2 SNOW AVALANCHES

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SUMMARY

For alpine countries, avalanches represent one of the major hazards, threatening people in villages as well as on highways and railways. Measures have to be taken to reduce avalanche risk: Avalanche hazard mapping as a basis for land use planning is one of the most cost-effective measures to reduce or even avoid avalanche exposure. In many situations, technical measures such as supporting structures and deflecting dams, or short-term measures such as avalanche forecasting, artificial avalanche release or evacuation might be the action of choice to reduce the avalanche risk to an acceptable level. It is important to evaluate the different measures within the frame of an overall risk management procedure.

2.1 INTRODUCTION

In the European Alps expanding settlements and increasing mobility due to tourism lead to a growing number of constructions in terrain threatened by avalanches. Eleven million people live in the Alpine region from France over Switzerland, Italy, Austria to Slovenia. Due to winter tourism this number is temporary tripled. A number of important highways and railways cross the Alps. For example over 19'000 vehicles daily cross the Gotthard pass, a very important transit route between Italy and Germany (CIPRA, 1998). Since the catastrophic avalanche winter in 1950/51 the mobility of people in terms of vehicle-kilometres might have increased by a factor of 100. It is therefore no surprise that avalanche mitigation has continued to play an important role in the life of the people living in the Alps. In Switzerland alone, over the past 50 years, about 1.5 billion Swiss francs have been invested in engineering construction work for avalanche protection such as snow supporting structures, deflectors or snow sheds. Together with the daily avalanche forecasting, the avalanche hazard zoning and sustainable silviculture of the protection forests this has led to a high degree of safety (compared to other hazards) in denseiy populated mountainous areas and on roads with high traffic volume.

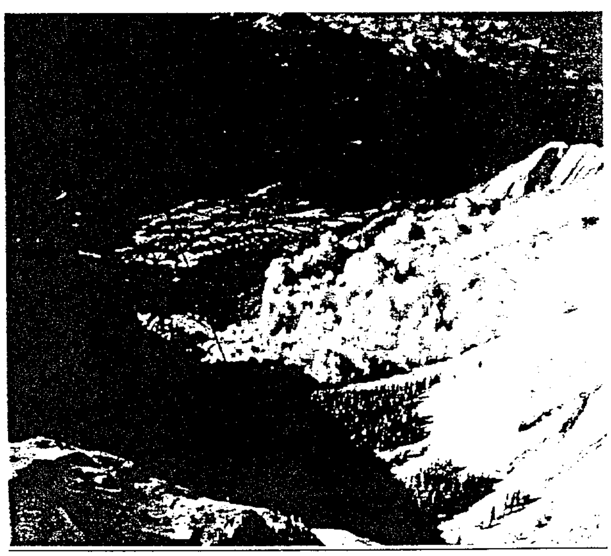


Fig.2.1 Devastating dense flow avalanches at Evolène/VS, Switzerland, causing 12 fatalities on 21st February 1999.

Fig.2.2 Huge powder snow avalanche, released for research purposes at the SLF test-site Vallée de la Sionne/VS, Switzerland on 10th February 1999.

Although avalanche research and avalanche hazard mitigation have made major progress in the last decades, there are still deficiencies and not enough knowledge and suitable tools to sufficiently *protect* life and property. The catastrophic winter 1998/99 with many hundreds of devastating avalanches all over the Alps clearly showed this. In Switzerland alone, 17 people have been killed during January/ February 1999, half of them in buildings, half of them on roads and in the backcountry. The total amount of *damages* is estimated at 1 billion CHF composed of 250 Mio CHF direct damage cost and 750 Mio. CHF indirect damage cost. The neighbouring alpine countries suffered from similar experiences during this devastating period. A total of 75 fatalities in the European Alps had to be counted in January/ February 1999.

2.2 AVALANCHE HAZARD AND DAMAGE SCENARIOS

Instabilities in the snow cover and external impacts can cause avalanches at slopes with an angle of 25°-45°. *Extreme weather situations* with heavy snowfall during several days may lead to catastrophic avalanches threatening villages, access roads and railways. Different kinds of avalanches occur depending on the characteristics of the snow pack, the snow volume involved, the slope angle or additional loading. *Slab avalanches* are most frequent and typically are of moderate size and involve snow masses in the order of a few 1000m^3 up to some 10'000m^3. On a long year average, most fatalities are due to accidental snow slab avalanche releases, initiated locally by off-piste skiers, ski mountaineers, or similar leisure activities (in Switzerland 24 out of 26 fatalities). Especially in the last decade only very few people have been killed on open roads or in settlements (Tschirky, 1998).

Fig.2.3 Situation at Goppenstein/VS in February 1999. Several dense flow avalanches from both valley sides threatened the Loetschberg railway, the access road and **a** temporary construction site for the tunnelling work.

This annual statistic may drastically change during a winter period with exceptional meteorological and nivological conditions as experienced in January/ February 1999. Situations with return periods of several decades may threaten a whole country severely endangering people and their settlements, vehicles on roads and railways, forest and agricultural landscape.

The devastating avalanches of January/ February 1999 were mostly big *powder-snow* and/or *dense flow avalanches* consisting mainly of dry, loose snow, which started to rupture spontaneously under their own weight. The rupture plane was often situated at the base of several snow layers, accumulating a **2 - 4** m thick snow pack. Huge snow masses up to more then 1 Mio m^3 were sometimes involved and the resulting avalanches advancing down to vailey level, endangering settlements, roads and railways (Fig.2.1 and 2.2).

In addition to direct damages in terms of fatalities, destroyed buildings, devastated forests and agricultural landscape, even much more important *indirect damage* costs result. These latter are costs due to interrupted roads and railways, failures in the electricity distribution and in communication, reduced accessibility of tourist resorts, and decrease in hotel reservations (Fig.2.3).

2.3 AVALANCHE PROTECTION MEASURES

2.3.1 General Overview

Several classification possibilities exist for the large variety of avalanche risk reducing measures. Most used is a sub-division into short- and long-term protection measures (Salm et al. 1990):

Short-term protection measures
- avalanche forecasting, warning
- artificial release of avalanches
- closure of roads and railways
- evacuation of people and cattle

Long-term protection measures
- hazard mapping, land use planning
- construction measures
- supporting structures (starting zone of avalanches)
- deviation dams (avalanche path)
- snow sheds (roads, railways crossing avalanche path)
- retaining dams (deposition zone of avalanches)
- retarding constructions (deposition zone of avalanches)
- silvicultural measures
- silviculture
- reforestation, combined with technical measures

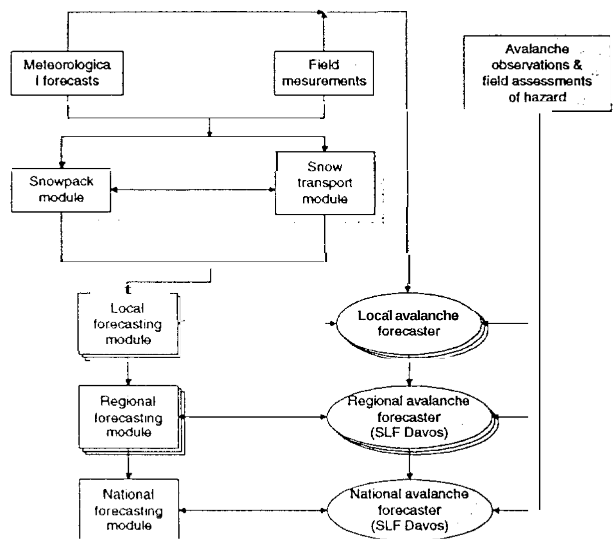
2.3.2 Avalanche forecasting

The avalanche hazard forecasting and the subsequent measures such as evacuation of people in exposed settlements, the shut-down of roads and railway lines and the artificial release of avalanches under controlled conditions are called organisational or short term measures. Efficient use of these measures need a close interaction and co-operation between all national, regional and local security commission staff-members and nation-wide public avalanche awareness programmes. All Alpine countries operate national and/or regional *avalanche warning centres*, which forecast the avalanches on a daily basis. With the introduction of the European Avalanche Hazard Scale in 1993 a common language to describe the snow cover stability and the probability of an avalanche release has been found which is now being used in all European countries (Meister 1994).

Avalanche warning has been a key task of the Swiss Federal Institute for Snow and Avalanche Research in Davos (SLF) since it was established over half a century ago. In the past, the predominant methods used for avalanche forecasting at SLF have been conventional, i.e. snow stability and avalanche hazards were predicted without analytical techniques such as formal numerical and symbolic algorithms. Until the early 1990s *avalanche forecasting* at SLF was mainly based on intuition, experience and local knowledge of the forecaster.

A paradigm shift is currently taking place: Information systems and computer programs are becoming more and more important, assisting the forecaster in collecting and analysing large amounts of field data (Russi et al., 1998). Mathematical analysis of measurements, numerical simulations of weather and snow-pack (Lehning et al. 1998) and symbolic and statistical computations of the avalanche hazard are the key elements of modem avalanche forecasting, which can be described as *computer-aided avalancheforecasting* ***(CAF)*** A similar approach is followed in France (Durand et al. 1998). However, *theforecaster* with his intuition, experience and local knowledge still plays a decisive role in the forecasting process. While the computer helps to assimilate information, to assess the hazard risks, to support the forecaster in his decision and to distribute forecasts via modem communication channels, it is still the forecasters ultimate responsibility to check and modify the computer's prediction.

A three level concept (national, regional, local level) for the avalanche forecasting is being realised within the Swiss concept *Avalanche Warning Switzerland CH2000*. The SLF provides the first two levels, the daily national bulletin and the regional bulletins, local security commissions are responsible for the local level (regional means an area of 1000 - *5000* km2, local an area of 100 km^2). The overall aim of this concept is to modernise avalanche warning in Switzerland and to improve the temporal and spatial resolution of avalanche forecasting on a national, regional and local level, thereby helping to prevent avalanche accidents. Fig.2.4 shows the general architecture containing all major modules and information paths. Shaded boxes denote input sources and white boxes indicate computer models.



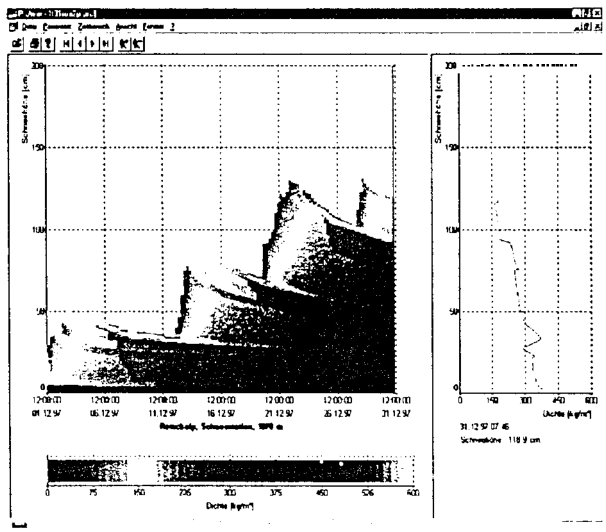


Fig.2.4 General architecture for the avalanche forecast in Switzerland (Russi et al., 1998)

Fig.2.5 Snow cover layering (seasonal density evolution), calculated with *Snowpack*, a computer model developed at the SLF (Lehning et al. 1999).

The *bulletins* represent an important tool for all local and regional security commissions in their risk management processes, e.g. to close a road, to evacuate people or to order the artificial release of potential avalanches. Basic information for the bulletins are gathered by a network of 75 snow and avalanche observers and 60 automatic measuring stations throughout the Swiss Alps (Russi et al. 1998). The forecaster's expert knowledge completed with a continuuusly operated *numerical snow pack model* (Fig.2.5, Lehning et al. 1999) analyse the extensive set of data. The numerical model evaluates the internal state of the snow cover involving temperature, density and grain type profile, moisture content, layering, surface or depth hoar. Additional software like e.g. NXD2000 (Russi et al. 1998) for the local level provides a fast and efficient decision support (Fig.2.6). Even so these models made good progress in the last years, they cannot fulfil all wishes of precision in space and time (Buser 1989, Fohn 1998).

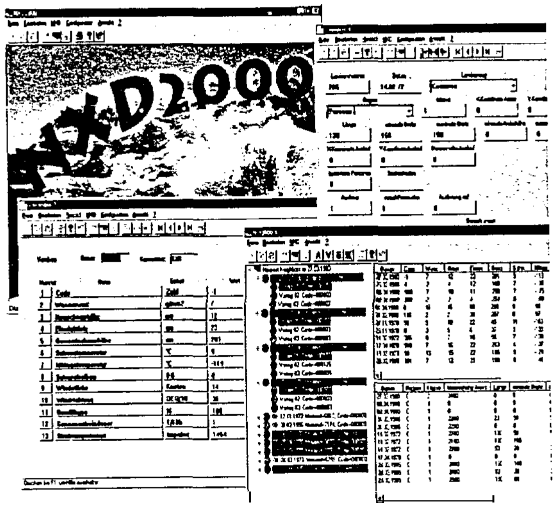


Fig.2.6 Input and output window of NXD2000, the Swiss local avalanche forecasting software tool.

While the web is the main information channel for the general public, a service called *InfoBOX* was set up by the SLF three years ago. This service links together national, regional and local avalanche specialists in Switzerland. So far, about 140 specialists, i.e. people who are in charge of avalanche safety in villages or towns, in ski areas or on highways, are using the SLF InfoBOX service. Via this service, snow and weather data from automatic stations or weather forecasts can be accessed 24h a day (Fig.2.7).

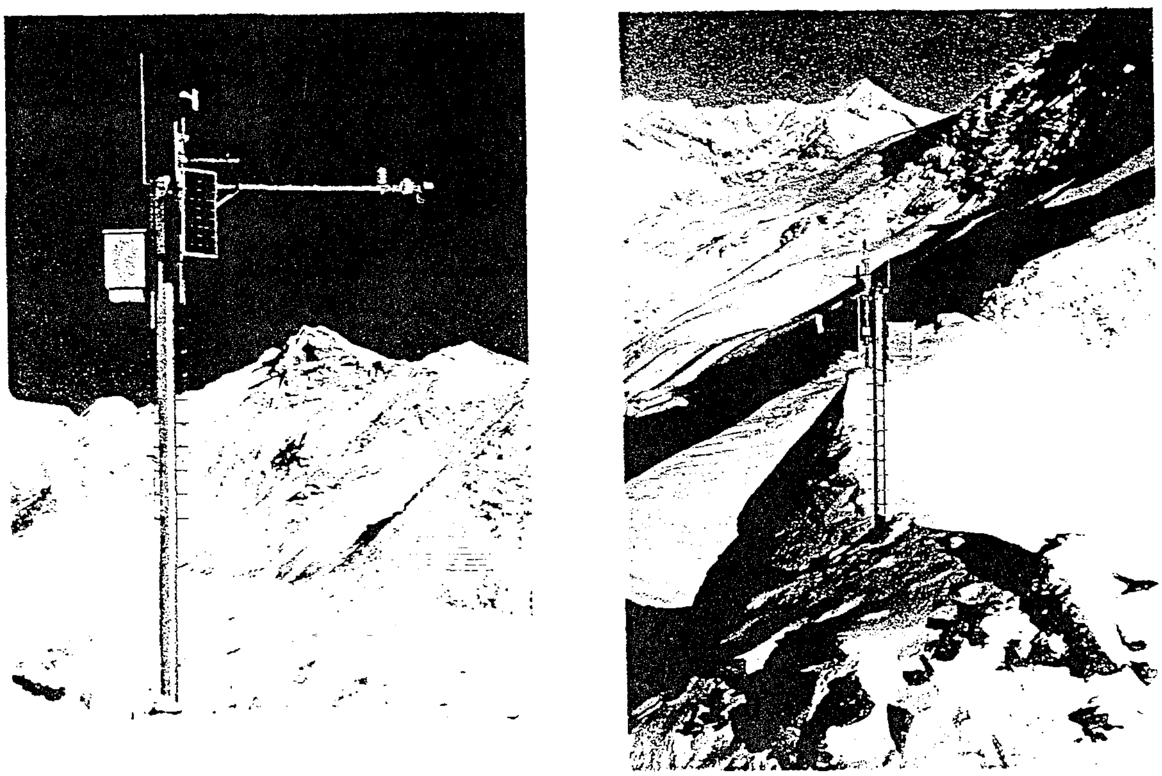


Fig.2.7 IMIS network. Automatic snow (left) and weather **(right)** station at Simplon Pass/VS Switzerland.

All other short-term, *temporary measures* like artificial release, traffic closure, evacuation of people and cattle are subsequent measures in critical periods. Stoffel (1996) discussed the different techniques for artificial avalanche release. Evacuation has to be based on well defined evacuation procedures to prevent additional hazardous situations for the people involved. In such critical situations the local government supported by avalanche experts has to take responsibilities.

2.3.3 Avalanche hazard mapping

Hazard maps serve as basic document for avalanche risk evaluation, especially with respect to land-use planning (for a more detailed overview see Margreth and Gruber 1998). In Switzerland hazard mapping begun after two catastrophic avalanche periods in January and February 1951. The first avalanche hazard maps in Switzerland were elaborated for Gadmen and Wengen in the Canton of Bern, 1954 and 1960, respectively. Dangerous zones were designated according to occurred disastrous events in a more qualitative way without taking into account climatic factors or quantitative avalanche calculations. In course of time the methods were improved and avalanche models introduced to calculate the dynamic behaviour. This development led for example to the *Swiss guidelines for avalanche zoning* (BFF 1984) and the *Guidelines for the calculation of dense flow avalanches* (Salm et al. 1990). The two publications are today the most important tools for the elaboration of avalanche hazard maps in Switzerland. In recent years numerical simulation, GIS and DTM tools led to substantial improvements (Gruber et al. 1998a,b). Two parameters were chosen to quantify the potential hazard for a given site:

- Expected *frequency* **of** an avalanche reaching a given site (frequency is normally expressed by the return period),

- *Intensity* of an avalanche (intensity is expressed by the avalanche pressure exerted on a wall of a building. As this pressure is assumed to increase with the square of speed and propcrtional to density, the kinetic energy of snow masses is also included).

To be able to distinguish variable hazard intensities and run-out scenarios, several *hazard zones* are defined:

Red zone: Pressures of more than 30 kN/m^2 for avalanches with a return period of up to 300 years, and/ or avalanches with a return period up to 30 years independent of pressure,

Blue zone: Pressures of less than 30 kN/m^2 for avalanches with return periods between 30 and 300 years,

Yellow zone: For powder-snow avalanches with pressure less than **3** kN/m^3, and return periods more than 30 years. For dry-snow avalanches with pressure unknown, and return periods more than 300 years,

White zone: No avalanche impacts to be expected,

Gliding Snow: Area of pronounced danger for gliding snow at locations without avalanches or with impacts larger than by avalanche effects.

The elaboration of hazard maps must strictiy follow scientific criteria and methods including expert knowledge. The goal is to determine the *extreme avalanche* on a reliable basis. Field visits to assess the avalanche terrain, the examination of the avalanche cadastre as a map with all known avalanches in history, including their extent and date, additional information from competent local people or from old chronicles, the check of local climatic conditions and dynamic avalanche calculations are important tools. The *dynamic calculations* are used for:

- Predicting an extreme event, probably not registered in a cadastre,
- Delimiting the hazard zones for the different return periods,
- Calculating run-out distances and pressures as a function of avalanche frequency.

In Switzerland the *Voellmy-Salm model* is used since more than 20 years for estimating avalanche speeds, flow heights and run-out distances of dense flow avalanches (Salm et al. 1990). The use of the Voellmy-Salm model requires a careful estimation of its input parameters as fracture depth, friction parameters *or* avalanche size (Margreth et al. 1998). To check the sensitivity the calculations have to be made with different input parameters. Critical assessment of the results is important. It has to be pointed out that dynamic calculations are just one part of hazard assessment. In recent years, many such dynamic calculation methods have been proposed, some of which are routinely and effectively used by practitioners (Salm et al. 1990). *Numerical methods* using FE- or FD- techniques have set new standards in the use of avalanche dynamics models (McClung et al. 1995, Bartelt et al. 1997). User-friendly GIS- and DTM-tools are additional assets to complete and facilitate avalanche hazard mapping (Gruber et al. 1998a, 1998b).

2.3.4 Technical measures

Technical, long-tenn avalanche defense measures are used in the starting zone to prevent the release of avalanches (supporting structures) and in the avalanche track and run-out zones (avalanche sheds, deflecting and catching dams) to reduce the damaging effect of descending avalanches.

Supporting structures

The wide application of supporting structures had its beginning after the severe avalanche winter 1950/51. Since then the technology has reached an advanced stage. More than 500 km supporting steel bridges and snow nets have been built over the last *50* years. **All** experience gathered through these decades is summarised in the Swiss Guidelines (1990). The aim of supporting structures is to prevent the start of large avalanches or at least to *limit* snow motions to an harmless extent. Fully developed avalanches can not be stopped and retained by supporting structures (Margreth 1996).

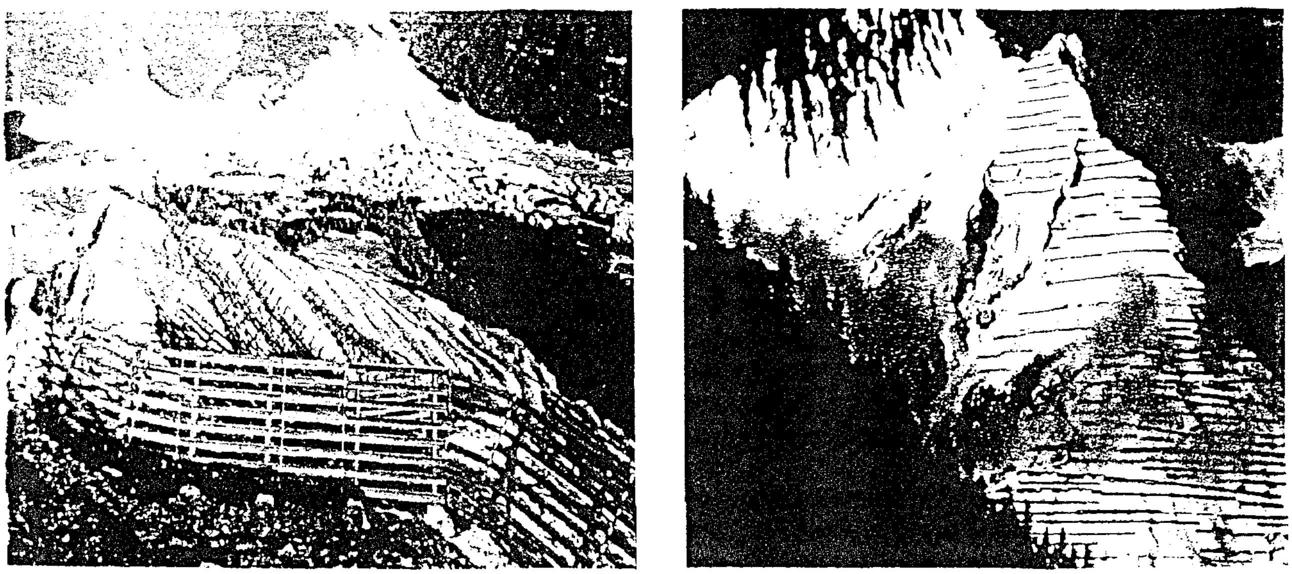


Fig.2.8 Steel supporting structure above Davos/Switzerland (Schiahorn).

The first effect of supporting structures is to introduce an overall increase in the *stability* of the inclined snow. The acting snow-pack forces are redistributed, compressive reaction forces are increased, shear forces, which dominate stability, are decreased. The second effect consists in limiting the *mass of snow* put in motion and in retarding and catching it. The vertical height must correspond to the extreme snow depth with a return period of at least 100 years. The adopted snow height is a crucial point for the design to guarantee the effectiveness of supporting structures. In February 1999, some lines of structures were overfilled with snow, more than 550 cm of snow were measured at 2500 m a.s.l. Technically feasible are constructions for up to 7 m of snow. Typical structure heights in Switzerland vary between 3m and 5m.

Today *steel bridges* and *flexible snow nets* are predominantly used. The costs for supporting structures are about 1.0 - 1.5 Mio CHF. Due to these high costs, supporting structures are mostly used for the protection of settlements. The constructions are designed for a period of 100 years. *Maintenance* of older supporting structures is therefore becoming more and more important.

Deflecting and catching dams

Deflecting and catching dams are relatively cheep compared to the supporting structures but need enough space and volume to be effective. Deflecting and catching dams are normally *earth darns,* sometimes combined with *stone masonry* to increase the slope-inclination at the impact side. The height of catching dams may reach 15 - 20 m, depending on the avalanche velocity and the snow volume to be retained (Fig.2.9). An overflow of the dam crest has to be avoided. Catching dams may also be used to retain mudflows.

Fig.2.9 Deflecting dam near Disentis/GR Switzerland.

Fig.2.10 Snow deposit of an avalanche near Elm/GL Switzerland (end of February 1999).

Avalanche sheds

Avalanche sheds to protect roads and railway lines are effective measures if the avalanche track is narrow and the shed construction sufficiently long (Fig.2.3). In situations where the avalanche deposition zone is widely spread, a shed construction would become too long. In such situations, and in view of an integral **risk** management, *road closures* are often the only cost-effective measures (Fig.2.10). Since a few years Swiss guidelines exist on the design of avalanche sheds (ASB/SBB 1994). One meter of snow shed costs, as an average, about 25'000 CHF.

2.3.5 Mountain forest

The mountain forest corresponds to the most effective **and** the cheapest protection for villages, roads and railways. The trees retain the snow; stabilise the snow-pack and prevent avalanches to start. The mechanical resistance of the trees is not sufficient to stop avalanches. Therefore, the protection function of the mountain forest against avalanches is only valid for *starting **zones*** below the timber-line. In Switzerland, about 1000 km^2 of forest area serves primarily as avalanche and rock-fall protection. If this effect would have to be replaced by technical means, a yearly investment of 2 Billion CHF would be necessary.

2.4 AVALANCHE RISK AND MANAGEMENT

Risk management is an integral approach of human thinking and acting covering the anticipation and the assessment of risk, the systematic approach to limit the risk to an accepted level and to undertake the necessary measures. Avalanche risk is the result of the temporal and the spatial overlapping of the two independent domains *potential avalanche danger* and *spatial area **in*** use. The avalanche danger is described by the avalanche probability and the extent of the avalanche. The spatial area in use corresponds to the probability of presence of any objects and the value of these objects (or the number of people present).

To avoid the disastrous effects of avalanches, different kinds of *prevention measures* are used to reduce the avalanche risk to an acceptable level. These measures have to be seen as an integral set of possible protection measures. In most cases a combination of the different measures is used. The optimal combination can be found by maximising the cost-effectiveness and cost-benefit of all possible avalanche control measures. The identification of the avalanche danger in terms of probability of occurrence, the estimation of the risk potential based on the vulnerability of the corresponding values exposed to risk, the assessment of protection goals and the cost-estimation for control measures are basic principles to be applied in an integral risk management approach (Wilhelm 1997 and 1998, Heinimann et al. 1998).

Cost-effectiveness can be expressed in terms of amount of money spent per saved life (Wilhelm 1997). For avalanche control measures, it varies to a large extent, depending on the actual situation (1 to 20 Mio CHF). The whole risk management process is iterative with several assessment and control loops. For preliminary design purposes Wilhelm (1998) established simplified cost-effectiveness evaluation charts which will be published as a BUWAL-Guideline for the **risk** assessment of roads and railways.

2.5 RESEARCH NEEDS

2.5.1 Physics and mechanics of snow

Snow as material for avalanches is a complex mixture of air, water and ice, which is in our environment always close to its melting point and henceforth changes its physical properties continuously in time and space. This metamorphic process which changes the shape of the snow particles from fine dendrites to rounded grains or other shaped particles depending on temperatures, density, solar insulation and wind has to be known in detail if the formation of the various types of avalanches should be predictable for detailed avalanche forecasting. Unfortunately, a massive lack of knowledge still exists to quantitatively describe shrinking, settling and re-cristallisation processes combined with the corresponding changes in mechanical properties such as shear resistance and cohesion within the snow pack.

2.5.2 Avalanche forecasting

To increase the acciiracy of avalanche forecasting in time and space, research has to concentrate on *questions* such as:

- How can the stability of a slope be quantitatively assessed and introduced in operational avalanche forecasting service? What are the triggering mechanisms for the release **of avalanches?,**
- How can the known local and temporal variability of the snow cover on slopes **and** of its stability be taken into account?,
- How can snow drift be quantitatively described on a local to regional scale and how can this description be used to improve avalanche forecasting? and
- How can the information available on a local, regional and national scale be combined and used as input to avalanche warning models (statistical methods, expert systems, neuronal networks) which support the decision process?

2.5.3 Avalanche hazard mapping

Avalanche hazard mapping is closely linked to avalanche dynamics. Various dynamic avalanche models have been developed in the last 20- 40 years based on different flow types (hydraulic, aerosol, mixed, granular). Also statistical models, based on a few topographical factors and observed run-out distances compete with the various flow type models as far as run-out distances are concerned (Lied 1998).

Significant improvements in the avalanche dynamics calculations which serve as a basis for hazard mapping could be obtained by:

- Improved knowledge of initial conditions (fracture area and depth of sliding snow layers, quality of sliding snow, e.g. friction coefficients) all dependent on the return period,
- Development of adequate physical models to describe the flow regime of dense-flow avalanches (Bartelt and Gruber 1997), the snow entrainment in powder-snow avalanches (Issler 1998) and the impact mechanisms on structures.

Validation of physical models and numerical modelling with field and laboratory data. Real progress will only be possible when field and laboratory data will be available covering all major parameters influencing avalanche dynamics. Since 1997, the SLF operates therefore a test-site in the Vallée de la Sionne/VS, Switzerland (Fig.2.2 and 2.10, Ammann 1998). There it is possible to study the overall dynamic behaviour of dense-flow and powder-snow avalanches and to measure avalanche impact forces along their path.

2.5.4 Technical measures

Avalanche defence structures and dams still need *improvements:*

- Design of the load bearing capacity of the foundations (anchors),
- Design of defence structures in permafrost sub-soil (Stoffel 1995),
- Implementation of maintenance strategies for existant structures,
- Design of deflecting and retaining dams (McClung and Mears 1995),
- Design of reinforced structures in the blue avalanche hazard zone.

2.5.5 Risk management

Major improvements in risk reduction may be achieved by a consequent risk management. Research efforts are needed in the following domains:

- The devastating events in January/ February 1999 demonstrated the importance of indirect damage costs. Damage patterns have changed, the increased mobility and missing awareness of the public are major reasons. To develop strategies to take care of this changed damage pattern will be an important task.
- What is the acceptable **risk** level? Has aversion to be taken into account?
- Development of tools to assess the cost-effectiveness of different defence strategies for settlements, roads, railways.

- Implementation of a strategy for the continuous education of local and regional avalanche safety responsibles.

Fig.2.11 SLF avalanche test-site Vallée de la Sionne. View on avalanche track with the location of different obstacles.

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