in Switzerland.

	3.3.6 Catching dams
	Transversal structures designed to stop or to initiate the stopping of flowing snow, built transversally to the flow direction of an avalanche. 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. The design of 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. There must be sufficient space above a catching dam to store the volume of snow corresponding to the tongue of the design avalanche successfully stopped by the dam. The effectiveness of catching dams to completely stop snow avalanches seems to be particularly uncertain. It seems that highly fluidized avalanche might not form shocks as more dense ones do.
	3.3.7 Deflecting dams
	Structures designed to deflect flowing snow out of an endangered area. The structures are inclined to the flow direction by a certain deflection angle. 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. The effectiveness of the dam largely depond on the height and the steepness of the dam. Several avalanches in the same path can fill up the dam which can cause overtopping by subsequent avalanches.

3.3.8 Breaking mounds

Breaking mounds are structures built in a dice pattern to slow down the speed of the avalanche. The structures are placed in the runout zone where avalanche speeds are relatively low. Braking mounds are usually built of earth materials, but concrete, reinforced earth structures and other materials are used as well.

The braking mounds are most effective against wet snow avalanches. Fluidized dry snow avalanche will usually not be stopped by braking mounds.

New dimensioning criteria for catching and deflection dams, plus breaking mounds are recently developed in the EU-Satsie project, but further studies, both practical and theoretical, are needed to validate the dimensioning criteria. (Jóhannesson et al 2008).

The costs of all three types 3.3.6-3.3.8 are moderate. The cost will largely depend on transport distance of the filling material. If in situ material can be used, the cost can be down to 3-5 € per cubic meter fill.

3.3.9 General issues about catching, deflecting and braking constructions

Steep dam sides towards the avalanche seem to be more effective than gentler inclined dam sides. Inclination of the dam side towards the avalanche should not be lower than 1:1, and preferably be built at least 2:1. Such steep inclinations make it necessary to strengthen the dam fill with dry walls of boulders, concrete, or other kinds of reinforced earth.

When dams are constructed one must ensure that the global stability of the construction is sufficient. 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.

	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 Advantages • natural loose deposits are often at hand • natural loose deposits are cheaper than other materials • maintenance costs are low • the appearance of nature like constructions are more easily accepted by the public as the visual impact is less than for an artificial structure such as a concrete dam. Drawbacks: • dams require much space. The volume of a dam is roughly proportional to: $h^2 \cdot \cot g\alpha$, per unit length, where h is the vertical dam height and α the inclination of the dam sides. The volume increases rapidly with the dam height. Although unit prices per m^3 will decrease with the volume of the dam, high dams with natural inclination of the dam sides will be costly. • by using earth materials it is difficult to obtain steep enough dam sides, and they are therefore less effective than dams made of concrete or reinforced earth • for deflecting dams in steep terrain, the effective inclination of the dam sides (measured perpendicular to the dam axis) will decrease with increasing terrain inclination. The angle of repose will in such cases be found along a plane between the direction of the cross section and the longitudinal dam axis. Retaining and deflecting dams are widely used as countermeasures. Dams are regarded as a fairly cheap countermeasure, which can be cost effective in many locations. Sufficient areas for the dams in the runout zone can be a limiting factor in many cases. Breaking mounds are less frequently used.

	3.3.10 Galleries
	Avalanche sheds or 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. Culverts of steel or concrete completely covered with earth might also be regarded as a type of avalanche shed. Avalanche sheds are constructed to let avalanches pass over without causing damage to the object. 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 the design avalanche. Loads from earth pressure and possible point loads from impact are also part of the design. 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. Construction materials for an avalanche shed normally consist of: • Concrete • Local backfill material (soil, rocks etc). • Steel (corrugated steel pipes in culverts) Sheds are expensive so careful cost analyses are required for their need, benefits and alternatives. Sheds are widely used for protection of roads and railroads, and are regarded to give near 100 % protection when properly designed. Costs differ greatly between countries and on the standard of the sheds. Normal cost per running meter for Norway is about 12000-14000 € per running meter.

	3.4 Structural countermeasures against rock avalanches
	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. Remedial countermeasures are normally not useful when dealing with a large rock avalanche due to the extremely high kinetic energy involved. The few measures that can be relevant are: - Removing unstable rock mass by blasting - Underground water drainage - Diversion of surface water Local conditions (volume, topography, geology) will decide whether such measures are relevant. The cost for such measures can be very high, and as the efficiency often is doubtful, the investment in such measures can hardly be justified.

3.5 Overview of types of structural measures

The main types of structures are listed in the following tables.
Effect: Range 1-5. 1: Low effect, 5: High effect
Cost: Range 1-5. 1: Low cost, 5: High cost

Table: Structural countermeasures against debris flows

Process	Counter measure	Type	Effect	Cost
Debris flow	Increase slope stability	Drainage	5	3
		Soil bio engineering	3	4
		Afforestation	3	4
	Consolidation / Stabilization	Sill	4	2
		Ramp	4	3
		Series of check dams	5	4
	Transformation of process	Debris flow breaker	5	5
		Drop structure	4	5
	Organic debris filtration	Open check dam (rake)	4	4
	Permanent debris deposition	Open check dam	3	4
		Deposition basin	5	3
	Temporary debris deposition	Open check dam	4	3
	Protection / Deflection	Protection and deflection walls / dams	5	2
	Discharge control	Transport channel	4	2

Table: Structural countermeasures against snow avalanches

Process	Counter measure	Type	Effect	Cost
Snow avalanches	Snow drift regulation	Snow fence	2	3
		Jet roof	1	2
		Wind baffle	1	2
	Stabilizing constructions	Snow bridge / rake	3	4
		Snow net	3	4
		Tripod	2	3
	Braking constructions	Avalanche breaker	2	3
	Deflecting and catching constructions	Deflecting and catching dam	3	3
		Gallery	4	5
		Tunnel	5	5
	Artificial release	Aerial cableway	3	3
		Preplaced explosives	3	3
		Gas exploders	2	3
		Guns	2	3
	Afforestation		4	4

Table: Structural countermeasures against rock avalanches

Process	Counter measure	Effect	Cost
Rock avalanches	Removing unstable rock mass by blasting	5	5
	Underground water drainage	3	4
	Diversion of surface water	2	3

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