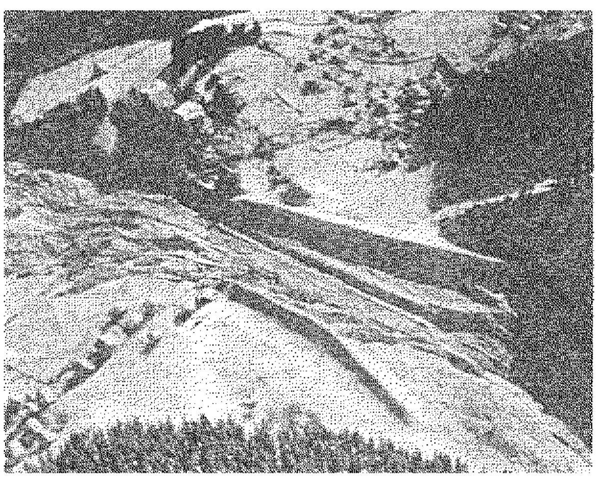
The first effect of supporting structures is to introduce an overall increase in the *stability* of the inclined snow. The acting snow-pack forces are redistributed, compressive reaction forces are increased, shear forces, which dominate stability, are decreased. The second effect consists in limiting 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 dams*, 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.



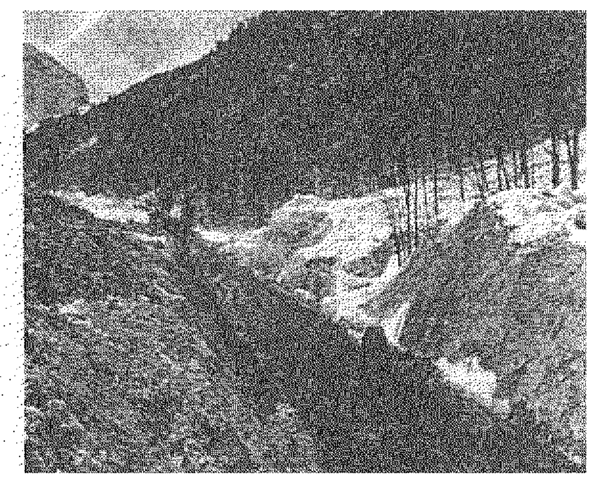


Fig.2.9 Deflecting dam near Disentis/GR Switzerland.

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 accuracy 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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