Effectiveness and maintenance of technical avalanche protection measures in Switzerland

Stefan Margreth[1]*

[1] *WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, SWITZERLAND*
**Corresponding author, e-mail: margreth (at) slf.ch*

ABSTRACT

In Switzerland, supporting structures are the most important structural avalanche protection measure with replacement costs of around CHF 1.5 billion. The analysis of the snow-rich winter 2018 gave new insights into the effectiveness and vulnerability of protective measures. The effectiveness and maintenance are important aspects in the service life of a protective measure. For efficient maintenance, a register of protective structures and periodic inspections are required. In future, maintenance will be more important than the construction of new protective measures.

1. INTRODUCTION

Switzerland has a high natural hazard risk. This is due to the mountain topography, to the very dense population and the large number of infrastructure facilities. Today's settlement patterns and societal functioning would not be possible without the existing protective measures. Around 22% of the Swiss population lives in flood-prone areas. The risk of avalanches is much lower. Less than 1% of the population lives in areas endangered by avalanches. In order to counter this risk, protective measures against natural hazards amounting to around CHF 50 billion have been implemented (Martin, 2009). The proportion of technical avalanche protection measures is much smaller. Estimates show that around CHF 2 billion has been invested in technical avalanche protection over the past 50 years. Supporting structures are the most important permanent structural protection measure in Switzerland. Today, more than 500 km of permanent supporting structures exist, with an estimated replacement value of CHF 1.5 billion. Major efforts are required to maintain the high safety standard. Two important tasks which are discussed in greater detail below are i) the analysis of the effectiveness and vulnerability of mitigation measures during major avalanche cycles such as in winter 2018 especially regarding the rezoning of hazard maps and ii) the management of maintenance to preserve the effectiveness of the mitigation measures.

2. AVALANCHE WINTER 2018

The analysis of avalanche winters provides valuable information to be able to verify the functioning of the protective measures in realistic situations. In January 2018, 2.5 to 5 m of snow fell widely at high elevations in the Swiss Alps over a period of 25 days. This was as much new snow as registered at certain stations every 75 years. On 22-23 January, a north-west storm led to a serious avalanche situation. The highest hazard level (5, very high) was forecasted for a widespread area for the first time since 1999. Many large and several very large avalanches occurred, with the cantons Valais and Grisons being most severely affected.

The humid snowpack at medium elevations slowed down the avalanches, which released as dry avalanches higher up, so that no settlements were hit. In some cases, however, they were only just missed. By the end of April, more than 360 destructive avalanches had been reported to the SLF. No permanently inhabited buildings were destroyed and no people were injured in settlements or on traffic routes. Numerous traffic routes were closed for up to 9 days due to avalanche danger. However, the 2018 avalanche winter was less extreme than the avalanche winter 1999. For the first time satellite images (SPOT 6) with a resolution of 1.5 m of all areas with hazard level 5 (very large) were evaluated to document the avalanche activity (SLF, 2019). More than 18’000 avalanches were mapped in the investigated area of 12’000 km^2, which covers about 50% of the Swiss Alps. Around 16% of the avalanches surveyed had a volume exceeding 80’000 m^3 and started in southern to eastern aspects.

3. PERFORMANCE OF MITIGATION MEASURES IN WINTER 2018

3.1 Snow supporting structures:

In January 2018 the snow distribution was rather irregular due to wind. As a result, several areas with supporting structures were locally overfilled with snow (Figure 1). Since an increase in snow depths was to be expected in the further course of the winter, emergency measures were drawn up in case new snowfall events overfill the structures extensively and reduce the effectiveness of the controlled areas. Surprisingly, relatively large avalanches triggered in around 10 sites with supporting structures during the avalanche cycle of 22/23 January 2018 (Figure 2). The fracture depths of these avalanches were rather small, mostly in the range of 0.5 m. Since the supporting structures were usually not completely filled with snow, the avalanche snow was slowed down and partly stopped by the lines of structures. The steeper the terrain and the more the structures were prefilled with snow, the less avalanching snow could be retained. With regard to the fracture propagation, the lines of structures showed practically no effect in some cases.

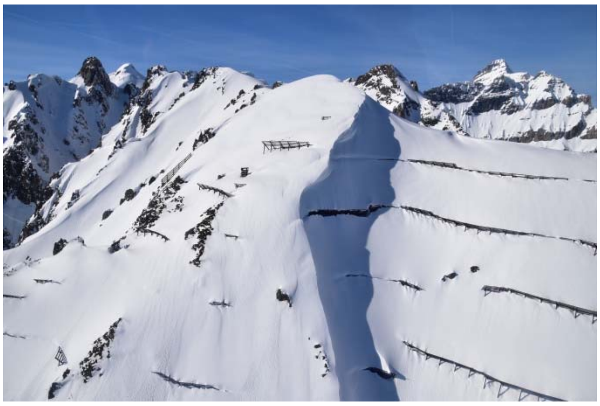


Figure 1 Supporting structures in the Valais, in the centre the structure height is 6 m. On 24 January 2018 the snow height was locally > 8 m (Photo J.J. Lugon).

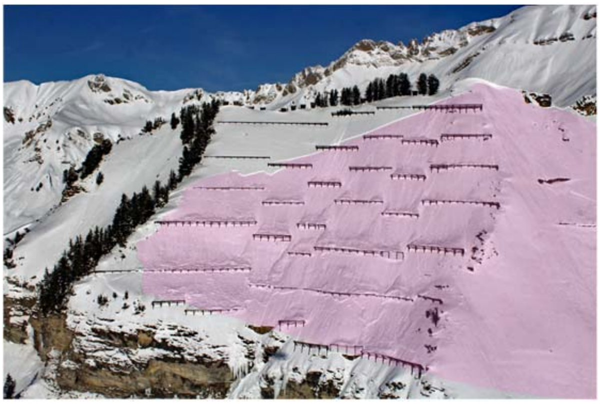


Figure 2 Supporting structures in the Bernese Oberland, on 22 January 2018 a large slab avalanche released within the controlled area (Photo U. Ryter).

The snow masses flowing out of the controlled perimeter were mostly small and caused no or only insignificant damage. As a result of high snow depths and strong snow gliding, the snow pressure loads on supporting structures were high in winter 2018. Consequently several supporting structures were damaged. In most cases, the damage was local and did not or not yet significantly affect the function of the structure. In the winter of 2018, the total amount of damage to supporting structures amounted to around CHF 1.5 million. In comparison to the total number of supporting structures, this figure is in the per mil range. The most frequent damage was to the valley-side buckled steel supports of snow bridges. Around 200 supports from older structures buckled out, because in addition to the normal force, a transverse force occurred (Figure 3; Margreth, 2007). The snow layer below can cling to the supports. In some snow-covered structures, girders and cross-beams broke or were bent. Such damages typically occur if a structure is overfilled with more than 1.0 m of snow. In some locations, where the distance between the lowest crossbeam and the ground was large (> 0.3-0.5 m), the uphill anchor bars were deformed or broken (Figure 4). This damage typically occurred in connection with strong snow gliding.

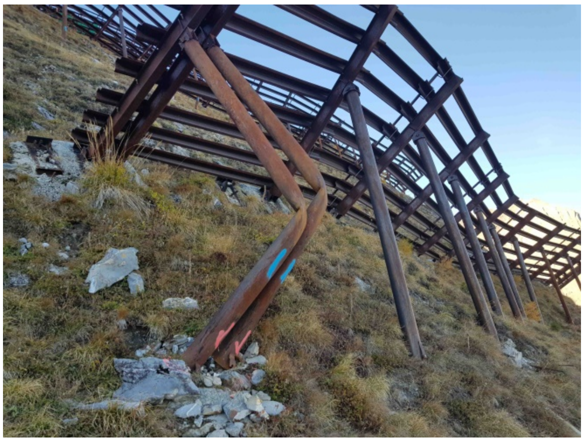


Figure 3 Buckled supports of end of line structures in the Valais. No lateral snow pressure was considered in the design (Photo Nivalp SA, 2018).

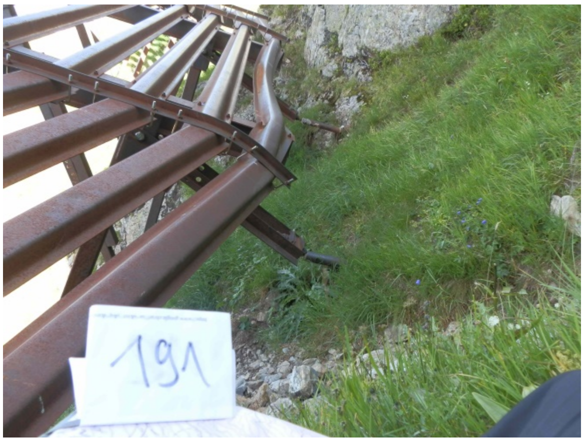


Figure 4 Deformed crossbeams and anchors because of a too large gap between lowest crossbeam and ground, canton Uri (Photo R. Planzer, 2018).

3.2 Snow drift fences

The combination of snow drift fences and wind baffles was efficient in conditions with snowfall and strong winds. Detailed observations are available from the snow drift fence at Tanngrindel in the Bernese Oberland. The 4 m high and about 90 m long fence reduces snow accumulations in an avalanche release area. The fence is located at a distance of 30 m from the edge of the terrain. On 27 January 2018, a laser scan-based snow depth map was prepared. Behind the fence about 40 m^3 snow per m was deposited. The maximum deposition height was slightly over 4 m. A total of about 5000 m^3 of snow was retained by the fence. Significant damage occurred at a 275 m long snow drift fence at Valtschamela in the canton Grisons, which was constructed in a 25° to 30° slope. Since the ground gap of the 4 m high fence was only about 40 cm, the fence was covered with snow relatively early in the winter. As a result snow pressure acted on the fence. Several steel girders and anchors were bent in the direction of the valley (Figure 5). The snow drift fence must be completely rebuilt. In inclined terrain, snow pressure as well as wind loads must be taken into account for the design of snow drift fences.

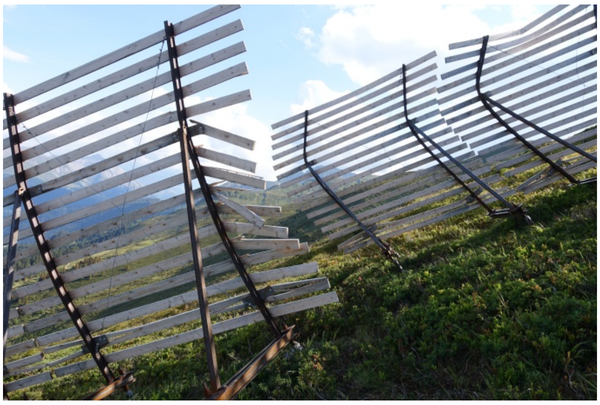


Figure 5 Snow drift fence damaged by lateral snow pressure acting in the line of slope, Valtschamela, canton Grisons (Photo S. Margreth, 2018).

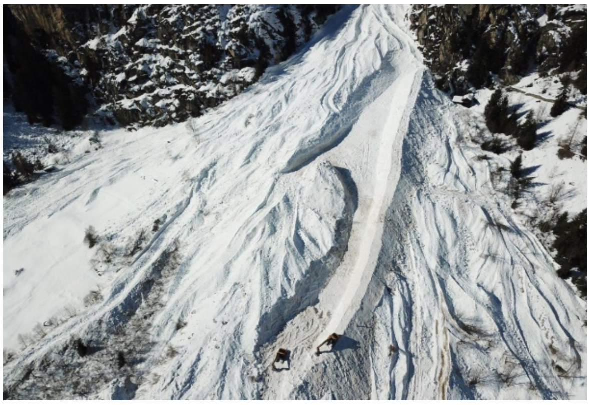


Figure 6 Deflecting dam made of snow, canton Valais (Photo W. Gitz, 2018)

3.3 Snow sheds and avalanche dams

At least 50 snow sheds were hit by avalanches in January 2018. One problem with snow sheds is their length, which is often planned to be as short as possible for financial reasons. At least ten snow shed portals were overflowed laterally. The structure of a snow shed protecting a railway line was damaged due to lateral snow pressure. A number of avalanches occurred in avalanche tracks protected with dams. However, only few avalanches reached the dams. In the Lötschental (Canton Valais), a site with supporting structures was largely destroyed by an avalanche in winter 1999. In order to protect the village and the supporting structures from avalanches, a 380 m long and 10 m high wedge-shaped deflection dam was constructed on a terrain terrace above. In January 2018, an artificially triggered avalanche reached a similar size as in 1999. The snow masses were completely deflected by the dam. At the upper end of the dam, the snow masses practically reached the top of the dam. In the Matter valley, 3 to 7 m high dams of snow were built in the lower part of four avalanche tracks in order to prevent the railway from being buried by subsequent avalanches, which could have a longer runout than usual in the smoothed out avalanche tracks (Figure 6).

4. MAINTENANCE MANAGEMENT IN SWITZERLAND

4.1 Overview

In Switzerland, protection against natural hazards is a joint task of the Confederation, cantons and communes. For the management of protective structures, this means that the Confederation issues the legal base, defines a minimum data model for the protective structure register and ensures partial funding. The cantons keep the register of protective structures and ensure their maintenance. The communes periodically check the protective measures they own and carry out simple repairs themselves (Frei, 2013). In the case of major maintenance measures, they receive technical and financial support from the Confederation and the canton. In the future, the focus will be on preserving the existing protective structures and not on constructing new ones. The goal of protective structure management is to achieve the longest possible service life for the structures. Since the effect of the protective measures is considered in hazard maps, structural safety and serviceability must be guaranteed. Both are influenced by aging. In the case of supporting structures, the quality of the building materials, the construction work, the climatic conditions, the effect of snow pressure and the geotechnical situation are decisive. Snowy winters and heavy rainfall with erosion can lead to faster aging. Timely execution of maintenance measures can have a positive counter-effect on aging. In order to be able to carry out maintenance measures in time and to know the long-term financial need for maintenance, an overview of the number and condition of all structures is required. A functioning protective structure management system includes a register of protective structures, a manual for structure inspections and multi-year planning.

4.2 Protective structure register

The register is kept by the cantons and gives an overview of "what measure is where and in which condition". An administrative data base contains all relevant information on the project perimeter such as name, commune, owner, person responsible for periodic on-site inspection, inspection cycle, protection goal, year of construction and cost. A spatial database contains the positions of the single structures with attribute tables showing the structure number, structure type, year of construction, structure height, foundation type, anchor length, date of inspections with structure state, observed damages, repair cost and so on (Figure 7). Additionally an archive of the project files such as the extent of the project perimeter, structure drawings, protocols on anchor pull-out tests and grout checks as well as correspondence and photos. The numbering of the structures is very important to allow on-site identifcation.

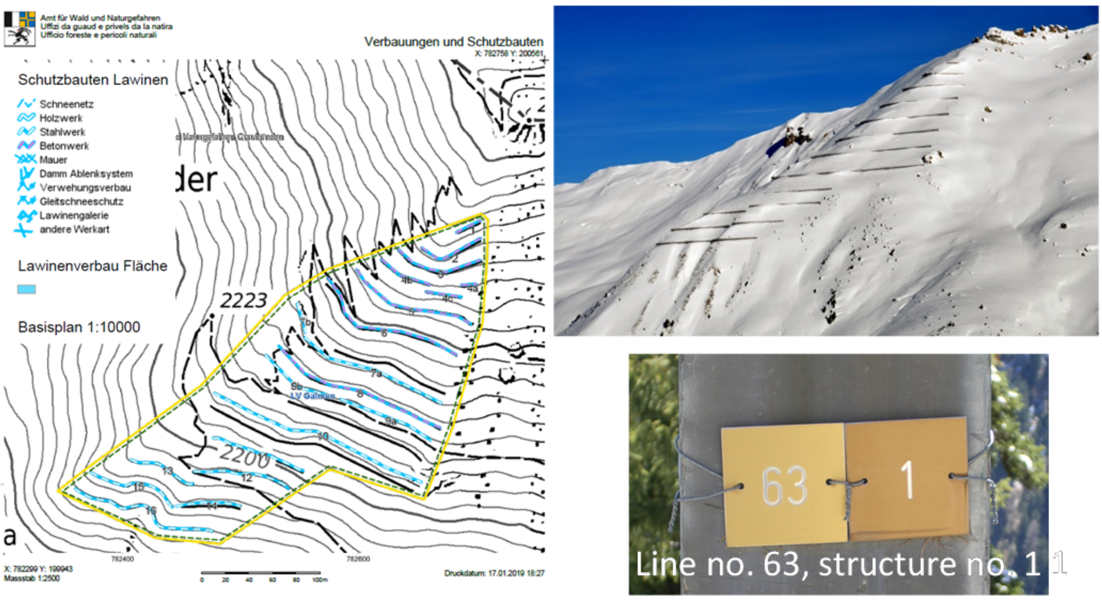
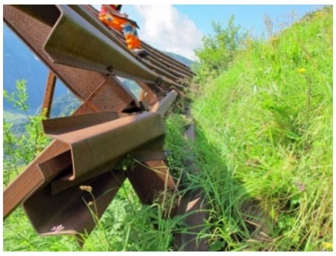
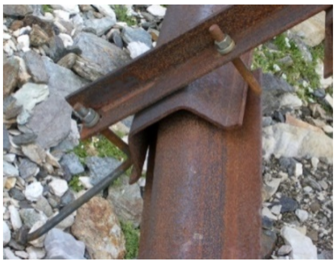
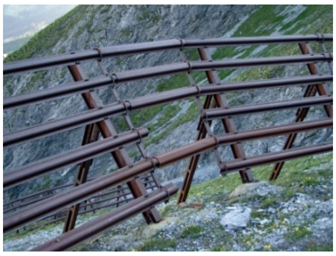
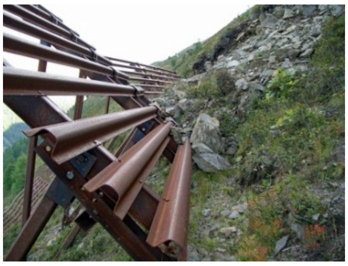


Figure 7 Protective structure register Canton Graubünden with extract of the map server, overview photo and structure numbering

4.3 Manual for structure inspections

Several cantons have developed a manual for the structure inspections (AWN et al., 2018). The two-stage procedure consists of an inspection of the single structure and an overall evaluation of the protection goal. The inspection on site is carried out visually by going from the general to the detail. Large-scale slope failures, local soil movements or soil erosion can lead to structural damages. The assessment of the geometry of a line of supporting structure often provides indications of possible damage. The single superstructure is analyzed visually typically in regard of deformation or failure of steel members or wire ropes, geometry changes, displacements of steel bed plates, erosion around foundations and cracks in anchor grout or concrete foundations. The manual contains a checklist with photos which show the most relevant and frequent damages or defects of supporting structures (Table 1).

Table 1: Example of a check-list for evaluating the state of crossbeams

Crossbeams	Damage and cause	Maintenance
	Crossbeams with dents, deformation or formation of cracks. Check if the girder is also deformed. Too high snow pressure (snow gliding, overfill with snow), impact of rockfall, impact of avalanches.	None, observation. Repair (straightening) Replacement
	Defect fastening of the crossbeams: broken brackets, missing screws, loose screws, shifted fastening rail. Particularly tricky when the direction of the crossbeams changes (convex position). Snow pressure, rockfall, wind load (vibrations).	Replacement; tighten screws.
	Missing crossbeams. Vibrations because of varying wind loads, avalanche impact, rockfall, overlapping of main and intermediate crossbeams often too small.	Replacement; check that overlap of main and intermediate crossbeam is > 5 cm; the planned distance is typically around 25 cm.
	Filling of the supporting plane with stones and earth. Problematic if the effective height is smaller than approx. 50 cm. Deposit from rockfall, erosion or landslide.	Removal of deposited material if thicker than 50 cm. Evaluate the cause of the ground instability and fix it if necessary.

The inspection made by local foresters or engineering companies is done as a negative check by documenting only damages. It is preferable that the inspection is always carried out by the same person, in order to detect changes better. The corresponding documents exist for reporting. The damages are classified into five condition classes (Table 2). Condition class 1 means very good, it is a new structure. Condition class 5 means alarming, i.e. the structure is heavily damaged or destroyed and should be repaired immediately. The most common forms of damage to supporting structures are deformations of the superstructure and foundations due to great snow pressure resulting from severe snow gliding or when the structure is overfilled with snow. The worst damage occurs during dynamic avalanche impact, especially if an avalanche enters the defense area from the top or the sides.

Table 2 Condition evaluation of snow supporting structures (AWN et al., 2018)

Condition level	State characterization	Urgency for maintenance	Time horizon for consequen-tial damage	Example of damages
1 very good	New structure	None	-	-
2 good	As good as new until first signs for aging	None	-	Natural aging, small deformation of cross beams
3 sufficient	Small damages, structural safety and serviceability fulfilled	Small urgency, observation	> 5 yrs.	Bent cross-beams, erosion around foundation < 10-20 cm, debris on the grate < 50 cm, uniform corrosion (rust)
4 poor	Damages and weak points, reduced structural safety, serviceability mostly fulfilled	Middle urgency, maintenance required in 1-2 yrs.	2-5 yrs.	Slightly buckled posts, a pressed in micropile, eroded anchors > 20-40 cm, displaced cable clips
5 alarming	Risk of collapse, structural safety and serviceability very limited	High urgency , maintenance required in less than 1 yr.	< 1 yr.	Buckled supports, broken or pulled out anchors, broken girders, broken wire ropes

The inspection cycle depends on the geotechnical conditions of the site, the snow situation (e.g. area with strong snow gliding), the complexity of the perimeter, possible rockfall activity, type, age and vulnerability of structures and the results of the former inspections. A rough visual inspection is performed yearly. A more detailed inspection where all structural members and foundation components are closely verified visually is performed at intervals of 1 to 5 years and after snow-rich winters. Specific inspections e.g. performing anchor pullout tests are arranged if the uncertainty on the structural state is very high or if a bigger maintenance project is planned. For future anchor pullout tests additional anchors representative of the types installed are drilled and marked accordingly.

The causes of damage to supporting structures can be systematized by differentiating between internal causes that directly affect the structure and external causes such as effects from the environment (Table 3). Further the two causes can be subdivided into typical causes such as normal aging or normal snow pressure loads and atypical ones such as design errors or the impacts of rockfall or avalanches not considered in the design. Atypical external causes are usually unpredictable, but can cause great destruction.

Table 3: Overview on causes of damage to snow supporting structures (Rudolf-Miklau et al., 2015)

Influence	Internal cause for damage (structure / material)	External cause for damage (effects from the environment)
Typical (predictable): considered in the design process of a supporting structure	Material aging (corrosion, embrittlement), load changes (material fatigue)	Snow pressure, impact of snow slides, erosion
Atypical (often unpredictable): not considered in the design process of a supporting structure	Material defects, design faults, construction defects, planning errors	Avalanche impact, cornice collapse, rock and block fall, falling trees, strong erosion, storm

5. CONCLUSIONS

The compilation of event analyses of avalanche winters is helpful for verification of the performance of protective measures in extreme avalanche situations. The 2018 avalanche winter showed that supporting structures do not provide 100% safety. Each protection measure is designed for a specific scenario. If this scenario is exceeded, there is a residual risk. Winter 2018 showed some weaknesses in protective measures that need to be eliminated. In Switzerland, maintenance will be more important in future than the construction of new protective measures. This requires efficient management of protective structures, which typically consists of establishing a register of structures and carrying out inspections. In the case of older structures, a conceptual review must be carried out from time to time to determine whether the structures still meet current requirements or whether a change in strategy is indicated in the protection concept. It is also conceivable that there are situations in which maintenance is no longer worthwhile and the dismantling of protective measures is envisaged.

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