Guidelines for Artificial Release of Avalanches

Contains information about:

- Formation of slab avalanches
- Risk reduction by temporary measures
- Effect of blasting on the snow cover

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Guidelines for Artificial Release of Avalanches

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List of Contents

1. Introduction 1

2. Measures for reducing risk 3
2.1 Introduction 3
2.2 Definition of risk in the context of protection from avalanches 3
2.2.1 Probability of event (danger) 6
2.2.2 Probability of presence 7
2.2.3 Extent of damage 7

3. Formation of slab avalanches 9
3.1 Introduction 9
3.2 Initial fracturing and shear fracture propagation 9
3.2.1 Summary 12
3.3 Deformability as the key parameter for snow slab danger 12

4. Artificial release of avalanches 15
4.1 Requirements for the method of artificial release 15
4.1.1 Determination of the areas endangered by avalanches 15
4.1.2. Reinforcement of installations and buildings 15
4.1.3. Assessment of avalanche danger or snow cover stability 15
4.1.4. Closure and evacuation of endangered zones 15
4.1.5. Rescue 16
4.1.6. Artificial release of avalanches and stability tests 16
4.2 Effect of blasting on the snow cover 16
4.2.1 Measurement of additional stresses in the snow cover as a basis for comparison of different triggering methods 18
4.3 Effective range 19
4.3.1. Size of an effective range of 100% for the blasting methods 19
4.3.2. Point of detonation 20
4.3.3. Charge size 20
4.3.4. Type of explosive 20
4.3.5. Type of snow, type of bedrock 21
4.3.6. Effective ranges of different types of explosives 22
4.4. Methods of artificial avalanche release 23
4.4.1 General points 23
4.4.2 Hand-thrown charges 23
4.4.3. Detonation above the snow with a charge attached to a pile 23
4.4.4 Ridge cantilevers, beams 24
4.4.5 Hand-thrown charges from the helicopter 24
4.4.6 Lowering charges from manned cable ways 24
4.4.7 Blasting cableways, charge deployment systems 25
4.4.8 Projectiles, rockets 25
4.4.9 Gazex® 26
4.4.10 Daisybell® and O'Bellx® gas explosion systems 27
4.4.11 Avalanche Guard (Lawinenwächter®) 27
4.4.12 Avalanche tower 28
4.4.13 Special cases cornice control and gliding snow 29
4.5 Interpretation of results and guidelines 30
4.5.1. Choosing the correct time for avalanche protection work. 30
4.5.2. Selection of the type of explosive charge/ gas mixture 30
4.5.3. Choice of the correct firing point 32
4.5.4. Stability tests 33

4.5.5. Determination of the blasting efficacy 34
4.5.6. Residual risk 34
4.5.7. Safety of the blasting team 34
4.5.8. Detection of artificially released avalanches 35

5. Concluding remarks 37

6. Source references 39

1. Introduction

The risk of an avalanche accident can be reduced by various measures. A distinction is made between permanent (constructions, protective tunnels, galleries, deflection dams, splitters, etc.) and temporary measures (avalanche warning, closures, evacuation, artificial release of avalanches and rescue). The temporary methods of protection against avalanches are becoming increasingly important. In particular, improved knowledge about the processes involved in the formation of avalanches, better automatic weather stations close to the avalanche fracture zones, modelling of the critical factors and computer-supported aids to decision-making in addition to improvements to the methods for artificial release of avalanches and avalanche detection enables the closure times to be reduced and at the same time lowering the residual risk of an avalanche accident.

For temporary measures, in order to permanently keep the accident risk low, it must be possible to close and evacuate at any time all endangered zones including the extreme run-out areas of the avalanches. Buildings and installations within the endangered zones must be reinforced to withstand the forces of the avalanche. Temporary avalanche protection measures are recommended above all for the protection of tourist installations and for traffic lines with moderate traffic volume.

Under certain conditions, optimised temporary measures together with reduced permanent measures could be employed for the protection of settlements and traffic lines with high traffic volumes. Different protective concepts can be compared with each other using risk and safety analyses. Such analyses, which naturally also have to take the costs of the various protective concepts as well as the benefits of measures into consideration, form the basis for decision-making for specifying the safety measure

2. Measures for reducing risk

2.1 Introduction

The objective of technical protection measures is to minimize negative consequences due to avalanche danger for people and goods in their settlements and along traffic lines, and also for skiers on ski runs or in ski-touring terrain (Rudolf-Miklau F. and Sauermoser S., 2011). The risk is used as a measure for safety. The lower the risk, the higher the safety. A simple partitioning into "safe" and "dangerous" is no longer adequate today. Many different potential hazards influence the risk. It is often possible to reduce the risk by combining different types of protective measures.

2.2 Definition of risk in the context of protection from avalanches

The risk of an avalanche accident is determined by three factors:

1. The probability of an avalanche occurrence or avalanche hazard at the location to be protected (**probability of event or danger**), such as for example a ski run or a road,

2. the **probability** of humans and other unprotected objects **being present** at this place (**probability of presence**) and

3. the **extent of the damage** that quantifies the possible damage arising from the impact of the avalanche.

All three factors can be influenced using temporary protective measures. Whatever combination of protective measures are applied, they must guarantee permanent low residual risk. Although individual measures such as closures or artificial release of avalanches are only applied from time to time, avalanche protection must be permanently guaranteed for persons and objects.

These considerations lead to the following requirements for the various parts of the proposed measures:

- Continuous execution of measurements and observations that are decisive for determining the development of avalanche danger.
- Determination of the characteristic properties (e.g. weak layers) of the presently existing snow cover in the avalanche fracture zone, which although not directly measurable, are important for the formation of avalanches.
- Local experience with the assessment of the avalanche danger maybe with the support of electronic aids to decision-making.
- Setting-up, implementation and supervision of closures, evacuations and reopening.
- Application of the methods for the artificial release of avalanches, verification of the effectiveness and the results of the blasting performed (mayor unloading of the potential fracture zone).
- Organisation and continuous maintenance of a rapidly deployable rescue service.

- Assessment of the success of the protective measures with respect to potential and effective accidents and damage.

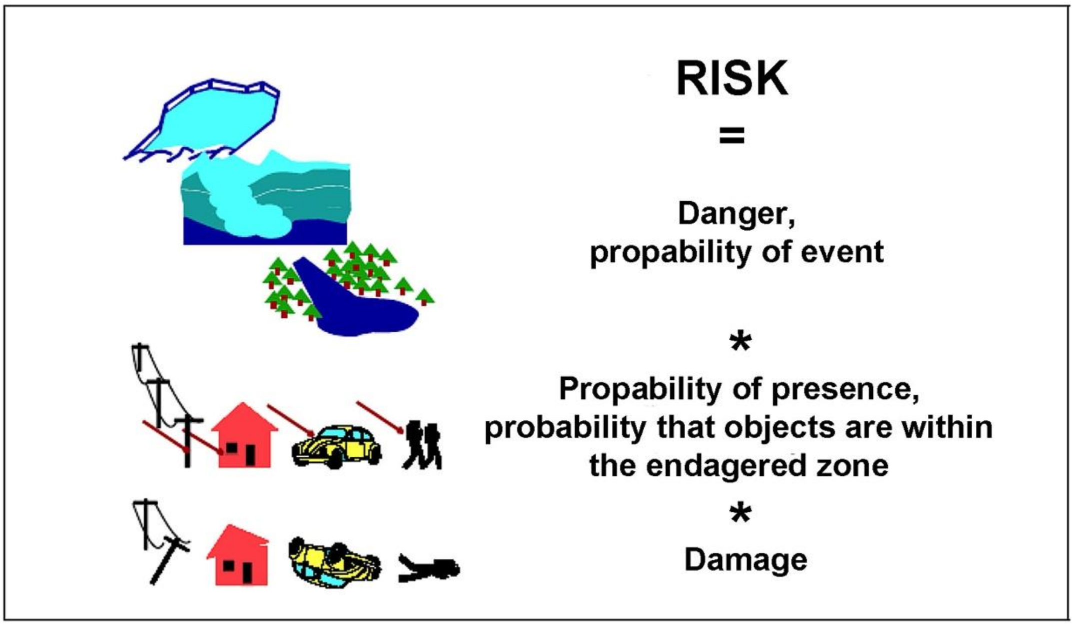


Figure 1: Definition of risk.

The aim of artificially releasing avalanches is to increase protection from avalanches for a limited period of time in the fracture zone and run-out area as well as in the avalanche path. The methods of artificially releasing avalanches not only permit potential fracture zones to be discharged, but principally, if minimum requirements are fulfilled, also allowing for an assessment of actual stability of the snow cover.

Risk analysis enables an assessment of different types of risk and corresponding appropriate protective measures for a given location. In order to be able to compare the operation and effectiveness of the different protective measures, the factors determining the risk will be defined and discussed below.

Risk is defined as the probability of an accident or damage occurring during a given time interval. We describe any type of damage or injuries caused by an avalanche on installations, buildings, forests or humans as an avalanche accident. If the risk is equal to 1, an accident will occur with certainty during a given time interval, but if the probability is 0, no accident will be anticipated.

Risk can basically be broken down into three mutually independent probabilities, that must be multiplied together (fig. 1): There is the danger or **probability of an event**, the probability of presence or **probability of damage** and the **extent of damage.**

For business enterprises and institutions the collective risk is extremely important. The collective risk is equal to the sum of the individual risks for all people and objects exposed to the event, multiplied by an aversion factor (= subjective factor, given by public acceptance and perception of the accident).

The risk remaining after all the safety measures have been taken into consideration is designated as **residual risk**. This calculated residual risk must finally be comparable with a tolerable, acceptable risk. A value of zero (absolute safety) cannot be achieved. The question "how safe is safe enough" cannot be answered on a purely scientific-technical basis. Subjective and irrational factors play a major role here. Often far higher individual residual risks are tolerated in the areas of leisure activities and sport than for example at work or when using public transport. The three risk factors are affected by different permanent and temporary protective measures:

Risk = **probability of event** * probability presence * *extent of damage*	
Temporary measures	**Permanent measures**
Artificial release of avalanches	**Supporting structures(1), diverting structures, avalanche retention dams, afforestation(2)**
AVALANCHE WARNING, CLOSURE, EVACUATION	AVALANCHE DANGER MAPS
Rescue	*Direct protection, object protection*

Table 1: Allocation of the temporary and permanent measures for protection from avalanches with regard to the risk factors.

(1) Each protective measure is dimensioned for a defined recurrence period of an event as e.g. maximum seasonal total snow depth, and to reduce the residual risk for a defined damage scenario. The height of snow retaining barricades depends on maximum seasonal snow depth, the distances between snow retaining structures within a potential fracture zone are based on maximum allowable movements of snow. The purpose of the standardised supporting structures (Margreth S., 2007) is to prevent extreme avalanche events from occurring. Supporting structures according to the guidelines do not prevent the triggering of small avalanches within and below the immediate vicinity of the construction area in every case.

(2) A forest must fulfil certain criteria in order to reliably prevent the formation of snow slab avalanches. Particularly deciduous forests must have a high trunk density (minimum diameter 0.1m) with a maximum separation distance of about 1.5 m (see Gubler H. and Rychetnik J., 1991).

2.2.1 Probability of event (danger)

In our case reducing the danger is identical to reducing the probability of an avalanche occurrence at the location where persons and objects are to be protected. This objective can be achieved with various measures:

1. Artificially increasing the stability of the snow cover in the respective fracture zones of avalanches possibly endangering the location to be protected .
2. Minimising the size of avalanches, or increasing the return period for large avalanches to decrease the probability of event at the location to be protected.
3. Measures for changing the avalanche paths and reducing the length of the avalanche run-out again to decrease the probability of an event at the location to be protected.

Basically we differentiate between permanent and temporary measures.

Permanent measures include lasting effective constructions such as supporting structures in avalanche fracture zones, possibly combined with snow fences, and deflecting, retaining and braking structures in the avalanche path. The stability of the whole snow cover is artificially increased by supporting structures in the avalanche fracture zones, possibly combined with snow fences to reduce the transport of drifting snow into the fracture zones by wind. Deflecting and braking structures and catchment dams in the avalanche run-out areas can reduce the distance of extreme run-outs. Permanent measures also include re-enforcements and protection measures at the object to be protected.

In contrast, the **temporary measures** do not have a long lasting effect, the danger can only be reduced for limited periods of time. These type of measures includes artificial release of avalanches, guidelines for tourists present in areas possibly endangered by avalanches, as well as closures and evacuations. Temporary measures do not prevent the formation of avalanches. Only the time and, under certain conditions, the maximum size of the avalanche (with limited success) can be influenced e.g. by the method of artificial release of avalanches.

Artificial release of avalanches allows to discharge potentially threatening snow masses from potentially dangerous fracture zones at selected points in time. This significantly increases the stability of the remaining snow in the fracture zones. In order to keep the residual risk of an accident low when employing temporary measures, it has to be possible to make the other two factors, namely the probability of human presence and the extent of damage, extremely low. This can only be achieved by evacuation, by minimum duration of stay in the area of danger and by local protection of the objects.

Thus the possible areas of application for the two categories of measures (permanent and temporary) for reducing the danger are fundamentally different. For areas that cannot be evacuated and closed off and with objects with only limited possibilities of protection such as settlements or forests, permanent protective measures are generally necessary. In suitable cases a combination of permanent and temporary protective measures (artificial release of avalanches with optimized and redundant fixed installations) can significantly reduce the requirements to the permanent measures (e.g.

the height of the deflecting and catchment dams). For traffic lines that can be closed and evacuated any time, a combination of object protection and artificial avalanche release is considered optimal. For the safety of ski runs, cross-country trials and winter hiking trails, all of which can be easily closed, the assessment of avalanche danger and artificial avalanche release are often sufficient.

However, the combination of optimised methods of artificial release of avalanches for lengthening the recurrence period for major to extreme occurrences with reduced permanent protective measures in the avalanche path and run-out demand a highly professional, sustained and well-organised safety management.

2.2.2 Probability of presence

The probability of human presence can be reduced with the aid of avalanche danger maps (similar to the hazard zone mapping in various Alpine countries) and avalanche warning. Using avalanche danger maps, buildings of any sort can be prohibited in avalanche zones (probability of presence = 0), or if the danger is lower, they could be permitted subject to construction requirements (e.g. re-enforced buildings to reduce extend of damage) and with an obligation for evacuation in case of increased danger at the time (reduction of probability of human presence). However, for assessment of the current danger a well-established avalanche warning is necessary.

The ski mountaineer must assess the local avalanche danger himself. Basic information can be found for example from the avalanche bulletin, but local avalanche danger can only be determined with an additional on-site assessment. By skilful choice of route and minimising the duration of stay in the endangered area, the ski mountaineer can reduce the probability of human presence.

Tourist installations and supervised downhill ski runs can often be relatively easily evacuated and closed. In most cases it is possible to effectively close and evacuate the endangered ski runs by not operating or shutting down the transportation facilities. Parts of the installation such as ski-lift masts must be protected by constructive measures. Local information to skiers in zones of increased danger can further lower the probability of human presence. It must be mentioned here that the unprotected skier is also extremely vulnerable to small slides. Special attention has to be paid to places where people gather such as lift stations, lifts, resting and waiting areas.

2.2.3 Extent of damage

The probability of survival of people buried under avalanches can be significantly influenced by rapid rescue. The prerequisite for this is well-practised assistance from the group, a well-organised rescue and ski patrol service and information to the skiers and users of potentially endangered roads or residential areas.

For existing buildings and installations, the probability of presence cannot be altered. On the other hand the extent of damage for buildings and parts of installations within the danger zone can be significantly reduced by constructive measures (object protection).

3. Formation of slab avalanches

3.1 Introduction

By far the majority of avalanches causing damage are slab avalanches. Loose snow avalanches only very rarely have volumes comparable to those of typical avalanches causing damage. The sequence of events described here is a plausible explanation for the formation of dry slab avalanches. Measurements and model calculations have verified that the different steps are necessary for their formation.

3.2 Initial fracturing and shear fracture propagation

A basic fact concerning snow stability serves as the starting point. Evidence has shown that a type of snow (defined by density, granular form and texture) in a particular state (temperature, moisture) and subject to a particular stress condition (e.g. shearing) does not possess a stability that can be expressed with only one parameter. Rather the influence of the speed with which the snow is being deformed (so-called strain rate) and the strain itself must be taken into consideration.

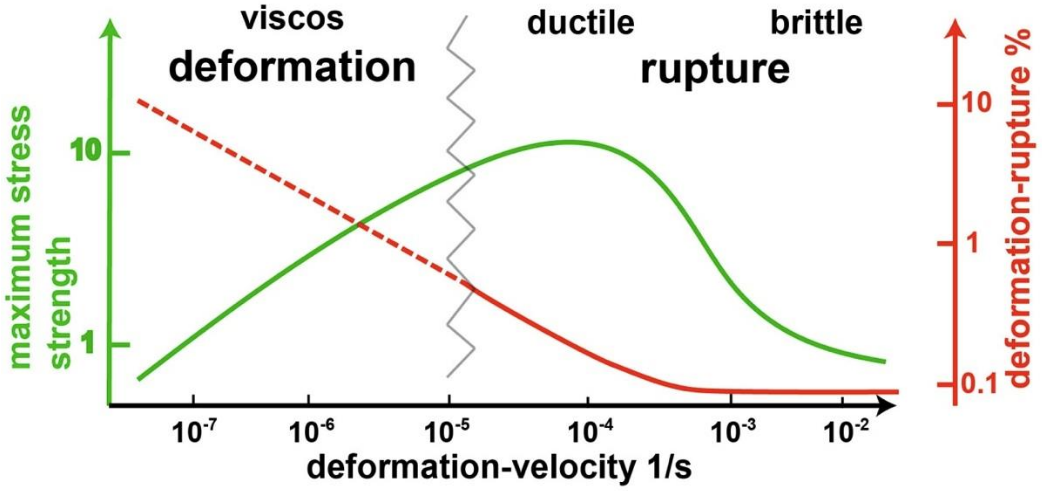


Figure 2: Maximum transferrable stress (“snow stability”) as a function of speed of deformation. Snow fractures only in the ductile and brittle region.

This can be illustrated in an example that principally applies for any stress condition, and thus also in the case of shear deformation. If a block of snow is pressed together at a pre-selected rate and the necessary pressure is measured, the following is observed: If the block is only pressed very slowly, the sample deforms, the measured force is low and a fracture does not occur even at very large deformation. If this is performed somewhat faster, the necessary force increases, but still no fracture is induced. This state is called viscous deformation. If the rate of deformation is again increased very high and varying force has to be applied, the block will eventually fracture (ductile fracture, fig. 2). But the snow only fractures if a critical strain rate is sustained and a critical strain/ deformation of the block is reached, at which point also the maximum transferrable stress occurs (“maximum snow stability”). Any further increase of the strain rate (of course in each case a new non-fractured sample must be used) now leads to a fracture and a maximum force (strength) drastically diminishing with increasing strain rate. At high strain rates the strength can be as low as 1/10 of the maximum strength. This is the transition from the so-called ductile (viscous) to the brittle (elastic) fracture (fig. 2).

In order to attain a fracture, the “peak” between the increasing and then again decreasing stability in function of strain rate must be overcome. A defined given force either leads to a collapse or not, depending on whether the state of deformation is viscous or supercritical. What is the significance of this for the mechanism of slab avalanche fracture?

A typical high winter situation with a dry snow cover is assumed, where there is a slightly consolidated snow layer lying on top of a weak and much thinner layer. If now this weak layer and all other snow and terrain conditions are identical over the whole slope (so-called neutral conditions), then a fracture at typical thicknesses and densities of the snow layer over the weak layer cannot occur under the weight of the snow alone. This is because the weight components of the overlying snow parallel to the slope are too small to be able to produce the necessary critical strain rate. Whether this is possible with an artificially created additional load depends on the strain rates created, the thicknesses of the layers and the deformability of the overlying layer.

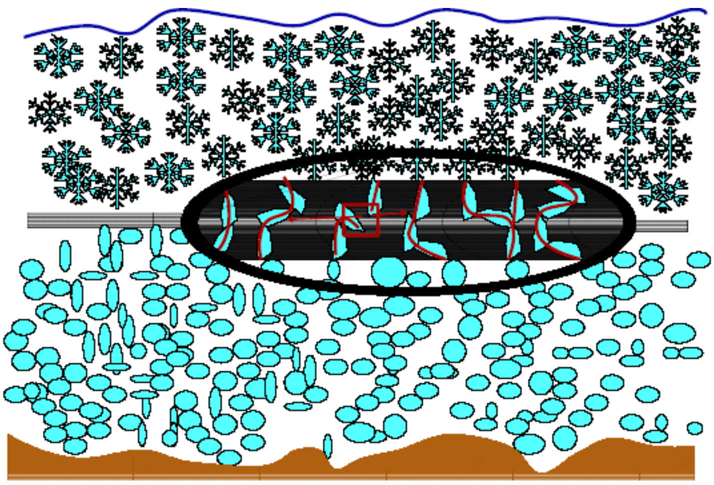


Figure 3: Snow cover with weak layer. Enlarged section shows the stress rearrangement following bond-fracture (initial formation of fracture).

Conclusion: Homogeneous conditions parallel to the slope – which of course are only possible under certain conditions – indicate more towards fracture stability, in spite of the existence of a weak layer.

For the formation of slab avalanches, the existence of a thin, easily deformable intermediate layer with low cohesion between the old snow layer and the new snow is a necessary but not a sufficient condition.

For the formation of dangerous avalanches with fracture heights of several tens of centimetres, such intermediate layers must have continuous and unbroken areas of at least some hundred square metres. The snow type determines the shear strength and viscosity of these weak layers.

Typical weak layers are: Buried surface hoar layers, thin, heavily metamorphosed layers (small grain kinetic growth forms) immediately below the surface of the old snow layer, the upper boundary layer (growth layer) of a depth hoar layer as well as cold, fluffy new snow on a cold hard old snow surface but also thin water-saturated cohesionless intermediate layers. The distributions of stresses and deformations along the weak layer depend on the distribution of the new snow over the weak layer, total snow height, slope angle, local obstructions in the base layer and the deformability of the layers.

As the weight of the new snow increases, the strain rate and the deformation in the weak layer increase, too. The severe local deformation leads to bond breakage between the snow granules and crystals (fig. 3). Thus the strength drops locally and local deformability increases, if only weaker new bonds are formed at new contact points. The high deformation speed within the thin weak layer to a large extent prevents the formation of new strong bonds. This process typically takes hours. The weak layer is severely deformed locally at relatively low stress levels.

If the remaining bonds in the weak layer cannot transfer the existing stresses, from the new snow layer to that of the old snow, the structure collapses locally. **Initial fracture areas** are formed. These local ductile shear fractures in the weak layer are mainly formed in places where the stress and deformation are concentrated due to inhomogeneity in the new or old snow layer and by obstacles that intrude into the old snow layer.

Measurements show that the magnitude of these initial fracture areas is of the order of one square metre. The mechanism of this initial fracture causes **super-weak zones (“hot spots”)** to be formed within the weak layer, which can transfer practically no shear stresses from the new snow layer to the old snow layer. Within these super-weak zones there will be a further concentration of shear deformations, and shear stress concentrates at their borders.

If the deformation at the border of one of these super-weak zones reaches its critical value depending on the actual strain rate (cf. fig. 2), the shear fracture may start to propagate along the weak layer. However, the super-weak zone must first of all attain a minimal area with a diameter of approx. 5 to 25 times the new snow height by coalescing of several initial fracture zones. Only then shear fracture propagation may start, at first slow then later faster.

It is conceivable that during the ductile initial fracture propagation phase, several initial fracture surfaces may coalesce and thus accelerate the brittle fracture propagation. The critical length L of the super-weak zone is proportional to the slab thickness D, the thickness d of the weak layer, and inversely proportional to the geometric mean of the shear deformation rates of the snow slab and weak layer. The probability of coalescence of several subcritical initial fracture surfaces to yield a super-weak zone increases with increasing rate of formation of initial fractures. This fact could be confirmed by infrasonic emission measurements in potential fracture areas.
The smaller the necessary critical length L, the greater is the probability of its being attained. L is minimal for high deformation speeds, if the geometric mean of the shear deformation rates of the snow slab and weak layer is large and the thickness d of the weak layer is small.

Thus, for example, for a hard, wind-pressed snow slab on an easily deformable weak layer, L will be greater than for a "typical" snow slab. But L will also be high for a very loose new snow deposit on a typical weak layer. The rapid shear fracture propagation (brittle fracture, primary fracture) along the weak layer is also possible through zones in the weak layer, in which otherwise an initial fracture is not possible due to increased local stability with respect to ductile fracturing.
A tensile fracture (fracture line, secondary fracture) occurs at the earliest when through the shear fracture propagating uphill, the tensile forces parallel to the slope attain the tensile strength of the new snow layer. The tensile fracture often follows obstacles or disturbances in the snow cover, which create local concentrations of tensile stress.
The size of the slab avalanche (or the fracture volume) is limited by the extend of the weak layer, the tensile strength of the sliding layer, the angle of the slope and local supports of the snow cover. The shear fracture can also propagate through areas of the weak layer where the new snow slab does not start to slide. Sliding avalanche snow can produce strong seismic waves in the ground. These seismic vibrations can also trigger off secondary avalanches.

3.2.1 Summary

The presence of an **extended weak layer** is a necessary condition for the formation of **slab avalanches**. The presence of weak layers can be determined by carrying out local snow cover tests, but also by a continuous analysis of weather conditions during the formation of the snow cover. If the slab avalanche danger is low, no such weak layers are present or the slab above is stiff enough to avoid local strain rate peaks. Even with moderate snow slab danger, local weak layers within the snow cover must be expected. Local initial fracturing must take place in order for the formation of super-weak zones to be a sufficient condition for shear fracture propagation. Small inhomogeneities parallel to the slope in the layer structure of the snow cover are responsible for the formation of initial fractures. It is generally not possible to predict where these initial fractures will occur. Thus extensive stability tests are necessary when artificially releasing avalanches. **The pressure waves artificially produced by blasting have to reach all parts of the possible avalanche fracture zones so that all possible weak spots ("hot spots") are subjected to additional loading.** This is also the reason why a definite conclusion about the avalanche danger cannot be made on the basis of a few ski tracks in a potential fracture zone.

3.3 Deformability as the key parameter for snow slab danger

The deformability or stiffness of the individual snow layers is a decisive factor for avalanche danger. In models and theory, (linear) viscosity is used to describe the deformability. The higher the **stiffness or viscosity** is, i.e. the lower the deformability of a snow layer, the more uniformly can stresses and forces be transferred to neighbouring layers.

The terms deformability and stiffness are not used here in an exact scientific sense, but should help to enhance the visualisation. Deformability should not be confused with stability. **Stability** or resistance characterises the fracture behaviour of a material. For thin weak layers or for layer transitions that often only have a thickness of one or a few grain diameters, deformation very often means rupture of the structure, i.e. the

cohesion is largely lost, the stability is reduced to internal friction, and the deformability increases after an initial minimum deformation (local collapse of structure).
The deformability of the top layer (snow slab) often depends mainly on its temperature and density. A rise in temperature causes a rapid increase in the deformability, but increasing density (in the case of intensive settling) causes a sharp drop in the deformability. The deformability of the top layer is a very important determinant for avalanche danger. Particularly for snow slabs that are not very thick (small to medium avalanches), varying temperatures caused by solar radiation and air temperature have a significant effect on the deformability of this top layer. Very often the deposit of new or drifted snow (20cm to 40cm) lies on top of a thin weak layer that is very deformable and fragile.

If the deformability of the overlying layer now increases due to warming up, the critical extension L for the initial fracture drops and the probability of an avalanche starting rapidly increases.

Thus it is not primarily the change in the shear strength (tensile strength) of the snow slab, or even the lower-lying weak layer that is decisive for the increase in the avalanche danger, but the increase in the deformability (drop in viscosity) of the top layer due to a short-term warming process.

This is also easy to understand, since the tensile and shear fracture areas perpendicular to the slope only constitute of about 1% of the total fracture area, so that the tensile strength in the top layer therefore cannot be the decisive factor for avalanche danger. The fact that these tensile fracture planes are always almost perpendicular to the sliding surface (shear fracture plane) proves also that in every case, a (primary) shear fracture initially propagates along the weak layer (sliding surface), before the tensile fracture areas perpendicular to the slope are formed. The slope-perpendicular fractures limit the size of the slab avalanche but are not responsible for its occurrence.

It can also be readily understood why air temperature and radiation effects are more significant the lower the thickness of the potential snow slab is, because the penetration depth of the daily fluctuation of the air temperature and the solar radiation are limited to a few tens of centimetres. The following drawings again summarise the conditions.

These findings are the result of theoretical deduction, as well as practical experiences.

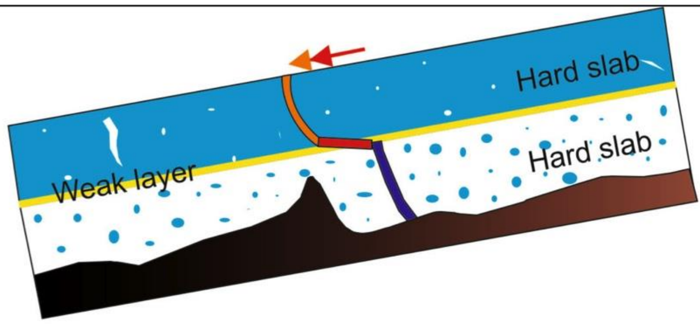
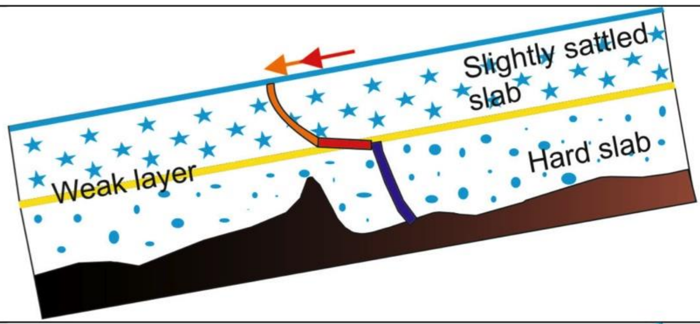
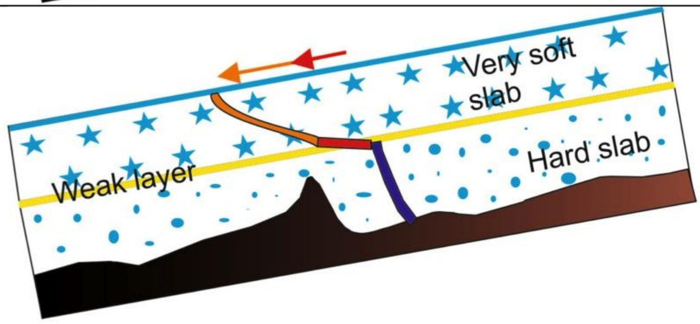
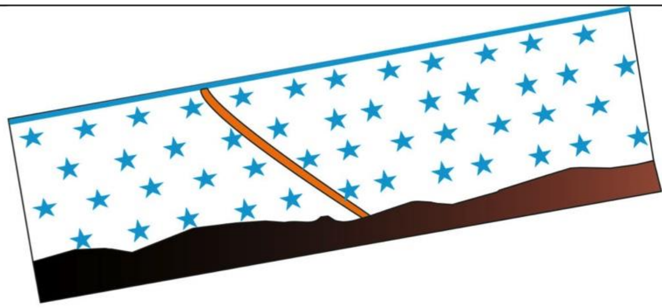
Case 1 • Hard slab on a weak layer • Low to moderate tension and deformation • Initial fracture unlikely	
Case 2 • Slightly settled slab on weak layer • High tension and deformation • **Initial fracture likely!**	
Case 3 • Very soft slab on weak layer • Low to moderate tension and deformation • Initial fracture unlikely	
Case 4 • Initial fracture within the slab unlikely • No weak layer, no tension and no deformation • No concentration of tension and deformation	

Figure 4: Typical situations that influence the stability of the snow cover.

4. Artificial release of avalanches

4.1 Requirements for the method of artificial release

The objective of artificial release of avalanches is to remove unstable snow from potential avalanche fracture zones and so minimise the risk of an unforeseen occurrence of an avalanche in a region to be protected for a limited time. This precaution also enables the snow cover stability in potential avalanche fracture zones to be tested. It is globally accepted as being the standard method for protecting ski runs and traffic lines (e.g. mountain roads). In the last few years very many different methods regarding the point of detonation and creating a pressure wave have been tested and put into operation. At the same time it should be noted that the use of conventional projectiles (e.g. army weapons), generally the use of explosives, and charge deployment from helicopters is legally restricted in some alpine countries.

The following requirements are to be considered.

4.1.1 Determination of the areas endangered by avalanches

Detailed avalanche danger maps are to be drawn up with the aid of avalanche registers, topographical features (e.g. slope angle), vegetation cover, modelling results and observed extreme run-outs. These danger maps form the basis for the construction of houses, mountain roads, installations and ski runs and the concept of their protection.

4.1.2. Reinforcement of installations and buildings

Installations (e.g. lift masts) and buildings that have to be located in potentially endangered zones have to be designed to withstand avalanche and snow creep and glide pressures.

4.1.3. Assessment of avalanche danger or snow cover stability

During wintertime snow cover stability has to be continuously assessed. The most important input parameters are: weather forecast (precipitation, temperature, wind, and cloudiness), snow profiles at different exposures and levels, new-snow accumulation, wind (drifting snow), snow temperature profiles, air temperature, short wave radiation and surface temperature. Direct observation of weak layer formation, settling of new snow (increase of strength and viscosity), direct stability and strength measurements (Rutschblock and various other manual stability tests, shear frame, blasting) further help to assess avalanche danger. It will be certainly useful to store these data together with avalanche observations in a database to allow comparisons between similar actual and past situations. Expert systems can be adapted to support the assessment.

4.1.4. Closure and evacuation of endangered zones

If the danger increases, the endangered zones have to be closed and evacuated. Warnings about avalanche danger have to be posted (only if it exists!), traffic roads and ski runs have to be closed and checked for people remaining in the endangered zones. In addition, ski lifts that have access to endangered zones have to be closed for public transportation.

4.1.5. Rescue

Well-trained and equipped rescue teams must be on hand any time.

4.1.6. Artificial release of avalanches and stability tests

Avalanches are released or stability is tested by applying additional stresses to the snow cover. The stresses are generated by the detonation of explosives, the explosion of gas mixtures etc.

The choice of a specific control method depends on the following criteria:

- **Safety of the patrol:** Dependent on the transport and handling of explosives as well as the accessibility of the firing point.
- **Tolerable residual risk:** Depends on the use of the endangered zone and on natural recurrence period of the avalanche occurrence there.
- **Maximum tolerable closure time:** Depends on how intensively the endangered area is used.
- **Cost-benefit analysis:** Is dependent on the resources available for protective measures, potential damage, and also on the loss of revenue arising from a possible closure.
- **Size and topography of the potential release zone:** These criteria determine the number of necessary firing points.
- **Legal requirements:** Depends on available permits, training of ski patrollers, permitted methods, restrictions concerning storage of explosives etc.

These criteria form the basis for the evaluation of appropriate protective measures. It should be noted that the different methods vary significantly in their dependence on weather conditions (visibility, wind, riming), execution times, achievable safety and costs.

Necessary installation and trainings to operate the protective measures selected have to be established, systems have to be tested in great detail, safety for the operating team has to be checked to make sure that neither the monitoring team nor the blasting teams are endangered during an operation.

4.2 Effect of blasting on the snow cover

The detonation of an explosive charge causes **a shockwave** in its immediate surroundings (rapid increase of particle velocity at the shock-wave front). With increasing distance from the point of detonation, this shock wave develops into an **N-shaped air pressure wave** (an elastic wave with large amplitude, N-wave), and finally it becomes **an acoustic wave** (a small-amplitude elastic wave). Within the snow cover and within the ground these disturbances propagate as different kinds of **pressure waves** (longitudinal (p), transversal (s), and surface waves).

If the combustion speed on an explosive is less than 1,000 m/s (propagation of the combustion zone by heat transport), then this is called an **explosion**, but if the combustion speed is greater than 1,000 m/s, it is called a **detonation** (formation of a detonation wave, reaction energy is created by adiabatic compression on the shock wave front, detonation speed).

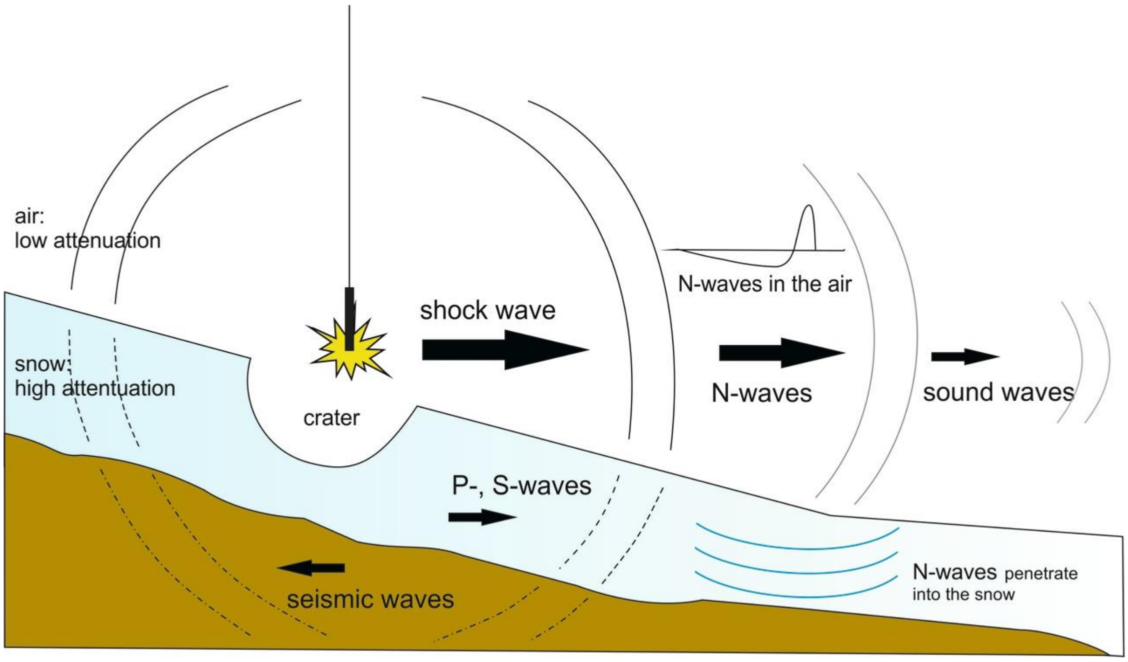


Figure 5: Propagation of the different types of pressure waves in the air above the snow cover, in the snow cover and in the underlaying ground.

Usually an explosion or detonation creates a pressure wave with sufficiently high amplitude to produce local fractures in the intergranular structure of the snow or at least a permanent deformation (crater) close to the detonation point. The amplitudes of the pressure waves above, below and on the surface too, are dependent mainly on the position of the detonation point relative to the snow surface. Snow absorbs the energy from shock waves very effectively. A 1kg explosive charge only causes a crater zone (radius of the permanent deformation) of about 1 m in diameter. The attenuation of the longitudinal and transverse pressure waves propagating in snow is very high compared to other media such as air, rock or dense, coarse sand.

Measurements and theoretical considerations (Gubler 1976, 1977) show some interesting details regarding propagation and interactions of pressure waves (e.g. transverse waves) in a seasonal, dry deep winter snow cover.

- The N-shaped air pressure waves penetrate through the pore system of the snow into the snow cover and generate stresses in the ice structure of the snow cover.
- The so generated dynamic stresses are proportional to the corresponding particle dislocation speeds in the snow cover.
- The amplitude of dislocation speed in the snow cover is more or less proportional to the air pressure amplitude of the expanding gas of an explosive detonation or the pressure amplitude of the N-waves in the air. However, this proportionality is dependent on the form of the N-wave, and in particular on the speed of the pressure rise in the pore system. The maximum deformation speeds and therefore the maximum additional dynamic stresses are thus at least in the initial

phase of structural deformation essentially determined by the rate of change of the pore air pressure and therefore with the N-wave pressure.

- Snow is a very effective frequency filter for pressure waves. In a typical seasonal deep winter snow cover, only pressure waves with a frequency lower than 100 Hz can be registered at a certain distance from the source. At intervals larger than 5 m to 10 m from the detonation point, only N-shaped pressure waves penetrating locally into the snow cover can cause high local deformation amplitudes and deformation rates. It should be noted that the attenuation of deformation waves in wet snow is basically very high.

4.2.1 Measurement of additional stresses in the snow cover as a basis for comparison of different triggering methods

Additional stresses σ in the snow pack can be roughly estimated from measured displacement speed with the following relation:

$\sigma = \kappa \rho_S v_S c_S$

ρ_S:Density of snow [kg/m^3]

v_S:Dislocation speed [mm/s] (fig. 6)

c_S:Wave propagation speed [m/s] (ca. 500 m/s)

κ: Constant dependent on the theoretical model (0.4 to 20), a safe value is κ = 1

In order to compare the various methods of artificially releasing avalanches (sources of pressure waves), the dislocation speed (within this context also named deformation speed) within the snow cover must be measured and compared at different depths (several tens of centimetres beneath the snow surface).

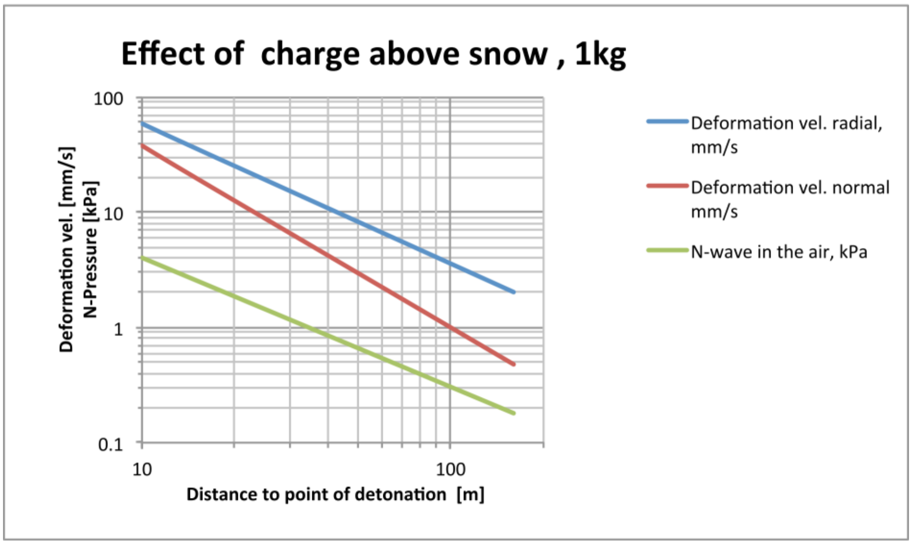


Figure 6: Effect of a 1kg explosive charge in the snow cover. In blue is the radial deformation speed, in red the speed of deformation normal to the slope and in green the N-wave in the air. As a comparison glass breaks at around 1 kPa and eardrum injuries from 35 kPa upwards.

Other measurements such as that of the air pressure wave are not sufficiently conclusive. However, these measurements are only possible with special sensors such as geophones or accelerometers that are tuned to the snow density.

4.3 Effective range

We have learnt from the theory that in most cases slab avalanches cannot be triggered from every point in the potential release zone. Initial fractures of critical size for fracture propagation can often also be activated by the additional stresses in natural weak spots (“hot spots”). Unfortunately the location of these “hot spots” in the terrain is not known in most cases. The situation is made more difficult by the fact that the distribution of these “hot spots” changes with the snow distribution and the weather conditions. Thus it is absolutely necessary to test the **whole potential release zone for “hot spots”**. It is therefore necessary to know exactly the effective radii of the various types and emplacements of pressure wave generators (detonations and explosions).

The effective range of a pressure wave generator is defined as the radius of a circular area with the centre at the source point where the additional stress within the snow cover exceeds a threshold value. This threshold value must be sufficiently large to initialise primary shear fracture propagation in a weak spot whose natural stability is previously higher than 1. This minimal additional stress (threshold value) should be comparable with the dynamic stress that a single skier exerts below a 0.5 to 1m thick snow slab.

The effective radius of a particular blasting method is thus defined as the distance from the point of detonation at which a minimal deformation speed (proportional to the additional stress) is created in a typical depth for weak layers. In cases where the release zone is skied on after a stability test with blasting, a higher threshold value and thus a reduced effective range must be required.

The effective range is dependent on the position of the detonation point relative to the snow surface, the charge size and the type of explosive (explosive, gas mixture etc.), and also on the type of snow slab (wet/dry, thin/thick, hard/soft) and in the case of blasting near to the ground, also the type of ground. It must also be taken into account that the theoretical effective range of a detonation can be significantly reduced by shadowing of the air pressure wave by terrain features.

4.3.1. Size of an effective range of 100% for the blasting methods

The effective range depends strongly on the position of the point of detonation relative to the snow surface. We define the effective range for a detonation of a given charge about 1m above the snow surface as the 100% range. The effective range of 100% of a 1 to 1.5kg of an explosive of high detonation speed, high explosion heat and gas volume amounts to about 85m (radius of a circular area around the point of detonation).

This 100% range reduces to about 50m if the area has to be skiable by single skiers after a stability test with explosives. Within these ranges additional stresses to the snow pack are larger than 100Pa (200Pa for reduced range). In most cases a minimal value of 300Pa is attained.

4.3.2. Point of detonation

The typical dependence of the effective range on the position of the explosive charge relative to the snow surface is shown in figure 7. Theoretically the optimal height of the charge above the snow surface depends slightly on charge weight. Optimal height increases from 1.5m to about 3.5m for charge sizes from 1kg to 15kg. In many cases the best height depends on local topography and has to be determined with the aim to counteract shadowing of the air-pressure wave as best as possible. Charges fired in contact with snow lose part of their energy by generating a typical crater in the snow pack. Although these charges cause higher local stresses in the snow pack, their effective range is drastically reduced. Small charges detonating in a deep snow pack usually do not even produce an open crater and therefore fail to cause an air-pressure wave.

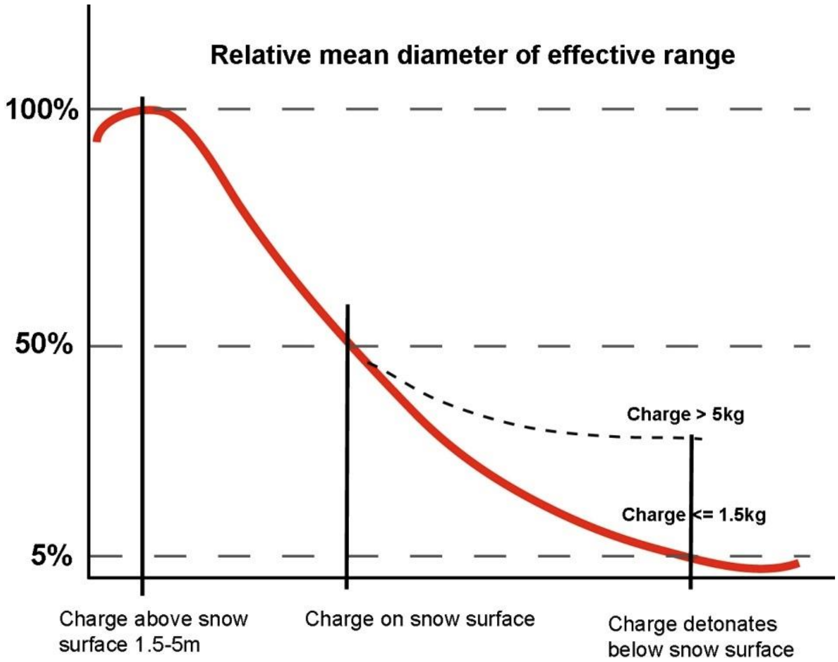


Figure 7: Dependence of effective range (radius of a circular area with the centre at the point of detonation) on the position of the point of detonation relative to the snow surface. For charge sizes above 5kg and depth of detonations in the snow cover under 1m the effective range is approximately independent of the depth at which the charge is sunk, but is significantly reduced compared to blasting above the snow.

4.3.3. Charge size

The effective range of an explosive charge detonated on or above the snow surface is proportional to the square root of the charge weight for a dry snow cover. For wet snow the respective value drops to less than the cubic root of the charge weight. The above scaling is approximately correct for charge weights between 1 and 10kg. This rule is only applicable for explosives of comparable detonation speed and specific energy.

4.3.4. Type of explosive

The effect of an explosive depends on its specifications. For detonations above the snow cover explosives with high detonation speeds (>6000m/s) are the most suitable. For detonations on or within the snow cover, explosives with moderate detonation speeds (4500 to 5500m/s), large gas volumes and high specific energy are most effective.

For common explosives with high detonation speeds the effective ranges vary within 25%. If, for example, an explosive with a high detonation speed is used inside the snow cover, its reduced efficiency can be corrected by increasing charge weight by 50%. But if ammonium nitrate (fertilizer) is used as an explosive (initialized with detonation cord or a similar booster) the weight of the charge has to be increased by as much as a factor of 5 to 10 in order to achieve a similar effective range. Similar arguments are applicable for the explosion of gas mixtures such as those used in Gazex® – installations (combustion speed around 1000m/s, explosion instead of a detonation).

We know that slow loading rates at high amplitudes (explosions) may produce local craters and release primary loose snow avalanches. For distances greater than about 10m from the detonation point, additional stresses are primarily created by N-shaped air pressure waves with a high rate of pressure increase (as is produced by detonating explosives).

The reason is that high deformation speeds are generated by high rates of increase of N-wave pressure in the pore system of the snow. The deformation speed has to be as high as possible to produce brittle fracturing at strain rates > 10^{-4} /s - 10^{-3} /s. This is because brittle fracture strength is significantly lower compared to ductile strength at lower strain rates (c.f. fig.2).

Explosions of gas mixtures produce lower deformation speeds in snow at distances of about 10m from the detonation point than common high explosives with high detonation speeds. Typical effective ranges of Gazex® systems are at maximum of around 80m (sideways, max. 45°) for the 1.5m^3 pipe and about 100m for the 3m^3 tube. These are estimates based on N-wave pressure measurements above the snow surface and measurements with ammonium nitrate (with comparable detonation speeds) without any direct measurements in the snow cover. Measurements made in 2011 (c.f. chap. 4.5.2) clearly indicate even significantly lower values for gas-mixtures. Suspended charges (e.g. the Wyssen avalanche tower) of 5kg have a comparable effective range of some 130m to 150m. If the charges are suspended by a cord, their height can easily be optimised.

It has to be added here that explosives with low detonation speeds used in large bombs can be quite effective to initiate a local discharge of low cohesion wet snow. This has been proved by Americans to sweep out wet snow in small couloirs using bags of ammonium nitrate.

At this point it should be stressed again that for typical dry slab avalanche formation only those locations of the snow cover within the potential effective range that can be seen from the position of the charge are adequately stressed!

4.3.5. Type of snow, type of bedrock

For shots buried in the snow and detonating close to the ground, snow type, type of bedrock and the vegetation cover have a significant effect on the effective range. Wet snow reduces the effective range in any case to an extended crater zone of less than 10 m, the effective range in this case being only slightly dependent on charge-size (for charges between 5 kg and 10 kg. Snowed-over bushes, shrubs, heather and marshy ground may also considerably reduce the effect of the detonation.

4.3.6. Effective ranges of different types of explosives

Height of detonation point	**Charge weight**	**Radius R_N** to prevent natural fracture	**Radius R_S** to prevent fracture initialisation by single skier
Detonation above snow (2-3 m) **Detonation above snow (2-3 m)**	5 kg 1.5 kg	135 m 85 m	70 m 50 m
Gazex® (forwards) **Gazex® (45° sideways)** **Gazex® (forwards)**	3 m^3 3 m^3 1.5 m^3	approx. 70 m (120 m) [1] approx. 50 m (100 m) [1] approx. 50 m (100 m) [1]	50 % -70 % of R_N
Hand charge	1.5 kg	30 m	----
buried projectile	<1.5 kg	15 m	----

Table 2: Effective range of different types of detonations and charge placements. Gazex®: propane-oxygen mixture. Explosives: high specific energy and medium to high detonation speeds. [1] According to measurements made in 2011 the previously assumed effective ranges (in brackets) for gas-mixture explosions are about 40 % too optimistic.

The following information should be taken into consideration when choosing the method of blasting:

- In large release zones, widely distributed charges (if possible connected with a detonation cord) attain better results than just a large individual charge
- Projectiles with highly sensitive impact fuses and very short delay times guarantee a detonation point near to the surface.
- A minimum charge weight of 1.5 kg is recommended for hand-thrown charges.
- In the case of blasting methods with a fixed detonation point (Catex, Gazex®, avalanche guard, avalanche pipe, avalanche towers), and a large avalanche fracture zone (large bowl) it is recommended to use systems with large effective ranges (large explosive charge, 3 kg to 10 kg). In this way the effective range can be optimised even if the point of detonation is not ideal.
- The potential fracture zone even of a large bowl has to be completely covered with slightly overlapping effective ranges. Therefore the minimum number of shot points depends on the blasting method.
- If charges are thrown from the helicopter, a charge of not less than 5 kg (equipped with double safety fuses) should be used. If necessary, equip charges with Recco transponders to enable any duds to be found more easily.
- System redundancy may be very important if probability and extend of damage are high.
- When selecting a method and shot points their influence on the release of secondary avalanches (avalanches that are released in neighbouring but separated release zones) has to be considered.

4.4. Methods of artificial avalanche release

4.4.1 General points

When selecting the blasting method, often the investment costs are used as the most important basis for decision-making. The selection of methods should be made based on protection goals as on accepted residual risk and closure times, and the targets to be protected. Number and position of shot points depends on the chosen method. The selection of a less appropriate method could result in the long-term in massive increased operating costs and higher residual risk and closure times.

The exact locations of installations, shot points in the terrain vary significantly with the system chosen!

4.4.2 Hand-thrown charges

With this method a person must be able to reach a safe position within throwing range of the desired detonation point. The weight of the hand charge is limited to 1.5 kg to 2.5 kg. It is recommended to safeguard charges with a cord. This prevents the charges sliding down a hard surface, permits duds to be retrieved and often enables charges that have sunk below the surface to be pulled to a better position. There are no investment costs and easily accessible fracture zones can be simply controlled and moreover the result of blasting is apparent immediately. However, this method requires a considerable expenditure of time and personnel and is often dangerous. Extreme weather conditions can prevent the desired point of detonation from being reached. The positioning of the explosive charge is at best on the surface of the snow and the effective range is expected to be limited due to the small charge weight.

4.4.3. Detonation above the snow with a charge attached to a pile

This is a dangerous method because patrollers have to enter the potential release zone to place the pile with the charge. The personnel must be belayed! On the other hand, this method is very effective especially for releasing hard slabs where large and even better distributed charges have to be used. Best results are obtained by connecting several 5 to 10kg charges at distances of about 30 to 50m with primer cord. This method requires a great deal of time and personnel expenditure, but successful blasting is apparent immediately. Extreme weather conditions can prevent the desired points of detonation from being reached.

4.4.4 Ridge cantilevers, beams

Cantilevers mounted on ridges are sometimes used to place explosive charges over the snow close to a ridge. They usually consist of a rod mounted on a pivot, which is fixed on a ridge. A charge can be placed at the end of this rod, a sufficiently long safety primer cord can be ignited and the charge swung into the desired blasting position. The blasting personnel must take cover before blasting. There are only small investment costs and easily accessible fracture zones can be simply monitored and moreover the result of blasting is apparent immediately. However this method requires a great deal of time and personnel expenditure.

4.4.5 Hand-thrown charges from the helicopter

Using helicopters for artificial release of avalanches is a widespread, very economical and efficient measure. In order to minimise the danger of duds, the hand-thrown charges must be equipped with two primers. Apart from any legal restrictions for throwing explosives out of the helicopter in certain countries, there are three main limitations of this method:

1. Fundamentally the weather must be good for flying, which means that the snow cover at the time of the helicopter operation has often become more stable. Thus it is often not possible to limit the size of the avalanche by early blasting.
2. The charges are usually thrown out the helicopter through an open door. This can give rise to various problems: The charge can slide off the hard surface or it sinks into soft snow. Furthermore duds that have not been marked can only be found with difficulty. Sliding can usually be prevented by making the surface of the charge rough or by fixing the charges to short wooden rods. In order to counteract a possible reduction in the effective range by the charge penetrating the surface of the snow cover, the charge size is increased (minimal charge weight 5kg)
3. The amount of time spent, the possible tight availability of the helicopter at the time required and the increased risk by flying very close to the ground are further disadvantages of this method.
4. The results can be assessed immediately and if necessary additional shot points can be selected.
5. This method is often used for clean ups after mayor storms during which main paths have been triggered repeatedly by fixed remote controlled installations.

4.4.6 Lowering charges from manned cable ways

This method can be used if an aerial cableway crosses potential release zones. Charges may be either thrown from the cabin – with two primers – or are lowered attached to a string and detonated above the snow surface. The distance between cabin and the detonation point has to be large enough to avoid damage to the cabin and to the traction and main cables.

4.4.7 Blasting cableways, charge deployment systems

Many blasting cableways are still in operation. Cable lengths vary from a few meters to several kilometres and thus the investment costs, too. The great advantage of blasting cableways is the possibility of blasting over the snow and the free selectable location of the detonation point along the cable line. Main problems are: riming of the cables, the large amount of time required, and swaying of the cables caused by heavy winds. Often it is necessary to have an automatic deriming system. To shorten operating times for long cableways, it is essential to have the possibility of remote firing of several charges. Moreover in complex terrain, it is a big advantage if the charges can be lowered to the optimal blasting height.

Heavy winds often make it impossible to operate blasting cableways. Masts, transport cable suspension and the charge deployment systems must be very carefully constructed in order to prevent cable derailing in the case of heavy icing and strong winds. The detonation point can only be varied along the cable line, therefore the layout of the cable lines has to be done very carefully.

4.4.8 Projectiles, rockets

Particularly in Switzerland, the following military ordnance is used for the artificial release of avalanches: recoilless cannons, mortars, anti-tank rockets. Common problems with most of the systems apart from the high costs per round are the low sensitivity of the mortar shell fuses and the very limited charge sizes. The big advantage of these systems is, that different detonation points can be reached from one location. Most of the projectiles penetrate the snow cover before detonating. Additionally a large proportion of the energy is lost due to acceleration of the shell casing fragments. On the other hand army ammunition can be fired under very bad weather conditions with very limited sight. The use of army ammunition is legally restricted in many countries.

The French Avalancheur is a gas pressure cannon based on compressed air similar to the American Avalancher. L'avalancheur counteracts the problem of delayed ignition by using a very elongated arrow like projectile, so that the detonation takes place at least partly at or over the snow surface. Additionally a two-component explosive is used, so that the strict legal requirements for storage and transport of explosives can be avoided. Duds become inert after about 24 or 48 hours.

Short range systems (e.g. the avalanche pipe) allow charges of up to 3 kg be fired to about 400 m (depending on the consistency of the available explosives). This same type of charge can be remotely fired from outside the potential fracture zone by the avalanche guard (Lawinenwächter®) and avalanche master.

The pointing accuracy of the systems described above generally drops sharply with increasing distance and strong winds.

4.4.9 Gazex®

In the Gazex® system the avalanche is released by igniting a propane-oxygen mixture (typical tube volumes 0.8m^3 to 3.5m^3). Here the legal requirements regarding system authorisation and personnel training for handling and operating the installation are far less restrictive than for the systems with explosives. Another big advantage is the large number of explosions that can be carried out with one gas filling. The level of investment and the overall operating costs per firing are comparable with those of other remote-controlled systems.

The explosion is triggered in an exploder tube installed in the fracture zone and causes a shock wave which initially exerts overpressure and then afterwards underpressure (N-wave) on the snow cover. Direct pressure is also exerted on the snow immediately underneath the exploder opening. The system is remotely controlled by radio or GSM. The gas and oxygen supplies to the exploder are fed via pipes in the terrain from a central supply container. The control system is also operated from this supply container which is installed in a secure location and is supplied with power from solar panels. Up to 10 exploders can be controlled from one supply container. However, the system redundancy is significantly decreased by controlling and feeding several exploders from one supply container. A malfunction in the supply container may affect all connected exploders. If a high system redundancy is necessary (often with overlapping effective ranges), the Gazex® alternative with separate supply units is to be preferred. The explosion of the propane-oxygen mixture generates considerably lower deformation rates in the snow cover (apart from in the immediate vicinity of the firing point), because the combustion speed is much lower than for high explosives (about 1,000 m/s). According to experience and the Swiss guidelines for artificial release, exploders with a volume <1.5m^3 are only to be recommended in very special situations (such as small fracture zones in steep couloirs) because of their very low effective range. It has to be added here that explosives with low detonation speeds, as gas mixtures can be quite effective to initiate a local discharge of low cohesion wet snow. This has been proved by Americans to sweep out wet snow in small couloirs (maritime climates characterized by wet snow covers most of the winter). It is important again to note here that the different remote controlled systems using either different sizes of explosive charges at different detonation heights or different types of gas mixtures (propane- oxygen or hydrogen-oxygen) are not direct replacements of each other. Differences in effective ranges and other system dependent features are decisive for the design of an actual system layout.

4.4.10 Daisybell® and O'Bellx® gas explosion systems

Daisybell® and O'Bellx® are new developments from the same manufacturer as Gazex®. A gas mixture (hydrogen-oxygen) is ignited in a bell-shaped container. The Daisybell® is suspended by a cable from a helicopter, then transported to the potential avalanche fracture zone and triggered while the helicopter is hovering. Ignition is triggered from the helicopter and the blast takes place above the snow cover. It is possible to fire several shots in a short time. The operation of this system is strongly dependent on the weather, the aeronautical demands on the pilot under real conditions are very high and the effective range under high winter conditions is small (strongly directed explosion with a small effective range and high dependence on the height of the detonation point). Nevertheless this method offers an alternative to throwing explosive charges particularly for safeguarding ski runs.

The O'Bellx® operates principally similarly, but is attached to a tower in the release zone and remotely radio/GSM-controlled. As with the $0.8m^3$ exploder, this alternative can be recommended for small fracture zones due to its very small effective range.

4.4.11 Avalanche Guard (Lawinenwächter®)

Avalanche Guards from the Innauen-Schätti Company are installed with a foundation or rock anchor in a secure location close to the fracture zones. They are equipped with one or two launcher-boxes each containing up to 10 explosive charges. The charges have to be manually installed in the launcher boxes on site before the start of winter by the operating staff. A battery is charged by solar panels for supplying power for controlling and operating the mechanism. Operation is also carried out using radio remote control from a PC in a command centre.

A big advantage of the system is that the charges can be fired at selected detonation points and individually triggered by remote control. An electrical igniter initiates a propellant, which propels the explosive cartridge about 150m into the avalanche fracture zone. As the explosive charge is ejected from the pipe, the pull-wire igniters ignite the safety fuses. The blasting caps detonate the 2.8kg avalanche explosive in the target area.

One disadvantage is that detonation take place at or below the snow surface. The charge may slide down on a hard snow cover and the recovery of duds is mostly difficult and hazardous.

4.4.12 Avalanche tower

Avalanche towers are installed within the uppermost section of an avalanche fracture zone or on ridges between couloirs or fracture bowls. Avalanche towers such as the Wyssen avalanche tower are also remotely radio controlled and lower 5 kg explosive charges to an optimal detonation height before they detonate.

The Wyssen avalanche tower consists of a permanently installed tower in the fracture zone and an attachable charge magazine. The towers are fixed in the bedrock with 4 or 5 anchors or micropiles in order to keep the impact on nature to a minimum. A docking system on the tip of the mast permits the charge magazine to be simply attached with a helicopter. The box contains 12 charges each with 5kg explosive, the lowering mechanism, the electronic control system, a battery, solar cells on the outer casing and a radio transmitting unit. No feed lines are required in the terrain. Ignition follows after the charge has fallen through the hole in the floor of the box and the igniters are activated by the energy of the drop. The construction is conceived so that with the aid of the helicopter and a special latch, the magazine can be readily docked and removed without a flight assistant. These operations to not require any onsite assistance. The weight of a fully charged magazine amounts to 650kg. As soon as the magazine has been placed on the docking system, it adjusts automatically its position and the successfull docking operation is confirmed to the pilot with a flash light. The electronic control is activated only after the magazine has been correctly docked. For refilling and maintenance work and storage during summer the magazine is flown back down to the valley. Such a system is specially suited for very remote and, during winter, inaccessible locations.

The charge magazine on the Innauen-Schätti Avalanche Master is permanently installed on the tower and the explosive charges are manually loaded by personnel, as described above for the Avalanche Guard. The charge is ejected by a pyrotechnic propellant. The explosive charges are tied to a retaining line, so that the charge detonates above the snow cover. With the same installation a combination of Avalanche Guard and Avalanche Master is possible. I.e. charges can be lowered or fired to a distant target from the same magazine. The charge weight is limited to 2.8kg.

The disadvantages of the systems described above are the high investment costs per detonation point (very similar for all remote controlled systems) and the fixed location of the system. Especially to control large bowls, large effective ranges are mandatory or multiple systems have to be installed. Depending on the location, helicopters are necessary for refilling the magazine.

4.4.13 Special cases cornice control and gliding snow

Removal of cornices has the double benefit of eliminating the danger from a natural falling cornice and releasing avalanches by the powerful impact on the snow below the cornice. The timing and frequency of cornice control varies, but midwinter to spring are generally important times (McClung D. and Schaerer P. 2006). Two different methods are in use for **cornice blasting**.

1. The cornice may be "cut free" from its anchorage by using explosives to open a trench. The best way to do so is to connect several buried charges along the cornice with primer cord. The sizes of the individual charges is approximately given by the following equation: *W[kg] = (hs/2)*^{3} where *hs*: Snow depth/ height of the cornice at the blasting location in [m] and 1kg < W < 10kg

   The distance between individual charges should roughly match hs. And the charges should be buried at a depth of hs/2.

2. A second method that proved to be quite successful is to hang large charges over the cornice so that the detonation occurs close to the foot of the cornice.

Caution: Cornice falls may trigger large avalanches on slopes below!

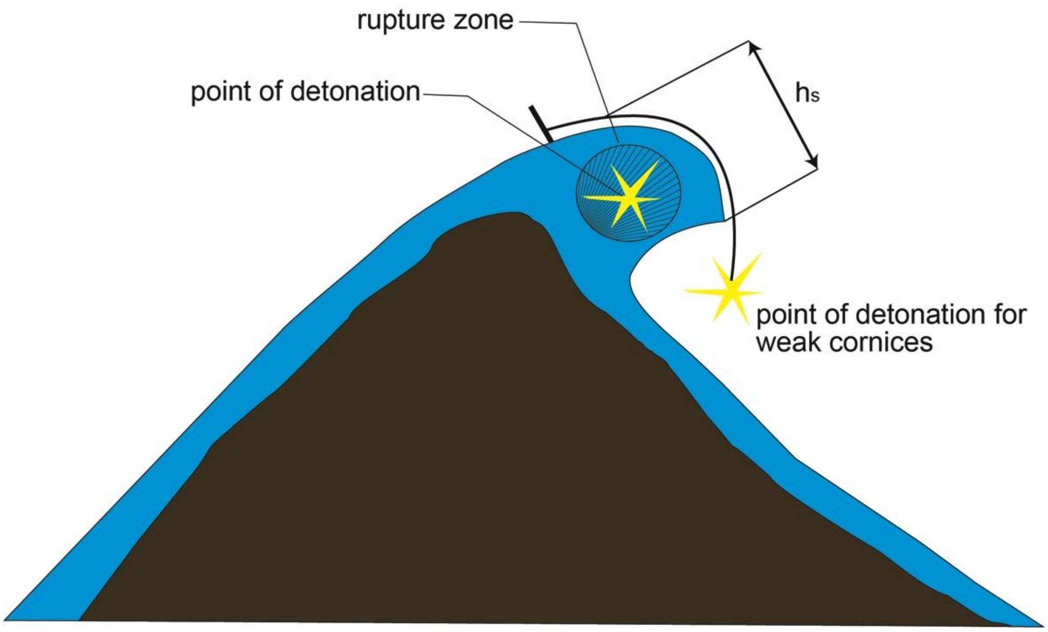


Figure 8: Diagram for removing cornices.

Winters with typical **gliding snow situations** to regions well above timberline in an alpine environment do not happen too often. Warm autumns and a significant first snowfall on the still unfrozen ground are typical prerequisites for gliding snow menacing installations and traffic lines all winter long. Typical signs are tensile cracks slowly opening at the upper limit of the very slow sliding slab and slowly forming large deformations in the bottom part of the slab. An artificial release of the slab ones the slab has formed and settled using explosives in a common way is very rarely successful. The formation of the slab has to be prevented by removing the snow while the snow cover forms or one has to wait until the slab metamorphoses to partly cohesionless snow during cycles of very warm weather. In these cases common methods of artificial release may help. Ones the slab has formed and slowly glides downhill, only 2 methods are known: artificially increasing the water inflow to the interface ground – snow or open a trench at the foot of the slab (pressure zone) using explosives in a similar way as described above.

4.5 Interpretation of results and guidelines

4.5.1. Choosing the correct time for avalanche protection work.

Avalanche protection work should be carried out whenever possible during or immediately following heavy snowfalls or heavy snow drifting events, before the stability of the snow cover increases. If avalanche size (run-out distance) is critical and has to be limited, protection work should be done at regular intervals during the snow fall or drifting phase at least on steeper slopes within the release area.

If blasting is carried out in starting zones, which are not very steep after only small amounts of new snow, the probability for the success of subsequent release efforts may be reduced. Negative blasting at an earlier time can increase the stability, at least locally, of the weak layer (by forced settling).

If the run-out distance (size) of particular avalanches could be critical, timing of the protection work is very important. Blasting too early can give negative results, and blasting too late may result in too much snow being released. Generally it is possible to unload steep slopes with appropriate methods several times during a storm to produce smaller avalanches. But it should not be assumed that a heavily loaded slope can be unloaded in portions by using smaller charges or by special placements of the charges. Usually if fracture propagation has started, it no longer depends on its initialisation. Information from special weather stations located closely to the release zones can be very helpful.

Slopes with extreme radiation conditions, i.e., slopes with a southerly exposure, should be released before slopes with insignificant radiation. Radiation accelerates snow metamorphosis as well as settling in the layer close to the surface (snow slab). These processes cause a decrease in stability for a limited period of time, but subsequently an increase of stiffness of the slab without affecting the weak layer. Therefore the conditions for initial fracturing and the start of fracture propagation are enhanced before strength of the slab and eventually the weak layer increase by settling and strengthening.

4.5.2. Selection of the type of explosive charge/ gas mixture

Explosives with high detonation speeds should be used when charges are placed above the snow cover (blasting cableways, poles, avalanche towers).

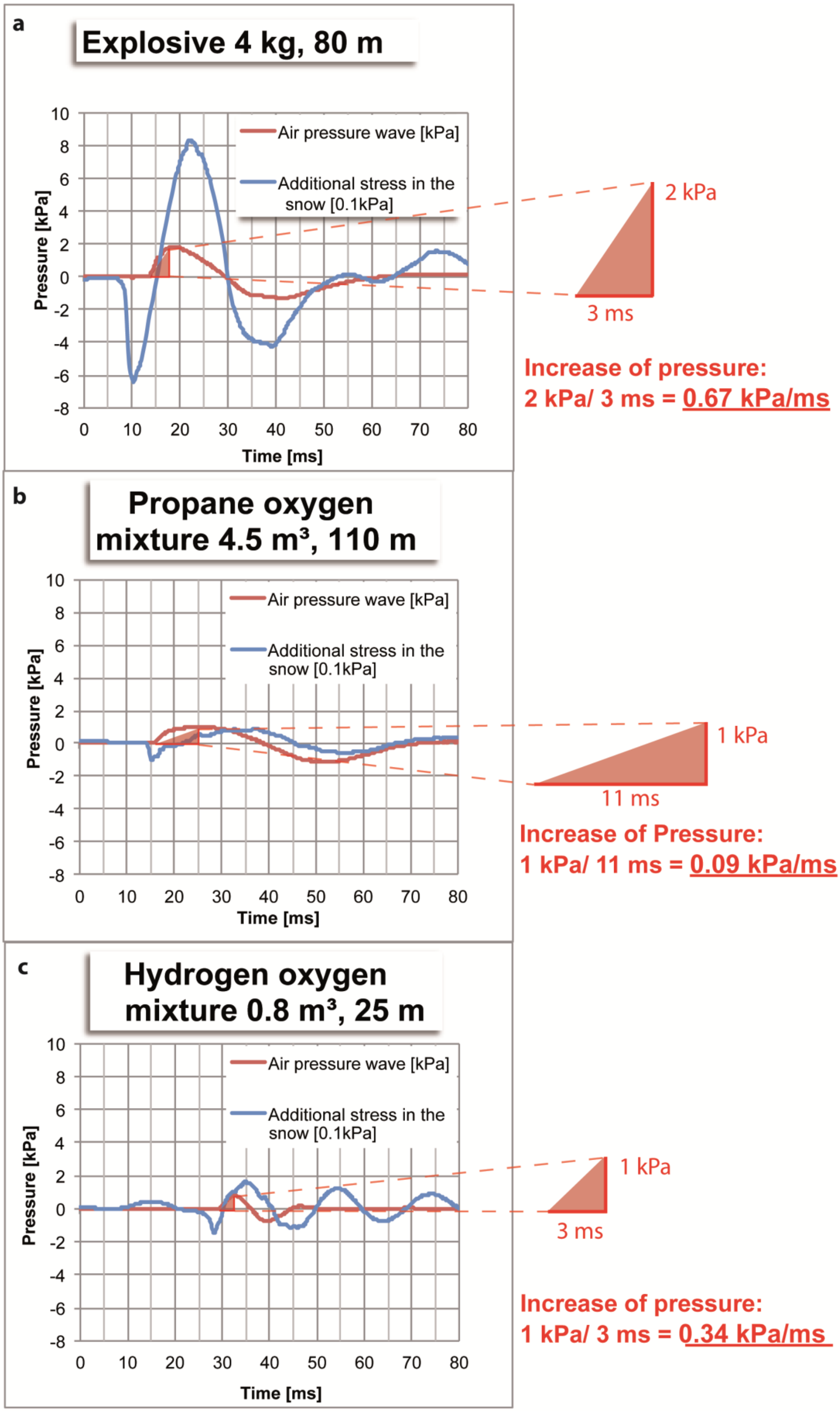


Figure 9: The effect of different blasting methods, measurements made in 2011; red: N-shaped are pressure wave on the snow surface; blue: Vertical component of the additional stresses in the snow cover All values are expressed in [kPa] (N/m^2) and milliseconds [ms]. **Explosives generate much higher additional stresses in snow (900 Pa at 80 m) than gas mixtures (100 Pa at 110 m) due to the high rate of pressure rise (0.5-1 kPa/ms)!**

As soon as charges have been positioned on or within the snow cover (hand charges or projectiles), an explosive with medium detonation speed (4000m/s – 5000m/s) is adequate providing the heat of explosion is high.

Explosions of gas mixtures have a much smaller effective range than explosives due to their very low combustion speed (<1000 m/s). This should be taken into consideration when choosing the detonation point!

A smaller effective range often means a larger number of shot points and thus a larger number of installations. Figure 9 compares the blasting efficiencies of the explosive Alpinit (i.e. avalanche tower) with those of a 4.5m^3 Gazex® exploder (propane- oxygen mixture) and the 0.8 m^3 Daisybell® (hydrogen- oxygen mixture).

The Gazex® (propane oxygen mixture) measurement was carried out at 45° to the tube axis at a distance of 110m. In order to obtain a direct comparison with Alpinit (explosive) measurements (distance of 80m from the detonation point), the Gazex® values must be increased by 50% for the V-values (additional stresses in the snow cover, blue line) and 80% for the M-values (N-wave amplitude, red line). On the other hand, the effect of a 4.5 m^3 tube at a distance of 110m is theoretically just comparable to the effect of the largest currently available 3 m^3 tube at a distance of 80m.

As has already been mentioned in chapter 3.2, that it is not the maximum amplitude of the pressure wave in the air that is crucial, but the rate of the rise in pressure, on order to generate a high deformation speed. Figure 8a shows that for Alpinit, 3ms elapse before the maximum pressure of the N-wave is attained (red line) whereas for Gazex® explosions 9ms are required (fig. 9b), or three times as long. This can be explained by the very low combustion speed of gas mixture explosions (<1000 m/s) compared to detonations of explosives (>5000 m/s).

The maximum amplitude of the Alpinit N-wave (2 kPa at 80 m) is only slightly higher than the interpolated value for the Gazex® explosion (1.8 kPa, calculated from 1 kPa at 110m + 80%). However, if the additional stresses are compared that are generated by the appropriate pressure wave in the snow cover (blue line), then the difference can be clearly seen. Alpinit generates additional stresses of around 900Pa at 80m and Gazex® explosions (4.5m^3) generate around 150Pa (calculated from 100Pa at 110m + 50%). These results must be borne in mind when choosing the location and the definition of the effective range, and thus the number of installations.

The measurements with the Daisybell® had to be made at a distance of 25m due to the low effective range. An N-wave pressure of approx. 800Pa is produced (red line) in a relatively short time (3ms, fig. 9c) The additional stresses produced at a distance of 25m in the snow cover amount to approx. 160Pa, approximately the same value as by the 4.5 m^3 Gazex® exploder tube at a distance of 80 m. This is only about one sixth of the additional stresses measured in explosive detonations at a distance of 80 m. This limited effective range demonstrates that the O'BellX® is only suitable for isolated interventions in very small release zones, and release attempts with the Daisybell® must be carried out in a very tight grid if the initial result is negative.

4.5.3. Choice of the correct firing point

The ideal locations are those with the lowest stability, i.e., the most probable location for initial fracturing. Due to the fact that such specific locations cannot be identified precisely, the entire potential release zone must be totally encompassed by the effective ranges of the individual detonations. In order to accomplish this in an economic fashion, with a minimum amount of explosives, one should strive for the largest possible effective range, and start with protective work at the locations, which according to experience have the lowest natural stability. Keep in mind: the deeper the slab, the higher the damping of the pressure waves before it reaches the weak layer, the smaller the additional stresses, the less probable is initial fracturing.

The largest effective ranges are achieved when the charge location is above the snow cover (slightly consolidated snow layer, low natural stability). For very hard slabs with high natural stability, the effective range for the large additional stresses necessary is very small, in most cases less than 10m. Quite often large charges fixed to poles are used or even charges buried in the snow cover.

Whenever a charge penetrates beneath the snow surface, the effective range is drastically reduced. If a hand charge is attached to a cord, it is often possible to pull the charge back to the snow surface after it has been thrown.

For charges or projectiles that basically cannot be prevented from penetrating the snow cover prior to detonation, firing points should be selected within the necessary effective ranges either with low snow depths or wind-pressed surfaces.

When the snow surface is extremely hard, the charge may slide down the slope and detonate outside the boundary of the potential target area. For this reason hand charges should be secured with a cord. This also allows duds to be easily retrieved.

When choosing a firing and detonation point, one should be certain that all parts of the release zone that are within the effective range are visible from the point of detonation. Locations, which are shadowed from the direct air pressure wave, experience insufficient additional stress.

In **wet snow** the effective range is generally very restricted (often limited only to an extended crater zone). Wet snow slabs are not easily released due to their strongly sintered structure and limited period of instability (Johnson J., 1980). In consequence, the timing of the detonation is very difficult to determine, because stability changes much faster in wet snow than in a dry snow pack. Experience has shown that the probability for triggering wet snow avalanches is highest if blasting is carried out shortly after the highest temperatures have been attained and cooling after sunset has set in. Furthermore, it should be noted that sliding avalanches can hardly be released with the methods presented here. Exact timing and large charges (5 kg, Gazex®) are crucial for increasing the probability of positive results. Often only small discharges are released in the immediate vicinity of the firing location. This indicates low stability, but with such a local release, a possible larger fracture area cannot be assumed to be safeguarded. Negative attempts to release avalanches cannot be interpreted as positive stability tests.

4.5.4. Stability tests

If no major avalanches have been released from a potential release zone using artificial avalanche protection methods, the result can be interpreted as a positive stability test if the following rules have been taken into consideration:

- the complete area of the potential release zone has to be covered with the effective ranges of the individual detonations.
- reduction of effective ranges by pressure wave shadowing has been taken into consideration
- Stability tests are only conclusive for dry snow covers.
- detonations must be verified either by the bang heard by an operator or by means of electronic measurements.
- After negative tests it is recommended to wait at least 15 minutes at high snow temperatures and up to 1 hour at very low temperatures before the zone can be classified as safeguarded (time for mechanical relaxation of the snow cover).

4.5.5. Determination of the blasting efficacy

The following conclusions may be drawn from observations of the blast:

- The sharper the bang of a detonation, the wider is the effective range, and the more muffled the bang, the lower is the effective range
- A flat shallow crater with rounded edges indicates a large effective range.
- Large snow fountains and deep craters indicate small effective ranges.

4.5.6. Residual risk

If a major avalanche has been released within a given release zone, the zone including the corresponding avalanche path and run-out areas can be regarded as being safe. Normally very distinct changes of weather conditions are necessary to decrease stability of the remaining snow in the release zone and therefore increase the danger again. However, it should be noted that remaining deposits in the avalanche path could again become mobile in the case of warming.

If no avalanche has been released (negative result) but the rules stated above have been carefully followed (stability tests), the residual risk of an unforeseen avalanche in most cases can be assumed to be small. But the development of snow and weather parameters has to be carefully assessed in order to recognise in good time any possible increase of danger.

4.5.7. Safety of the blasting team

Safety of blasting routes and charge delivery points has to be continuously checked with regard to all potential avalanches, including all possible secondary or remote releases.

Before a charge is fired, the blasting team must ensure that all possible endangered zones (including endangered zones of possible secondary avalanches) have been closed and evacuated. The blasting team must also be aware that the length of the run-out is often difficult to estimate.

Therefore the blasting team must be in permanent contact with the base team and continually report their procedure and all observations to them.

4.5.8. Detection of artificially released avalanches

In order to establish the result of an artificial release attempt, irrespective of weather and the time of day, so that further safety-relevant decisions can be made, there are various methods available for measuring. Most of these methods are also suitable for registering natural avalanches. All methods require the permanent setting-up of measuring systems in the avalanche paths or in the region of the extreme avalanche run-out in the valley. The measuring methods include:

a.)Short range microwave Doppler systems (detection range up to a maximum of 300m) at the border of the avalanche path, ground movement measurements in the region of the avalanche path, and avalanche pressure measurements;

b.)Microwave Doppler radar with a large range (detection range up to 2km) and infrasonic measurements.

The measurement methods under a) have been used for over 20 years in avalanche alarm systems. These systems are quite reliable and tested, but require installations in the region of the upper part of the avalanche path. Corresponding systems are currently available on the market. Especially a special low power, low price seismic system has proved its reliability. Measurement methods b) are presently in a final development phase. These systems are installed in the valley or on an opposite slope. In particular the state-of-the-art long-range avalanche radar can be viewed as a very promising and robust method. The success of using infrasonic detection systems depends very much on the location although this detection method has also been tested for many years. All systems provide information seconds to minutes after an avalanche has been detected, in many cases in form of an SMS.

5. Concluding remarks

Comprehensively guaranteeing the acceptable, very low residual risk with active and passive temporary avalanche protection measures is a very demanding task. Apart from good basic knowledge, it demands a great deal of experience from all involved. **The methods used for the artificial release of avalanches have to be carefully selected appropriate to the situation, then installed, monitored, maintained and operated.**

There is a wide choice of systems currently being offered on the market. Each of these systems has advantages and disadvantages with regard to effectiveness, safety, operation and maintenance. Unfortunately, systems are continually being offered that do not fulfil the basic requirements of effective range and operational readiness. Such systems are admittedly capable of releasing avalanches under certain conditions, but the residual risk (of unforeseen avalanches) following negative release attempts remains high.

On the basis of the effectiveness, detonations of explosives are to be preferred over gas mixtures. If the restricted effective range of gas cannons is taken into consideration, they have their advantages in handling. For both systems there are no significant safety-relevant differences in operation. Both systems generate air pressure waves of high amplitude and can trigger avalanches. There are no great differences in handling of explosive substances (gas mixtures, explosives or inert explosive components) or when dealing with duds in the broadest sense (explosive charges that have not detonated, gas mixtures that have not exploded or mixing systems that are defective). Today, unexploded charges do not cause any major safety problems, because the impact sensitivity of most of the present-day explosives is negligible. And if needed, duds can be marked with transponders (e.g. Recco). Further blasting using the same method for reducing the avalanche risk is usually possible.

Stoichiometrically faulty gas mixtures, which produce significantly weaker explosions, often remain unnoticed and can lead to a false interpretation of the blasting result. The handling of explosives and combustible gases are justifiably subject to different legal regulations and different instruction in their handling is necessary. There are no differences for the remote controlling of both systems, and the safety requirements are identical.

The most commonly used methods for artificial release of avalanches are summarised in the following table.

Methods Criteria	Hand charge	Blasting cableway, catex, bomb tram	Charge fixed to pole	Charge fixed to at beam, cantilever at a ridge	Military projectiles (≈ 8cm), Avalancheur / Avalanche pipe	Helicopter blasting/ Daisybell	Avalanche Tower	Gazex®	Avalanche Master(Detonation above snow)
Range [m]	30	10-5000	-	3-15	≈ 3000, ≈ 2000/ ≈ 400	unlimited	remote controlled	remote controlled	Master remote controlled onsite range 400m
Safety of blasting team	+	+++	-	+	+++/+++	+++	+++	+++	+++
Effective range	+	+++	++	++	-+/+	+/-+	+++	++	++
Quality of the stability test	+	++	+	+	-+/+	+/-+	+++	++	++
Cost (per shot point)	low	medium to high	low	medium	medium to high	medium	high	high	high
Overall assessment	good, but with restricted placement possibilities	good, adaption of charge placement restricted by layout. Wind and riming can be limiting factors.	useful only in special situations with high natural stability.	useful with appropriate topography. Release zone near ridge crest, cornice removal.	good, if large range and timing of firing are important. independent of weather costs per shot high	good, but restricted by weather conditions. Build up of large avalanches can not be avoided.	good, fixed location, very good effective range, charge up to 5kg no intervention at tower location required (Wyssen).	good, fixed location, moderate effective range. No explosives	good, fixed location, limited size of charge. When used as an avalanche tower suspended charge (2.8 kg) with detonation over snow

Table 3: Methods or artificial avalanche release (modified after Stoffel L. 2001).

Key: +++very good
++good
+satisfactory
-+adequate
-inadequate

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