Experiences on the Use and the Effectiveness of Permanent Supporting Structures in Switzerland

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Key Words: Avalanche Protection, Supporting Structures, Hazard Maps

ABSTRACT

First the principles of supporting structures are explained. Two case studies of winter observations in areas controlled by supporting structures are presented. The task of supporting structures to prevent avalanches or to limit snow motion to a harmless magnitude is investigated by field studies. Examples of the interaction between moving snow and the structures are given. Then the main criterias for safety analysis are described and recommendations for the use of supporting structures are given.

1. PRINCIPLES OF SUPPORTING STRUCTURES

The principle, calculation and design of supporting structures are explained in the "Swiss Guidelines for avalanche control in the starting zone" (1990). All insights and experiences accumulated over several decades are summarized there. The Swiss Guidelines (1990) are the base for all applications of supporting structures in Switzerland.

The task of supporting structures is to prevent large avalanches or at least to limit snow motions - they cannot be completely eliminated - to a harmless magnitude. Fully developed avalanches cannot be stopped by supporting structures. The first problem is to produce an overall increase in the stability of the sloping snowpack by additional compressive stresses and reduced shear stresses in the weak layer due to the wall. The second problem consists in limiting the size of the snow masses which have been set in motion and in retarding and catching them.

Slopes from 30° to 50° are generally considered to be in the range that justifies constructions. The primary location for supporting structures is below the highest fracture line that is observed or is expected. The continuous arrangement of structures in lines with lengths between 20 m and 50 m is preferred. The height of a structure is decisive for the avalanche safety during situations of intense snow accumulation and for the design of the structures. In Switzerland the vertical height of structure must correspond at least to the extreme snow depth with a return period of 100 years. The study of the snow depth distribution over the project area is very important. Typical structure heights used in the Swiss Alps are 3 m, 3.5 m and 4 m. In the Swiss Guidelines (1990) the distances along the slope between lines of structures are determined according to following criteria's: The structures have to withstand the maximum static and dynamical snow pressures. Furthermore they have to reduce the velocities of small avalanches by the roughness of the supporting plane.

Today steel snow bridges and flexible snow net systems are most commonly used. The snow pressure loads are up to 100 kN/m. The foundations are made with micropiles and anchors. The costs for supporting structures are high: one hectare costs about 1 million Sfr. The costs of an avalanche control project are typically shared in the following way: Federal Government 60-70%, Can-

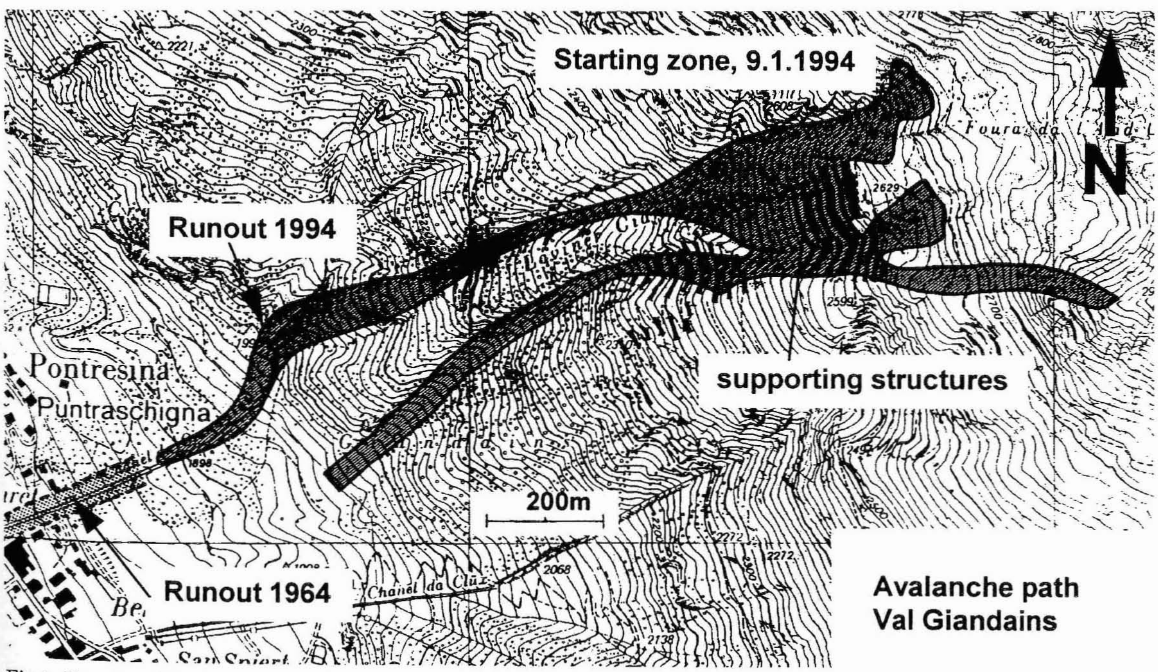

Fig.1: Situation Val Giandains-Pontresina

Starting zone:	A: situation of 1964	B: situation of 1994	
	no structures	no structures	structures
width/flow depth	290m/0.9m	90m/0.9m	200m/0.5m
speed	19.1m/s	19.1m/s	10.0m/s
friction values μ/ξ	0.25/1000	0.25/1000	0.27/500
flow rate Q_1 and Q_2		$1547m/s^3$	$1000m/s^3$
total flow rate Q/volume V	$4983m/s^3$ / $47'500m^3$	$2547m/s^3$ / $33'000m^3$	

Track and runout:	A: situation of 1964	B: situation of 1994
Begin of runout/slope	1870m/12.4°	1870m/12.4°
speed	17.2m/s	12.2m/s
width/flow depth	80m/3.6m	70m/3.0m
friction values μ/ξ	0.25/1000	0.27/1000
runout distance s	295m	85m
observed runout s	300m	50m above 1870m

Tab.1: avalanche dynamic calculations, Pontresina - Val Giandains

ton 15-20%, Community 5-15%. Because of the high costs supporting structures are used mostly for the protection of settlements. In the Swiss Alps supporting structures in the starting zone have been used for avalanche control for about 120 years. Until today supporting structures with a total length of some 470 km have been built.

2. CASE STUDIES

The interaction of supporting structures with the snowpack has been studied for several winters in selected areas. After critical avalanche periods monitoring flights to controlled areas have been made by SFISAR and local responsibles. If possible field visits were added. Two examples are given to illustrate avalanching in defense areas composed of modern supporting structures:

Pontresina - Val Giandains, 8/9.1.1994

Avalanche defense work above the village of Pontresina in the Engadin valley began at the end of the last century with stone terraces and afforestation. In the main starting zone of the Val Giandains avalanche 1360 m of 3 m high steel constructions have been built between 1982 and 1989. About 25% of the entire starting zone of 8 hectares is protected. In the northern gully and above the controlled area are secondary starting zones.

The Giandains avalanche occurred during the night of January 8/9, 1994, after a snowfall from the 7th to the 9th of about 105 cm on a weak snowpack. The mean density of the new snow was 111 kg/m³. The snowheight was estimated to 120 cm, that means one third of the structure height. During the period of snow fall heavy winds blew from the south. The Swiss avalanche bulletin indicated a high degree of danger.

Pictures show that at first a small dry slab avalanche started at 2800 m in a leeward slope. Afterwards the whole starting zone fractured, in the controlled area (inclination 38°, slope distance between the lines 19 m) too. The crown surface occurred along the supports of the structures. In the average about 20-50% of the sliding snow was stopped by the structures. The propagation of the shear fracture could not be avoided. The avalanche stopped at contour line 1890 m, well above the houses. No damages have been recorded. The height of the snow deposits was less than 1 m (Fig.1).

On March 30, 1964, an avalanche with exactly the same starting zone like 1994 had been observed. At that time there were no structures in this starting zone. The snow height was 140 cm. The new snow height in the starting zone from 27th to 29th was about 110 cm with a mean density of 77 kg/m³. The snow fell on the icy surface of an old snowpack only 0.6 m deep. The avalanche stopped on the main road of Pontresina in between the houses. The runout was 350 m longer than 1994. The snow deposit was several meters high.

How can this difference be explained? The main starting zone is between the contourlines 2620 m and 2500 m. The width of the unconfined slope is 290 m and the inclination ψ is 37°. At first avalanche dynamic calculations with the Voellmy-Salm model without any supporting structures are made (situation A, 1964). The slab thickness d is 0.9 m.

Then calculations are made for a width of 200 m with structures and for a width of 90 m without structures (situation B, 1994). The slope distance among the 6 lines is 19 m (Fig.2). It is assumed that the slab avalanche started simultaneously on the whole area. In the controlled area the slab is separated by the lines of structures. The snow impacts the next line before it reaches full speed. Through the impact a loss of energy and mass occurs. This is taken into account by varying the turbulence coefficient ψ from 1000 to 500 m/s² and by reducing the flow depth d from 0.9 m to 0.5 m. The speed v in relation to the covered distance x can be expressed (Voellmy, 1955):

$$v^2 = d\xi \sin\psi - \mu\cos\psi \, ((1-e^{-(2g^a x / d\xi)}).$$

The flow rate Q flowing through the bottom of the controlled area is calculated with the smaller speed and the reduced flow depth. Because of the smaller speed and the smaller volume of the avalanching snow the dynamic friction coefficient ψ is increased from 0.25 to 0.27 in the track and runout.

The calculations show that the structures reduced the speed of the avalanche at the end of the starting zone from 19.1 m/s to 10.0 m/s and the flow rate from 4983 m³/s to 2547 m³/s (Table. 1). Because of the smaller flow rate the calculated runout in the situation of 1994 is about 210 m shorter.

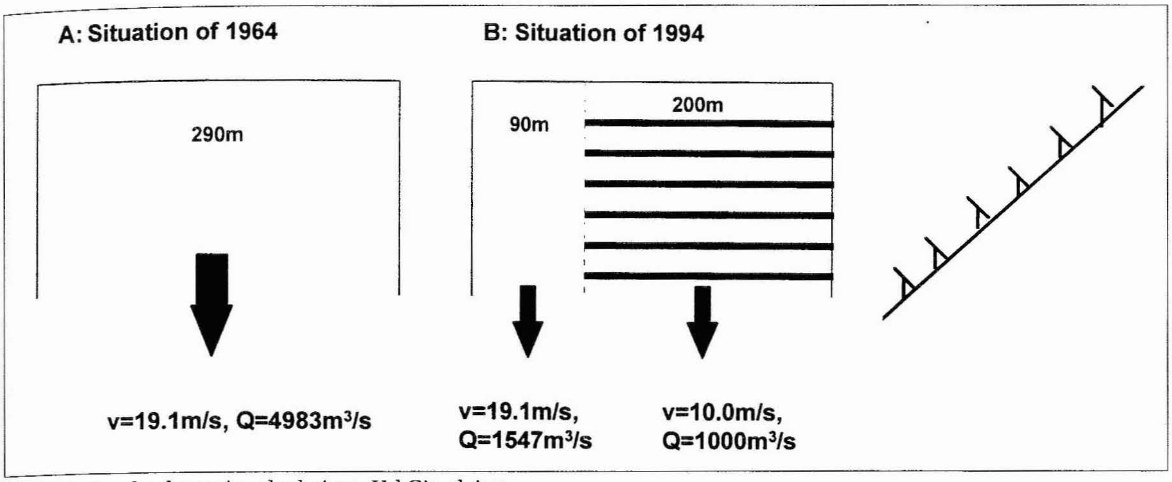

Fig.2: Avalanche dynamic calculations, Val Giandains

Seewis - Vilan, 12.1.1995

The snowstorm from 8th to 12th of January 1995 brought large amounts of new snow to the eastern Swiss Alps, with cold temperatures and strong NW-winds. The increase of snow depth within 3 days was about 100 cm. The mean density of the fresh snow was 80 kg/m³. The snow fell on a thin and loose snowpack of only 0.2 to 0.5 m. The degree of danger in the Swiss avalanche bulletin was high. Pictures taken the 13th of January show that a big slab was released about 50 m below and 100 m beside the controlled area (Fig.3). The slab thickness was estimated to be 1 m, the width 250 m and the volume 20'000-30'000 m³. The avalanche stopped after a track of 1.5 km and a height difference of more than 700 m. Small damages to afforestations were recorded.

In the controlled area between the lines of structures No. 10 and 11 a small slab with a width of 28 m and a thickness between 0.5 m and 1.7 m was observed too. Profiles of the snowpack (Fig.4) before and after the avalanche made it possible to estimate the catching efficiency of the structures. About 45% of the fractured snow was stopped by the next and 30% by the after next line of structures. The inclination of the surface of the banked-up snow was about 7°. Only a few snowballs left the controlled area.

Between the next 4 lines of structures above line No. 10 long tensile cracks in the snow pack were observed. Mostly the cracks occurred along the supports because of the stress concentration due to the perforation of the snowpack. The propagation of the shear fracture and the release of a slab seemed to be impeded by the additional compressive stresses due to the structures. In the uncontrolled area these artificial zones with a higher snowpack stability are missing.

Without detailed snow stability measurements it is not possible to answer the question if a big slab would have been released, if the area had not been controlled with structures.

3. ANALYSIS OF THE EFFECTIVENESS

The analysis of considerable avalanche cycles in the winters 1984, 1994 and 1995 show generally satisfactory results. No destructive avalanches were released in areas controlled by supporting structures according to the Swiss Guidelines (1990). Only small slabs and loose snow avalanches occurred between the structures. Outside of the controlled areas large avalanches could be observed. It appeared that one of the most problematic points is the extent of the controlled area:

- Some slabs have been released above the controlled areas. It is crucial that the fracture line lies within the back-pressure zone of the topmost structures. Nevertheless in some cases the flowing avalanches were retarded by the lines of structures to a harmless degree (Munt, February 1984, Giandains, January 1994). But if the avalanches are too fast the structures can be damaged.
- Some big avalanches were released below and beside controlled areas (Grindelwald First, Rietstöckli, January 1995; Clavaniev, Crap Stagias, February 1984). In some cases avalanches spread into the controlled area. There were areas only partly controlled either because the constructions were not yet finished or by insufficient financial means. To prevent the release of catastrophic avalanches the whole starting zone has to be controlled by structures.

It is rather difficult to quantify the stabilizing effect of supporting structures by means of field investigations. The observed avalanches between the structures were mostly released either after very loose or heavy new snow falls or during spring time situations. Soft and wet slabs seem to be more problematic than hard slabs. After the initial shear fracture and the secondary crown tension fracture, hard slabs were often stopped by the next line of structure after downslope displacement in the centimeter to meter range without breaking into blocks (Fig.5). Soft and wet slabs are breaking up immediately. Further the propagation of a shear fracture is limited in a controlled area because the weak layer is interrupted by the lines of structures and has a smaller extent due to the additional compressive stresses behind the structures.

Salm (1995) theoretically checked the distance between structures on the basis of mechanics of snow slab formation. The result was that with a relative high snow gliding

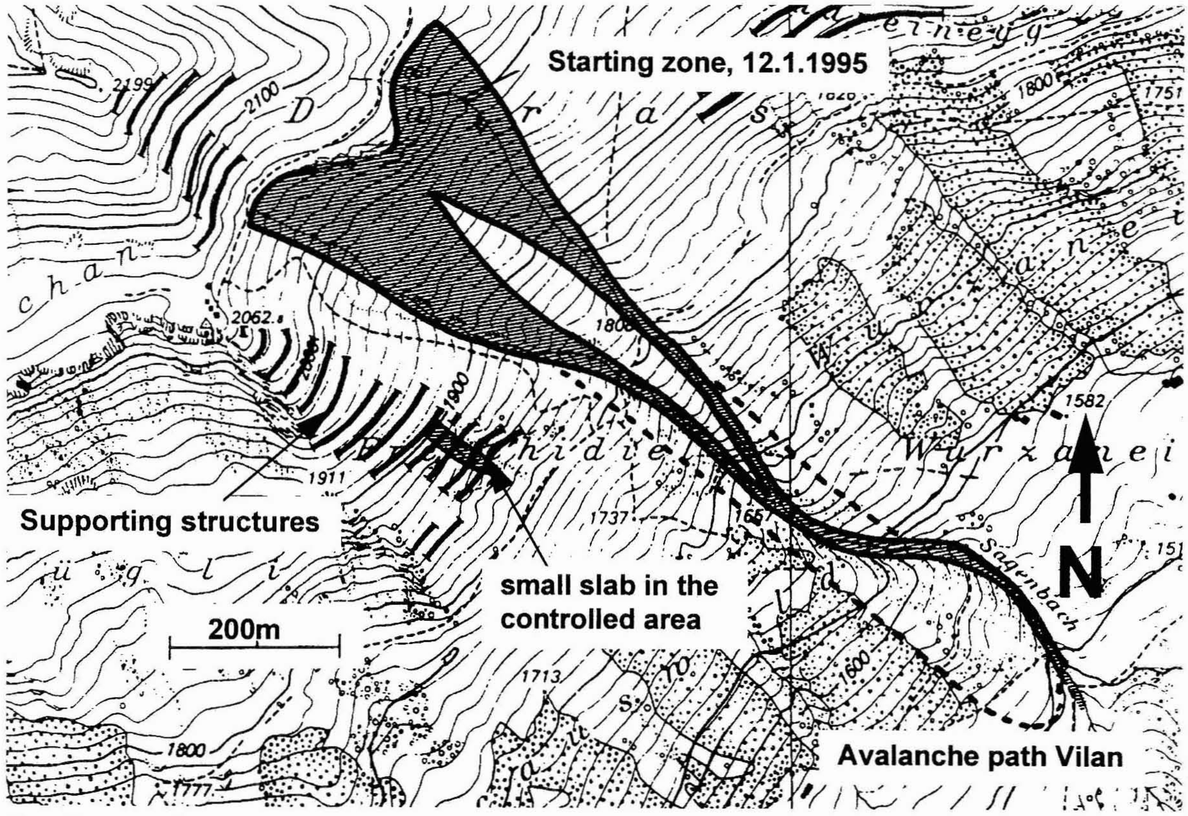

Fig.3: Situation Vilan-Seewis

the efficiency of the structures is generally satisfactory. But without gliding a slab release is possible.

Rychetnik (1985) investigated the influence of supporting structures on avalanche frequency by comparison of a period of 10 years before and a period of 13 years after their installation on the Stillberg test area near Davos. In the area of continuous arrangement of structures the slab avalanche activity was reduced between 48% and 58% and in the area with staggered arrangement between 21% and 16%. Most of the slabs had a rather small size.

After the failure of a slab the catching and retarding effect of the structures becomes important. This effect depends on the snow quality, the height of the natural snowpack, the fracture height and the density of the supporting plane.

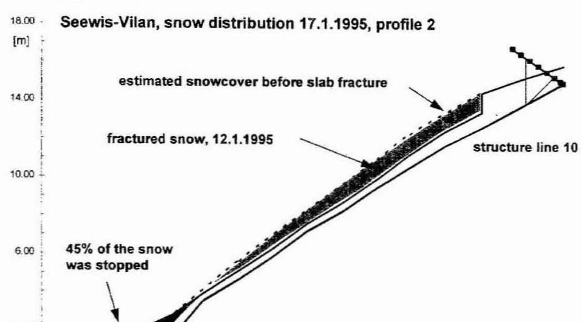

Fig.4: Slope profile, Vilan-Seewis

The efficiency of steel bridges with a distance between the crossbeams of about 25 cm is generally satisfactory. For cohesive or wind-deposited snow which is typical of major avalanche situations the catching capability is up to 100%. Very loose snow in combination with small fracture depth is more problematic. Then the catching capability can be much less than 50%.

In two areas controlled with steel bridges and snow nets the differences between the two types of structures were studied:

- At the Oberalp site the catching and retarding effect of snow nets with a mesh width of 25 cm and a density of about 7% was negligible (Fig.6). During the same situations the steel snow bridges caught an important amount of the avalanching snow.
- To ameliorate the catching effect in the Duchli area the nets were covered with dense meshrope stripes fixed diagonally on the net in distances of 50 cm. A density of 50% could be achieved. Observation shows that even with these stripes the catching effect is too low. The distance of 50 cm seems to be too large to stop loose sluffs. Also in this situation the lower steel bridges caught most of the snow flowing through the nets.

To improve the catching capability of the nets the supporting plane should be protected with a wire net with a mesh width of 5 cm or dense meshrope stripes diagonally fixed in distances of 25 cm. No premature filling up of the structures because of the higher density could be observed. Mostly these small slabs flowing through the structures are not destructive to the objects to be protected. If such small slabs have to be prevented as well, the distance between the lines of structures should be reduced and the supporting plane should be more dense.

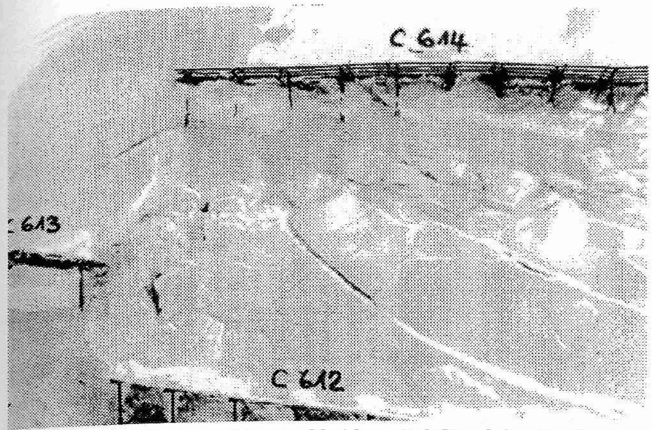

Fig.5: Hard slab stopped by steel bridges, Val Giandains-Pontresina

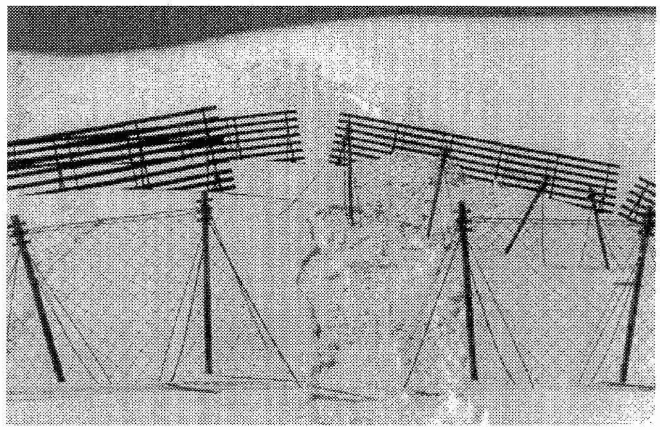

Fig.6: Snow net and steel bridges in a springtime situation, Oberalp

4. SAFETY ANALYSIS OF AREAS CONTROLLED WITH SUPPORTING STRUCTURES

After the building of supporting structures the protective effect has to be taken into account for the revision of hazard maps with respect to land-use planning. Supporting structures reduce the probability of avalanche fracture and their extent. The following questions are crucial: which degree of safety can be attained below controlled areas, how much smaller are the hazard zones? According to our experience there are no general solutions. Every single case has its own characteristics. In Switzerland the responsibles are very cautious in reducing hazard zones. Changing a red zone (high hazard) into a white one (no hazard) after the realization of supporting structures is an exception, often a blue zone (low hazard) is introduced. To determine the residual risk below a controlled area the following criterias should be checked:

- Extent of the starting zone

  Often the terrain of starting zones is very complex. Beside or below the main starting zone which is controlled there are secondary ones which are then decisive for avalanche dynamic calculations. The frequency of these avalanches is often smaller compared with those of the main path.

- Arrangement of structures

  The arrangement of the structures should correspond to the Swiss Guidelines (1990). Important points are the upper and lower boundaries of the controlled area, the slope distance between the lines of structures and the length of the lines. In every starting zone there are places like narrow gullies or steep rockcliffs that are more difficult to control. Avalanches released in controlled areas are calculated with reduced flow rates due to smaller velocities or lower turbulent friction parameter ξ. Either the speed is calculated after a distance that corresponds to the slope parallel distance between two structure lines or the turbulent friction parameter ξ is reduced to 280 m/s^2.

- Extreme snow depth

  According to the Swiss Guidelines (1990) supporting structures are designed for the 100-year extreme snow depth expected at the site. However for hazard mapping events up to 300 years have to be considered in Switzerland. There is a risk that structures are filled up before an important snow fall occurs and a slab is released over the structures. At Weissfluhjoch (2540 m a.s.l.) maximal snow depths are recorded normally between March and May and the most frequent snowfall periods are in average between December and February. There are no approved methods yet to determine realistic fracture depth for avalanche dynamic calculations as a function of extreme snow depth and for a return period T of 300 years. In practice the following rough estimates could be used:

I. It is assumed that the difference ΔH between the structure height H_k and the 300 years extreme snow depth H_{ext} expected in the starting zone corresponds to the mean fracture depth. The necessary data originate from observation series over up to 60 years of the SFISAR network. With the mean slope ψ the slab thickness d_0 can be computed from the snow depth difference ΔH according to Salm et al. (1990).

Example for Weissfluhjoch (2540m):

H_{ext}=456cm (T~300years)

H_k=411cm (T~100years)

ΔH =456-411=45cm

II. It is assumed that the probability P_k that the snow height equals the structure height H_k times the probability P_Δ for a certain increase of snow depth within 3 consecutive days (H3, is equal to 1/300, corresponding to the probability used in hazard mapping:

Example for Weissfluhjoch (2540m):

H_k=411cm $-_\Delta$(T~100years– P_k =1/100

1/300=1/100 – P_Δ – P_Δ=1/3(T_Δ=3years

An increase of snow depth within 3 consecutive days ΔH3 of 79 cm corresponds to a return period T_Δ of 3 years. This is nearly the double compared to I. Probably it is overestimated because of less intense snowfall during the time of maximum snow depth. With the mean slope ψ the slab thickness d_0 can be computed from ΔH3 according to Salm et al. (1990).

- Winter and snow conditions

  After supporting structures are completed in an area snow deposits and snow movements should be regularly observed, especially in order to judge the effectiveness of the structures during major avalanche situ-

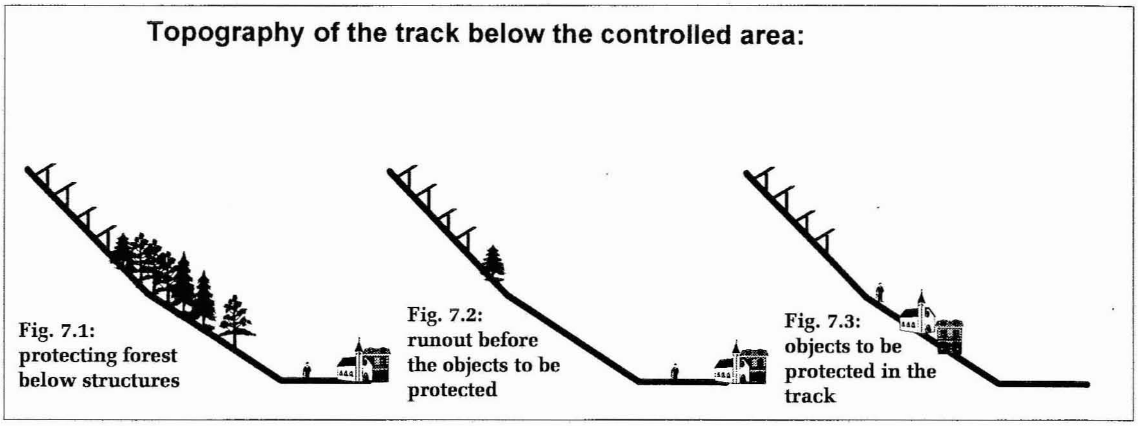

Fig.7: Avalanche path

ations. Sometimes the structures are locally overfilled with snow drifts and additional measures against snow drift have to be taken.

- Topography of the track below the controlled area

  Very important for a safety analysis is the position of the object to be protected in the track. The highest safety is achieved if the structures are combined with an afforestation (Fig.7.1) and the object to be protected is at the bottom of a valley. As the protecting forest grows, the level of safety increases. Avalanches released in the controlled areas are limited to a harmless magnitude by the forest. If there is a runout zone between the track and the objects to be protected (Fig.7.2), then often avalanches released in the controlled area can not reach them. These avalanches have a much shorter runout than an extreme avalanche without any protection work. The hazard can be determined with runout calculations.If the objects to be protected are located in a steep track below the controlled area or at ist end (Fig.7.3) without any retardation zone, also small slabs can reach this zone. The hazard can be estimated by the calculation of avalanche pressures exerted on obstacles and frequency analysis.

5. RECOMMENDATIONS FOR THE USE OF SUPPORTING STRUCTURES

Supporting structures are suitable to prevent extreme destructive avalanches with long return periods and long runouts. In Switzerland the expensive supporting structures are widely used to protect zones or objects which are difficult to evacuate or to close during high avalanche hazard. These are mostly settlements that have been built a long time ago in the runout of extreme avalanches. Generally during catastrophic situations the supporting structures stood the test. If possible the structures have to be combined with an afforestation to increase safety.

Their use for the protection of roads is justifiable if the starting zone has a limited altitudinal range. The closer the road is situated to the slope the higher are the safety requirements for the controlled area. If there is no runout in front of the road the lowest structures should have a dense supporting plane or additional deposition space should be established as close as possible. Snow sheds normally povide a higher degree of safety.

In ski areas supporting structures are generally not recommended for the protection of skiruns, but they are suitable to protect for example terminal stations or pylons. As shown before in areas controlled with supporting structures, small slabs can start and kill a skier. The arrangement and design of supporting structures according to the Swiss Guidelines (1990) are not made for the protection of persons in or directly below the controlled area. To achieve this the space between the lines should be smaller, the supporting plane denser and the entire starting zone has to be protected. Some protected areas above ski runs which do not fulfill these strong requirements have to be controlled additionally with artificial release. The use of supporting structures for the protection of skiruns seems only justifiable if artificial release is not possible.

The effectiveness of supporting structures will be investigated in more detail in a future SFISAR research project.

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