track and run-out zone (avalanche sheds, deflecting and catching dams) to reduce the damaging effect of descending avalanches.

SUPPORTING STRUCTURES

The wide application of supporting structures, which started in the last century, took a big step forward following the severe avalanche winter of 1950–51. The technology has since this period reached an advanced stage. More than 500 km of supporting steel bridges and snow nets has been built over the last 50 years (Figure 7). All the experience gained through these decades is summarized 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 so that they remain harmless. Fully developed avalanches, however, cannot be stopped and retained by supporting structures (Margreth, 1996).

The first effect of supporting structures is to create an overall increase in the stability of the inclined snow pack. The acting snow-pack forces are redistributed, compressive reaction forces are increased and shear forces, which often dominate stability, are decreased. The second effect is to limit the mass of snow put in motion, retarding and catching it. The vertical height must correspond to the extreme snow depth occurring with a return period of at least 100 years. The snow height adopted 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 was measured there at 2 500 metres above sea-level Construction for up to 7 m of snow is technically feasible. The typical structure heights used in Switzerland vary between 3.0 m and 5.0 m.

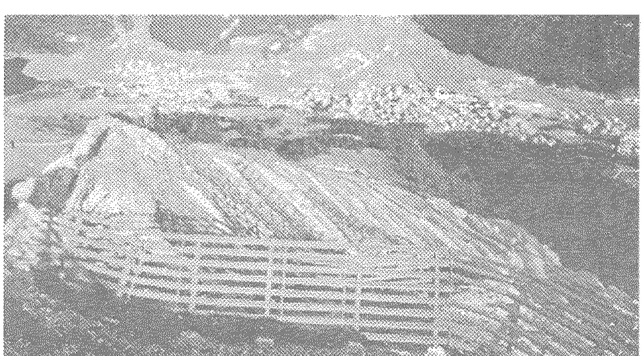
Steel bridges and flexible snow nets are predominantly used today. The costs for supporting structures are about 1.0–1.5 million Swiss francs per hectare. Due to these high costs, supporting structures are mainly used for the protection of settlements. The structures are designed for an avalanche return period of 100 years. Maintenance of older supporting structures is, therefore, expensive and becoming more and more important.

Deflecting and catching dams

Deflecting and catching dams are relatively cheap compared to supporting structures but need enough space (with respect to volume) to be effective. Deflecting and catching dams are normally earth dams, sometimes combined with stone masonry to increase the slope-inclination on 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. An overflow of the dam crest has to be avoided. Catching dams for avalanches may also be used to retain mudflows.

Avalanche sheds

Avalanche sheds are very effective measures to protect roads and railway lines if the avalanche track is narrow and the shed construction sufficiently long (see Figure 8). In situations where the avalanche deposition zone is widely spread, however, a shed construction would become too long. In such situations and from the perspective of integral risk management, road closures are often the only cost-effective measures. Swiss guidelines for the design of avalanche sheds (ASB/SBB, 1994) have existed for a few years. One meter of snow shed costs, on average, about 25 000 Swiss francs.



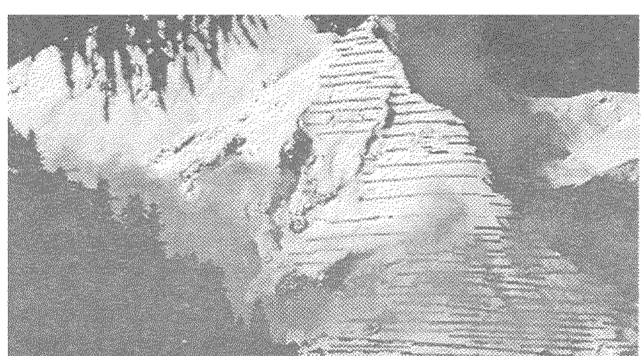


Figure 7. Steel supporting structures above Davos/Switzerland (Schiahorn). *Left side: View from above in summertime, right side: View from the opposite valley flank in wintertime.*

3.5 MOUNTAIN FORESTS

Mountain forests is the most effective and the cheapest protection for villages, roads and railways. The trees retain the snow, stabilise the snow-pack and prevent avalanches from starting. The mechanical resistance of the trees is not, however, sufficient to stop avalanches. In consequence, the protective effect of mountain forest, against avalanches, is only valid for starting zones below the timberline. In Switzerland, about 1000 km^2 of forest area serves, primarily, as avalanche and rock-fall protection. If this effect were to be replaced by technical measures, a yearly investment of 2 billion Swiss francs would be necessary.

4. AVALANCHE RISK ASSESSMENT AND MANAGEMENT

Risk management is an integral approach of human thinking and acting. It incorporates the anticipation and assessment of risk, a systematic approach to limiting the risk to an acceptable level and undertaking 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 combined probability, or the risk (R) as a product of the avalanche hazard (A), of the probability that human beings, dwellings, vehicles or other goods are endangered in a zone (Z), and of the value of or damage probability of these goods (D) has to be evaluated for each area:

$$R = A \cdot Z \cdot D$$

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 the presence of any objects and the value of these objects (or the number of people present).

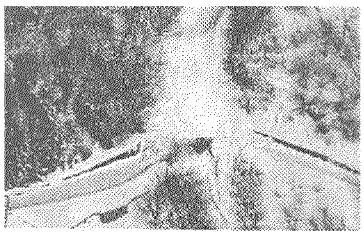


Figure 8. Example of a too short avalanche shed Brn/GL Switzerland (end of February 1999).

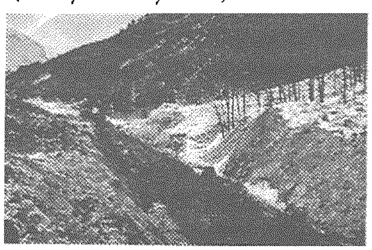


Figure 9. Snow deposit of an avalanche near Linthtal/GL Switzerland

To avoid the disastrous effects of avalanches, different kinds of preventive 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. Basic principles to be applied in an integral risk management approach include 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 (e.g. 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 million CHF). The whole risk management process is iterative with several assessment and control loops. For preliminary design purposes, Wilhelm (1998) has established simplified cost-effectiveness evaluation charts which will be published as a BUWAL-Guideline for the risk assessment of roads and railways.

5. RESEARCH NEEDS

5.1 PHYSICS AND MECHANICS OF SNOW

Snow as material for avalanches is a complex mixture of air, water and ice which, in our environment, is always close to its melting point and henceforth changes its physical properties continuously in time and space. This metamorphic process changes the shape of the snow particles from fine dendrites to rounded grains or other shaped particles depending on temperatures, density, solar insulation, wind, etc. These physical properties need to be known in depth if the formation of the various types of avalanches is to be predictable for detailed avalanche forecasting. Unfortunately, however, very little is known on the quantitative description of, for example, the shrinking, settling and re-crystallisation processes within the snow pack combined with the corresponding changes in mechanical properties such as shear resistance and cohesion. Consequently, the numerical simulation of snow pack layering is still lacking of many details.

5.2 AVALANCHE FORECASTING

An overview of avalanche forecasting models and methods has recently been published (Föhn,1998), and the research needs may be briefly summarized as follows. In order to increase the accuracy of avalanche forecasting in time and space, research has to concentrate on questions such as:

- How can the stability of various slopes with different aspect, altitude and slope angle be quantitatively assessed by simulation models and introduced in operational avalanche forecasting service? What are the most likely triggering mechanisms for the release of avalanches in a given situation?
- How can the known local (in hundreds of metres) and temporal (in days) variability of the snow cover on slopes and 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 ?
- 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, neural networks) which support the decision process?

5.3 AVALANCHE HAZARD MAPPING

Avalanche hazard mapping is very 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). In addition, 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 could be obtained in the avalanche dynamics calculations which serve as a basis for hazard mapping by:

- Improved knowledge of initial conditions (fracture area and depth of sliding snow layers, quality of sliding snow, e g various friction coefficients), all dependent on the return period;
- Development of adequate physical models to describe the flow regime of dense-flow avalanches (Bartelt *et al.*, 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 become available covering all major parameters influencing avalanche dynamics. Since 1997, therefore, the SLF operates a test-site in the Vallée de la Sionne/VS, Switzerland (Figures 2 and 10, Ammann, 1998). At this site, 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

5.4 TECHNICAL MEASURES AND RISK MANAGEMENT

Avalanche defence structures and dams still need improvements in:

- The design of the load bearing capacity of the foundations (anchors);
- The design of defence structures in permafrost sub-soil (Stoffel. 1995);
- The implementation of maintenance strategies for existing structures;
- The design of deflecting and retaining dams (McClung, 1995); and
- The design of reinforced structures in the blue avalanche hazard zone.

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 showed clearly the importance of indirect damage costs. Damage patterns have changed, the increased mobility and poor public awareness are major reasons. To develop strategies to address 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 managers (e.g. members of avalanche commissions).

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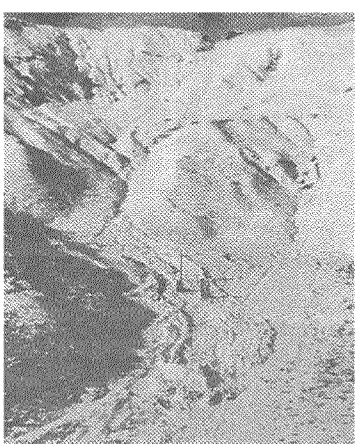

Figure 10. SLF avalanche test-site, Vallée de la Sionne. View on avalanche track with the location of the different measuring equipment.

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