SNOW AVALANCHES

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ABSTRACT

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 the avalanche risk. Avalanche hazard mapping, as a basis for land use planning, and avalanche warning are the most cost-effective measures to reduce or even avoid avalanche exposure. Long-term technical measures, such as supporting structures, deflecting dams and afforestations, or short-term measures, such as avalanche forecasting, artificial avalanche release or evacuation, might be chosen to reduce the avalanche risk to an acceptable level. It is important to evaluate the different measures within the framework of an overall risk management procedure.

1. INTRODUCTION

In the Alps and elsewhere, expanding settlements and increasing mobility due to tourism have resulted in a growing number of structures under threat by avalanches. Eleven million people live in the Alpine region from France through Switzerland, Italy, Austria to Slovenia and this number is temporarily tripled due to winter tourism. 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 may have increased by a factor of 100. Therefore, it is no surprise that avalanche mitigation has continued to play an important role in the life of 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 daily avalanche forecasts, the avalanche hazard zoning and sustainable silviculture of the protection forests, has led to a high degree of safety (compared to other hazards) in densely populated mountainous areas and on roads with high volumes of traffic.

Although avalanche research and avalanche hazard mitigation have made major progress in recent decades, there are still deficiencies and not enough knowledge or suitable tools to sufficiently protect life and property. The catastrophic 1998–99 winter, with many hundreds of devastating avalanches all over the central Alps, clearly showed this. In Switzerland alone, 17 people were killed during January–February 1999, half of them in buildings and half of them on roads and in rural areas. Total damages are estimated at 1 billion Swiss francs, composed of 250 million Swiss francs in direct damages and 750 million Swiss francs in indirect damages Neighbouring alpine countries suffered from similar experiences during this devastating period. In the European Alps, a total of 75 fatalities were counted during January–February 1999.

2. AVALANCHE HAZARD AND DAMAGE SCENARIOS

Instabilities in the snow cover and external impacts can cause avalanches on slopes with an angle of 25°–55°. Extreme weather situations with heavy snowfall over 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, additional loading, etc. Slab avalanches are most frequent and are typically of moderate size and involve snow masses in the order of a few 1 000 m^3 up to some 10 000 m^3. Over the long-term, on average, most fatalities are due to accidental snow slab avalanche releases, set-off locally by off-piste skiers, ski mountaineers or similar leisure activities (in Switzerland these kind of avalanches caused 24 out

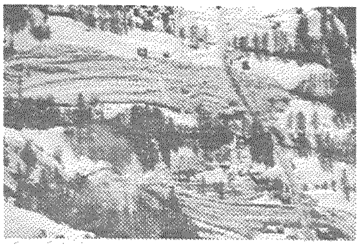


Figure 1. Devastating dense flow avalanches at Evolène/Valais, Switzerland, causing 12 fatalities on 21 February 1999.

of 26 fatalities). Only very few people have been killed on open roads or in settlements (Tschirky, 1998), particularly during the last decade.

This annual statistic may drastically change during a winter period with exceptional meteorological and snow 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 and 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 million m^3 were sometimes involved and the resulting avalanches advanced down to valley level, endangered settlements, roads and railways (Figures 1, 2 and 3).

These avalanches caused direct damages including fatalities, destruction of buildings, devastation of forests and crops damages. These damages, in turn, generate costs because of interrupted roads and railways, failures in electricity distribution and in communications, reduced accessibility of tourist resorts, decrease in hotel reservations, etc.

3. AVALANCHE PROTECTION MEASURES

3.1 GENERAL OVERVIEW

Several classification possibilities exist for the large variety of avalanche risk reducing measures. Most often used is a sub-division into short- and long-term protection measures (Föhn, 1994; Salm, 1994):

Short-term protection measures:
- Avalanche forecasting, warning;
- Artificial release of avalanches,
- Closure of roads and railways,
- Orientation and evacuation of people and cattle.

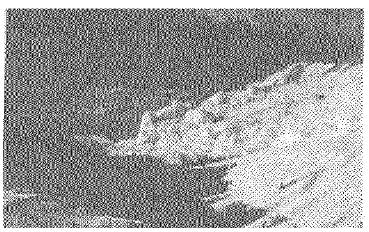


Figure 2. Huge powder snow avalanche, released for research purposes at the SLF test-site Vallée de la Sionne/ Valais, Switzerland on 10 February 1999.

Long-term protection measures:
- Hazard mapping, land use planning;
- Construction measures;
  - supporting structures in zones where avalanches are triggered;
  - deviation dams in the avalanche path;
  - snow sheds (roads, railways crossing avalanche path);
  - retarding constructions (deposition zone of avalanches);
  - retaining dams (deposition zone of avalanches);
- Silvicultural measures;
  - afforestation;
  - reforestation, combined with technical measures;

3.2 AVALANCHE FORECASTING

Figure 3. Situation in Goppenstein/ VS in February 1999 Several dense flow avalanches from both valley sides threaten the international Loetschberg railway, the access road, and a temporary construction site for the tunnelling work.

Avalanche hazard forecasting and subsequent measures, such as evacuation of people in exposed settlements, the closing of roads and railway lines and the artificial release of avalanches under controlled conditions, are called organizational or short-term measures. Efficient use of these measures requires close interaction and cooperation 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 avalanches on a daily basis. With the introduction of the European Avalanche Hazard Scale in 1993, a common language to describe snow cover stability and the probability of an avalanche release has been found which is now being used in all European countries (Meister, 1995).

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 by synoptic methods, as in meteorology. Avalanche forecasting was mainly based on data analysis and experience and intuition, supplemented with some statistical programs.

A paradigm shift is now slowly 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 (Föhn,1998; Russi *et al*., 1998). Statistical analysis of measurements, numerical simulations of weather and snow-pack (Lehning *et al.*, 1998) and symbolic computations of the avalanche hazard are the key elements of modern avalanche forecasting. A similar approach has also been initiated in France (Brun *et al.*, 1992, Durand *et al.*,1998).

However, the forecaster with his intuition, experience and local knowledge still plays a decisive role in the forecasting process. While the computer helps to assimilate information, propose the appropriate hazard risks, support the forecaster in his decision and distribute forecasts via modern communication channels, it is still the forecasters ultimate responsibility to check and modify the computer's prediction.

A three level concept for avalanche forecasting (national, regional, local level) is being implemented within the Swiss concept "Avalanche Warning Switzerland CH 2000". The SLF provides the first two levels, the daily national bulletin and the regional bulletins, while local security commissions are responsible for the local level (regional bulletins cover an area of 1000–5000 km^2, and local bulletins an area of 100 km^2).

The overall aim of this concept is to modernize 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. Figure 4 shows the general architecture containing all major modules and information paths. Shaded boxes denote input sources and white boxes indicate computer models.

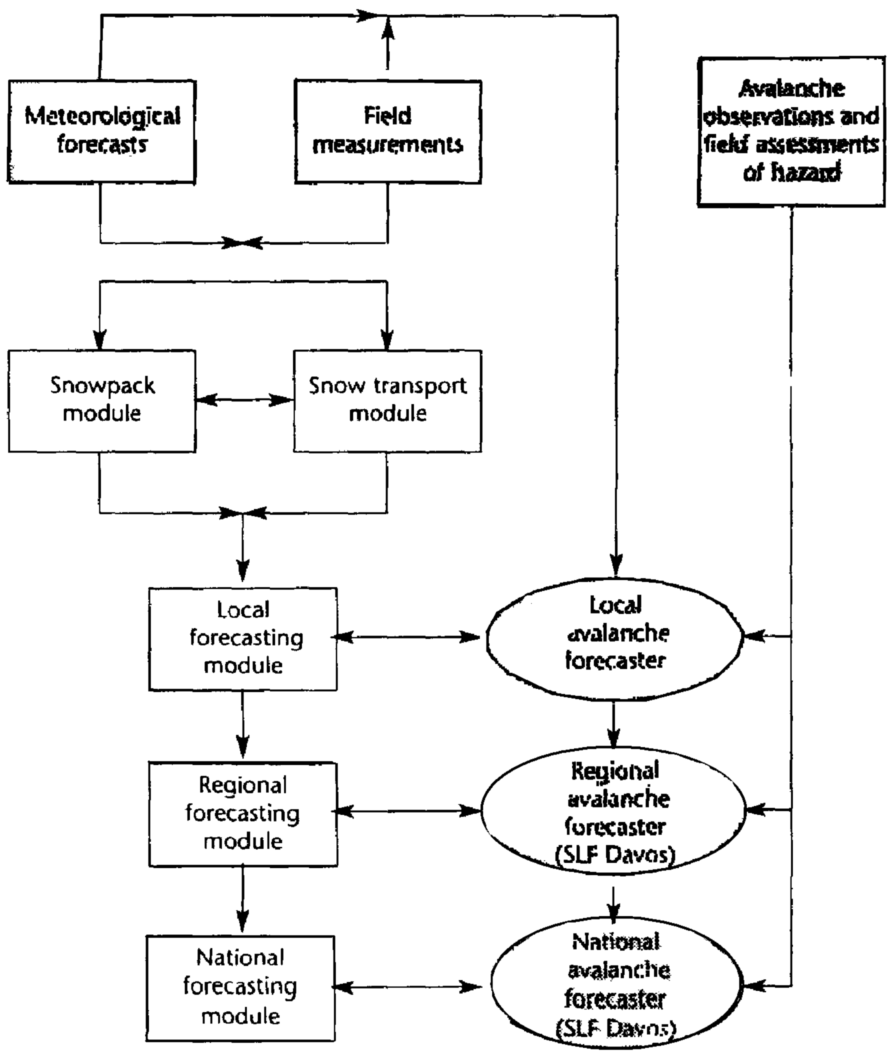


Figure 4. General architecture for the Future avalanche forecast in Switzerland (Russi et al., 1998).

The avalanche warnings (bulletins) represent an important tool for all local and regional security commissions in their risk management process, e.g. to close a road, to evacuate people or to order the artificial release of potential avalanches. Basic information for the bulletins is 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, supplemented by a continuously operated numerical snow pack model (Figure 5, Lehning *et al.*,1999), is used to analyse the extensive set of data. The numerical model evaluates the internal state of the snow cover (temperature, density and grain type profile, moisture content, layering, depth hoar).

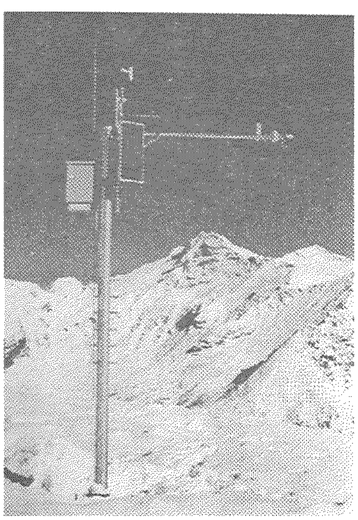
Additional software such as, for example, NXD2000 (Russi *et al*, 1998) will provide fast and efficient decision support for the local level. Even though these models have made good progress in recent years, they cannot fulfil all requirements for precision in space and time (Buser, 1989, Föhn,1998).

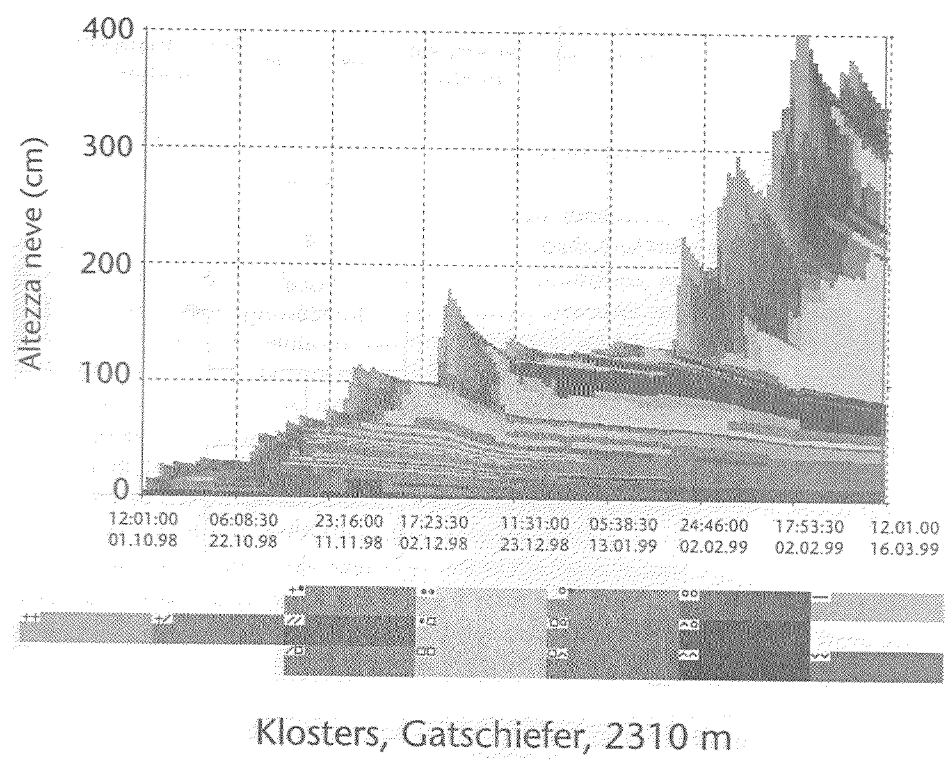
While the Web is the main information channel for the general public, a service called InfoBOX was set up by the SLF three years ago This service links together national, regional and local avalanche specialists in Switzerland. At present, about 140 specialists (i.e. people who are in charge of avalanche safety in villages or towns, in ski areas or on highways) are using the SLF InfoBOX service Snow and weather data from automatic stations (see Figure 6) or weather forecasts can now be accessed 24 hours a day using this service.

All other short-term, temporary measures, like artificial release, traffic closure, evacuation of people and cattle, are subsequent measures in critical periods. Stoffel (1997) has discussed the different techniques for artificial avalanche release. Evacuation has to be based on well-defined warnings and evacuation procedures to prevent additional hazardous situations for the people involved. In such critical situations, the local authorities, supported by avalanche experts, have to assume grave responsibilities. The catastrophic avalanche period of February 1999 clearly showed that, in all concerned Alpine countries, there is a definite need for improved links between avalanche experts and regional and local authorities on one hand and between avalanche experts and the local avalanche commissions in the communities (which finally recommend the evacuations of endangered zones) on the other.

Figure 5 (right) Snow cover layering (seasonal snow layers with grain shapes), calculated with "Snowpack", a computer model developed at the SLF (Lehning et al, 1999).

Figure 6 (left). IMIS network. Automatic snow and weather station at Simplon Pass, Valais Switzerland.





3.2 AVALANCHE HAZARD MAPPING

Hazard maps serve as basic documents for avalanche risk evaluation, especially with respect to land-use planning (for a more detailed overview see Margreth *et al.*, 1998). In Switzerland, hazard mapping begun after two catastrophic avalanche periods in January and February 1951. The first avalanche hazard maps in Switzerland were developed for Gadmen and Wengen in the Canton of Bern, in 1954 and 1960 respectively. Dangerous zones were designated in a rather qualitative way, on the basis of previous disastrous events, without taking into account climatic factors or quantitative avalanche calculations. In the course of time, methods were improved and avalanche models introduced to calculate the dynamic behaviour (Föhn and Meister, 1982). 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). These two publications are, today, the most important tools for the preparation of avalanche hazard maps in Switzerland. In recent years, numerical simulation, GIS and DTM tools have led to substantial improvements (Gruber *et al.*, 1998*a, b*). The two following parameters were chosen to quantify the potential hazard for a given site

- The expected frequency of an avalanche reaching a given site (frequency is normally expressed by the mean return period);
- The 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 proportional to density, the kinetic energy of snow masses is also included).

Several hazard zones are defined in order to distinguish variable hazard intensities and run-out scenarios:

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: pressure less than 3 kN/m^2, return period more than 30 years. For dry-snow avalanches: pressure unknown, return period 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 follow strictly scientific criteria and methods, including expert knowledge. The goal is to determine the extreme avalanche on a reliable basis. Important tools are field visits to assess the avalanche terrain, the examination of the avalanche record as a map with all known avalanches in history, including their extent and date, additional information from competent local people or from old chronicles and checks of local climatic conditions and dynamic avalanche calculations. The dynamic calculations are used for:

- Predicting an extreme event, probably not recorded in historical records;
- 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 has been used for more than 20 years for estimating avalanche speeds, flow heights and run-out distances of dense flow avalanches (Salm *et al*, 1990). This model requires careful estimation of its input parameters such as fracture depth, friction parameters or avalanche size (Margreth *et al.*, 1998) The calculations have to be made with different input parameters to check the sensitivity. Critical assessment of the results is very important. It must 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 (Harbitz *et al.*,1998). Numerical modelling 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 in completing and facilitating avalanche hazard mapping.

3.3 CONSTRUCTION MEASURES

Technical, long-term, avalanche defence measures are used in the starting zone to prevent the release of avalanches (supporting structures) and in the avalanche