FORSVARET

Handbook in Winter Service – Snow Awareness

Adopted for use by the Norwegian Armed Forces

Rena, 11 June 2020

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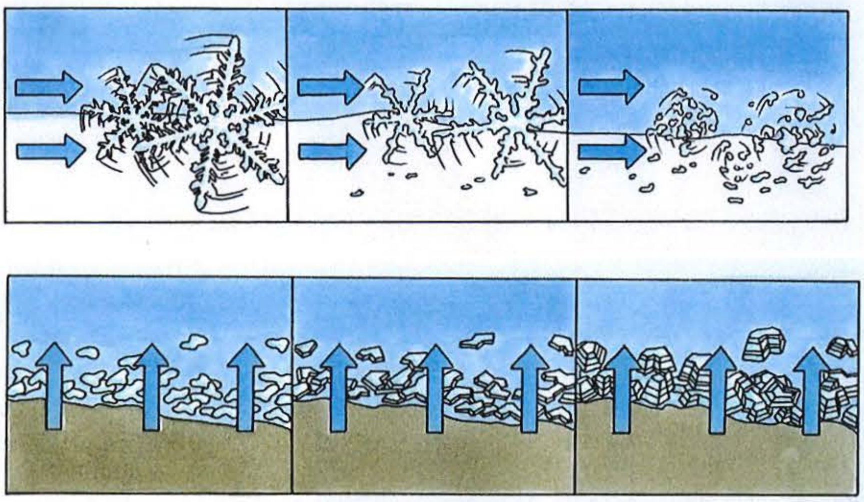

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Contents

1 Introduction

1.1 Purpose and aims

This manual has been prepared for the Norwegian Armed Forces by the Norwegian Armed Forces School of Winter Warfare in collaboration with the Norwegian Geotechnical Institute (NGI) and the Norwegian Water Resources and Energy Directorate (NVE).

The purpose of this manual is to provide a theoretical basis for the training of personnel within avalanche-related topics. The manual covers topics which will help to increase understanding and awareness of snow cover, weather and terrain. To acquire the best possible understanding of the topic, it is necessary to gradually build up a knowledge of the topic over many years. It is also important to maintain the theoretical basis and to keep abreast of developments within the discipline.

1.2 Target group

The target group for the manual is Norwegian Armed Forces personnel whose duties include the issuing of avalanche warnings, the crossing of avalanche terrain and/or the identification of safe marching routes.

2 Background

2.1 General information concerning avalanches and key factors

The Norwegian Armed Forces must be capable of engaging in combat under any type of conditions in Norwegian terrain. This requires our units to be able to operate in demanding terrain under the most challenging weather conditions to be found in Norway. Safety and the selection of safe marching routes remain key factors during both war and peacetime. Appropriate routines must be established through knowledge and training, so that the selection of a safe marching route becomes second nature to officers and soldiers alike.

In connection with activities in avalanche terrain, it is important that training is provided to enable military personnel to avoid becoming involved in avalanche-related incidents. It is vital that personnel have the skills and equipment needed to handle a situation if they are affected by an avalanche or in the vicinity of others who are affected. Because extensive use is made of mountainous areas during the winter, the Norwegian Armed Forces must ensure that our soldiers are able to cope with winter conditions and possess the skills they need in order to select safe marching routes.

During the period 1972 to 2018, a total of 243 people lost their lives in avalanches in Norway (NGI, 2018). Around 80 percent of these died when travelling through natural landscapes, with the remainder losing their lives on vehicular roads or in buildings hit by an avalanche. Despite a strong focus on preventive work concerning avalanche safety and a growth in the popularity of learning about avalanches and avalanche hazards, occasional winters still occur when many people lose their lives (2010–11: 13 fatalities, 2018–19: 13 fatalities). The chances of anyone who is completely buried by an avalanche surviving decreases rapidly with time. 'Completely buried' means the head and upper body are covered by snow. Statistics from Switzerland indicate a 50% survival rate for anyone who is completely buried by an avalanche (Haegeli P et. Al., 2011). Statistics from similar surveys indicate that as many as 25 percent of avalanche victims die from mechanical injuries.

Avalanche victims have a 50 percent likelihood of perishing if they are completely buried!

As many as 25 percent of avalanche victims die from mechanical injuries!

To prevent accidents in the future, it is important to raise awareness of the factors that are of physical significance to avalanche risk. The four main factors are:

a) Snowpack
b) Weather
c) Terrain
d) People

2.2 Structure of this manual

The first part of this manual covers the three factors of snow, weather and terrain separately. The interaction between the various factors and their importance is then explained in more detail. The final, and probably most important factor is people and our perception of the situation (Figure 2.1). The human factor concerns our knowledge, experience, perception, subjective interpretation, evaluation, peer pressure and so on. The human factor is discussed on many occasions in this manual, as people impact on many of the topics covered by this manual.

Figure 2.1: The four avalanche evaluation factors

The weather, snowpack and terrain are all factors which must be evaluated if avalanche risks are to be understood. People, the fourth factor, are pivotal to the evaluations, and we all make more or less subjectively influenced decisions based on our interpretation of the other three factors.

2.3 History

Every winter, both major and minor accidents occur as a consequence of avalanches. The Norwegian Armed Forces have been spared avalanche accidents involving the loss of human life since 1994. Between 1986 and 1994, the Norwegian Armed Forces lost a total of 18 soldiers in avalanche accidents. The most significant accident in a military context occurred on Wednesday 5 March 1986 in Vassdalen during the *Anchor Express Exercise*. A few minutes after 13:00, an avalanche swept down Storebalak mountain into Vassdalen. The avalanche struck 31 men from the North Norway Brigade while they were in the process of ascending the mountain along a small valley on the north side of Storebalak. All personnel were struck by the avalanche and buried to a greater or lesser extent. 15 men survived, while a further 16 men perished. The heavy snowfalls and strong winds during the week prior to the accident led to circumstances that were exceptionally unfavourable in terms of avalanche risk. However, there were many old avalanche paths along the trail and several avalanches had recently occurred in the area.

On Thursday 6 February 1992 at around 06:05, an avalanche occurred on a small mountain slope in the Bjørnevatn–Hovden area of Setesdalen. Two cadets from Gimlemoen Military Academy were struck by the avalanche during a ski march in darkness and poor visibility. Both cadets were buried in the avalanche; however, one of them was only partially buried and managed to break free from the snow. The terrain at the accident site had been assessed as an avalanche risk on the previous day and it was decided that no personnel were to enter the area. However, in darkness and poor visibility, the cadets made a navigational error and entered the very area that had previously been assessed as posing an avalanche risk. It had also been extremely windy, and it had snowed heavily during the days prior to the accident. The avalanche victim was found after approximately 45 minutes in a primary search field in which assisted rescue with ski poles was carried out. The ski pole was barely long enough to reach the avalanche victim. CPR was performed as soon as the victim had been dug out and this continued until a doctor arrived at the scene of the accident at 08:15, and declared the patient dead, some 2 hours and 10 minutes after the avalanche had occurred.

In March 1994, a total of 17 Home Guard soldiers were completely buried when an avalanche struck their bivouac area in Tussagjelet near Kvamskogen in the county of Hordaland. The bivouac area was located deep inside a gorge, and during the night, large amounts of snow had accumulated due to strong winds and heavy snowfall, which eventually turned into rain. The avalanche was presumably triggered naturally and resulted in the soldiers being buried in their tents. Fortunately, some personnel had not been buried and they were able to dig out those who had been struck by the avalanche. One soldier died. The sentry post at the base had been struck by an avalanche three hours before the main avalanche occurred. However, nobody had fully realised the danger. Following the accident, some members of the division were hit by a subsequent avalanche while on their way out of the area, along a marching route that had been assessed as safe. According to the rescue parties and the police present at the scene, it was a miracle that no more lives were lost that evening/night.

These are three examples of recent avalanche accidents that have resulted in fatalities in the Norwegian Armed Forces. In addition to these accidents, there have been several near-misses. Since the Vassdal accident, a strong emphasis has been placed on avalanche training and the selection of safe marching routes. This manual will also help to ensure that the Norwegian Armed Forces maintains its positive statistics following the Kvamskogen accident, i.e. no avalanche accidents resulting in loss of life.

3 Avalanche formation

3.1 Avalanche types

3.1.1 Subdivision of avalanche types

Avalanches are divided into three main groups:

a) Loose snow avalanches
b) Slab avalanches
c) Slush avalanches

3.1.2 Loose snow avalanches

Loose snow avalanches can be triggered in either dry or wet loose snow. This type of avalanche generally occurs on the surface of the snowpack, when bonding between the snow crystals is poor. This typically occurs a few hours after heavy snowfall with light new snow in calm weather conditions, or during the spring when the sun and rain melt the bonds between the snow crystals. Loose snow avalanches are most often triggered at a single point and spread out in a fan or pear shape. Loose snow avalanches usually occur on slopes with a slope angle of 45° to 60°. Loose snow avalanches will normally trigger themselves when a small amount of snow is set in motion on a steep slope and this spreads outwards, causing the volume to gradually increase downslope. The terrain must be sufficiently steep for the bonds between the snow crystals (cohesion) and friction to be overcome. The layer of fresh snow becomes most vulnerable when the bonds between the new snow particles start to break down. Loose snow avalanches are often triggered because the weight of the fresh snow eventually overcomes the bonds and the forces holding the snow in place, setting the snow in motion. This can occur through persistent precipitation or through weakening of the bonds between the snow crystals.

Loose snow avalanches are rarely triggered by personnel. If they are triggered, the individual(s) responsible for triggering a loose snow avalanche will usually be located above the avalanche.

Loose snow avalanches often represent a low risk to skiers, as the fresh layer is not fast enough for a fracture to propagate sideways on the slope and become a major avalanche. The fresh snow has therefore not yet formed a slab.
However, one should be careful about defining fresh, loose snow as *safe*. The weight of the fresh snow causes an increase in the load on the snowpack. Loose snow and soft slabs also enable the transfer of forces from a skier, for example, down into weak layers beneath. If there is a slab beneath the loose snow, a loose snow avalanche can trigger a slab avalanche deeper in the snowpack.
In order for a fracture in the fresh snow to propagate to other areas of a slope, slab formation is required. Wind will often affect certain parts of the mountainside, and a soft slab can form across a limited part of a slope. This can often be the uppermost part of the slope, in the transition between less steep terrain where the wind has gained more of a hold. It is sufficient for a limited, soft slab to set some of the snow on a slope in motion, which carries the loose snow across much of the slope below with it.

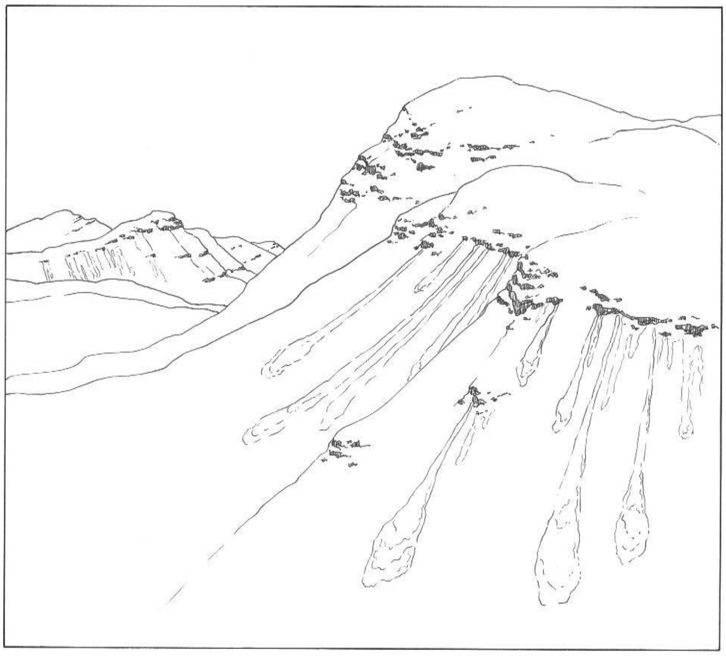


Figure 3.1: Loose snow avalanches

The avalanches are initiated at a single point on the slope without propagating to the sides. The avalanches then gradually increase in volume down the mountainside.

Loose snow avalanches normally pose little threat to military personnel, except in steep terrain immediately after heavy snowfall.

3.1.3 Slab avalanches

This type of avalanche is characterised by fracturing of a weak or loose layer in the snow, and through the snow on top sliding out as a coherent slab. A sharp fracture line is created perpendicular to the surface. Slab avalanches can spread across several hundred metres and comprise large quantities of snow. The fracture line can be several metres high. The slab will break into smaller blocks further down the avalanche path and can end up as a flowing loose mass. In the case of fast-moving dry snow, the snow masses can become airborne along the avalanche path. Once the slab avalanche has come to a stop, the snow will solidify immediately. It can sometimes become as hard as concrete. This is due to mechanical decomposition, heating and compression, followed by subsequent cooling.

Even if the snow is light and loose in the valley bottom, there may be a risk of slab avalanches being triggered higher up the mountainside where the terrain is more exposed to the wind, enabling slabs to form more easily.

Slab avalanches can be either wet or dry. As a result, such avalanches can behave differently. It is therefore important to understand the differences between wet and dry avalanches, what triggers them and how they move. Wet slab avalanches can be triggered in terrain with slopes as gentle as 20°, but higher additional loads are required to trigger them than in the case of dry slab avalanches. Avalanches can also start as a dry slab avalanche higher up the mountainside and carry with them wet snow lower down the avalanche path.

The table below shows the differences between wet and dry slab avalanches.

	Dry slab avalanches	Wet slab avalanches
What triggers the avalanche?	The avalanche is triggered because the weight of the snow or persons exceeds the forces holding the snow in place. The load is greater than the strength.	The avalanche is triggered because the strength of the snowpack/bonding between the snow crystals is weakened.
To what extent are people involved?	Triggered by people or naturally.	Rarely triggered by people, usually triggered naturally.
What type of weather causes this type of avalanche?	Wind transport of snow or intense snowy weather.	Usually triggered by rain, persistent melting by the sun or high temperatures
How does the avalanche move?	Fast (100–200 km/h), usually in a cloud of snow (airborne).	Slowly (35–100 km/h), like flowing cement, without a snow cloud.

Table 3.1: Differences between wet and dry slab avalanches

There are differences between the triggering mechanisms and speed of wet and dry slab avalanches.

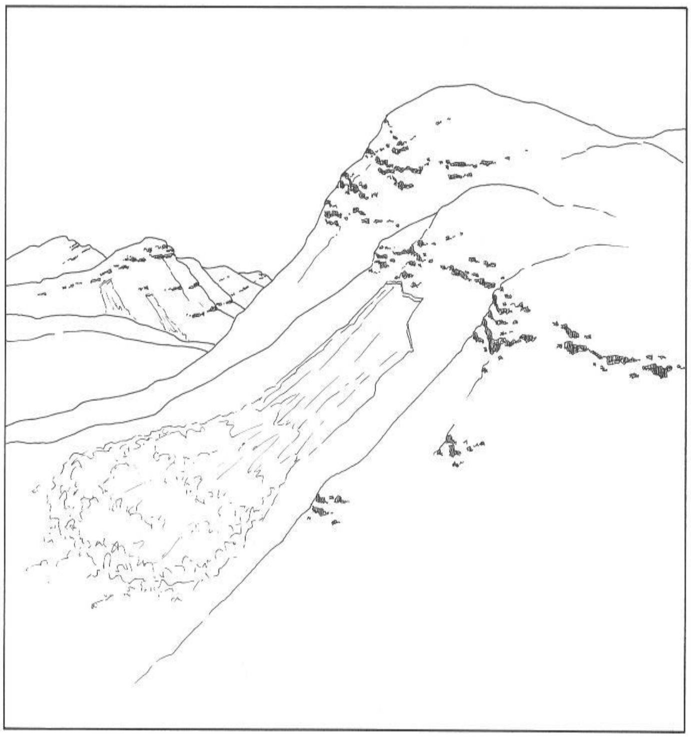


Figure 3.2: Slab avalanches

Slab avalanches have a distinct fracture line at the top of the release area and start as a coherent slab.

Dry slab avalanches pose the greatest threat to military personnel in terrain, as they can be triggered from distance and become large. Wet slab avalanches pose a greater threat to military bivouac areas, as they are self-triggered.

3.1.4 Slush avalanches

This type of avalanche comprises a fluid mixture of snow and water. Slush avalanches behave like a viscous river. Slush avalanches may occur following a major snow melt or heavy rain on the snowpack.

The melting of water in the snow is often apparent from the colour of the snowpack, with wet snow having a greyish or bluish colour. In such conditions, it is advisable not to assemble below depressions in the terrain, on creek beds or where large streams flow into the bottom of the valley. Slush avalanches may be triggered at slope angles as low as a few degrees, and may have a range well in excess of the run-out lengths of slab avalanches, as they contain large quantities of water which can flow great distances across flat terrain.

Mountainsides that face the wind are often most exposed to slush avalanches. This is because the leeward sides of mountains receive more warm air and experience the most intense snow melt and the heaviest precipitation in the form of rain (Lied and Kristensen, 2003).

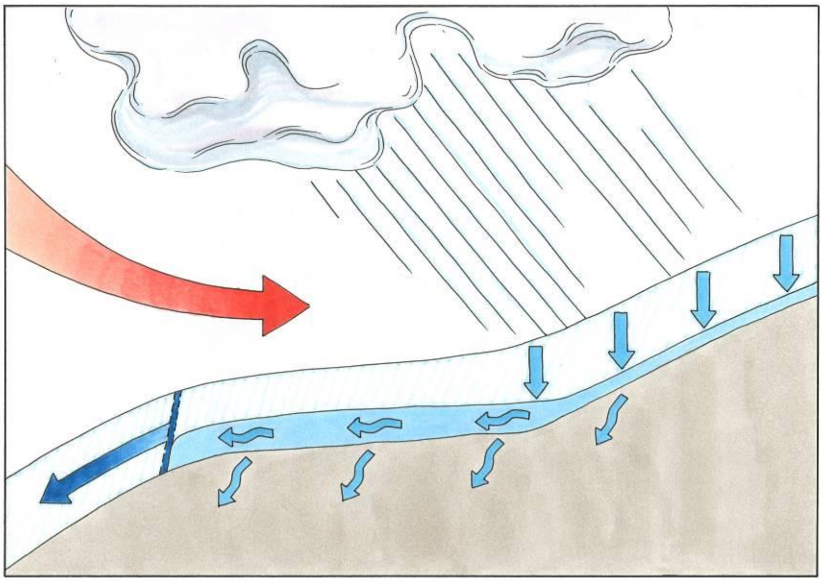


Figure 3.3: Slush avalanches

Water from precipitation and melting snow becomes dammed and can lead to a slush avalanche when the snow becomes oversaturated with water and the dam gives way.

The risk of slush avalanches is likely to increase when high temperatures or heavy rain are forecast. This must be taken into account when forecasting avalanche risk or evaluating stability.

The Norwegian Armed Forces' avalanche map does not take account of slush avalanches, which can have longer run-outs than slab avalanches.

3.2 Forces that impact on a snow slab

Slab avalanches are often triggered by human activity. Slab avalanches are considered to pose the greatest threat to personnel in avalanche terrain. For these reasons, this manual primarily focuses on slab avalanches. In order to understand how a slab avalanche is triggered, it is necessary to study the forces at work in the snowpack in more detail.

On a slope, the snowpack will be influenced by gravitational forces which pull the snow downwards. As the shape of the terrain varies and the snowpack consists of different layers which can move relative to each other, the movement of the snow crystals will vary from place to place in the snowpack.

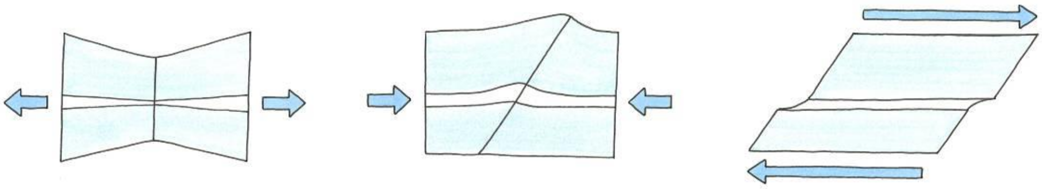


Figure 3.4: Tensile, compressive and shear forces
The various forces which impact on a slab and the layering of the snowpack.

On a slope, the slab will be affected by differing forces. It is necessary to distinguish between tensile, compressive and shear forces. Tensile forces occur at the top of the slope. Compressive forces occur against the snow at the bottom of the slope. Shear forces occur against the sides and between layers.
The slab's ability to tolerate stresses is determined by the snow's tensile, compressive and shear strength.

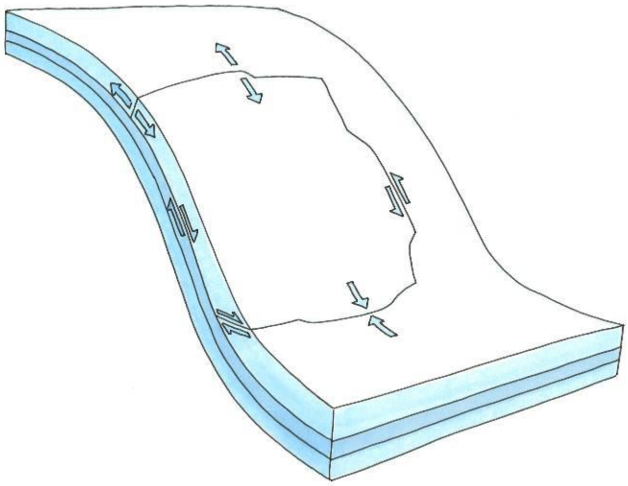


Figure 3.5: Forces acting in a snowpack on a slope
Uppermost are tensile forces, at the base are compressive forces, at the sides and between the layers are shear forces.

If the forces acting on the snowpack exceed the anchoring forces, an avalanche will be triggered. Avalanches can be triggered by external factors. Examples of triggering factors include:

a) a rise in temperature, which increases the creep rate in the snowpack
b) precipitation, which increases the additional load or weakens the bonds in the snowpack
c) accumulation of snow due to wind transport
d) one or more skiers exerting pressure on the snowpack

Most accidents involving skiers occur because the skier or someone in the group triggers the avalanche, unlike naturally triggered avalanches, which are triggered without any human intervention. In 90 percent of avalanche accidents, the avalanche is triggered by the victim themselves or another person in the group.

3.3 Snow creep and stresses in the snowpack

The constant effect of forces on the snowpack will lead to movement of the snowpack, known as 'snow creep'. Snow creep is a result of the effect of gravity and settlement in the snowpack. Settlement in the snowpack is the tendency of the snowpack to collapse as the snow crystals are transformed and the amount of air in the snow is reduced. The snow moves slowly down the slope parallel to the surface as it becomes compacted and the snow grains move towards the ground. These movements are known as snow creep and settlement of the snowpack. New snow has a low density and a high pore volume, i.e. a high proportion of air spaces. Hence the crystals move more easily relative to each other in new snow. Consequently, the greatest movement and settlement occur at the top of the snowpack.

Snow creep leads to stresses in the snowpack and tensile forces at the top of the slope, compressive forces at the bottom and shear forces between the snow layers. It is precisely these stresses in the snowpack which can be triggered when the pack is subjected to load, which in turn can trigger an avalanche.

The movement in the snow will be fastest in the upper part of the snowpack, where the snow has a low density and is less solid. Greater snow depths also increase the speed. At high temperatures, the rate of snow creep will also increase, particularly if it rains on the snowpack. Snow creep is greatest on steep mountainsides. The snowpack may also slide along the ground if the surface is slippery, e.g. a bare rock-face or sward. The consequences of such creep and slippage can be seen on trees on steep, nival slopes, which characteristically bend from the roots and part way up the trunk.

Tensile forces develop particularly over convex terrain forms ("roll-overs"). For example, in an icefall, the speed on the downside of the convex form will be greater than on the upside. The snowpack may also be thinner over the convex part of the slope. This can cause substantial stresses which are waiting to be released in the vicinity of convex ball-shaped formations in the terrain.

It is important to note that avalanches can be triggered deeper in the snowpack, away from the influences of mild weather and rain. This is explained by an increase in snow creep in the upper part of the snowpack, causing an increase in the forces being exerted on it. This can lead to failure and avalanche release deeper inside the snowpack, even though the increase in temperature has not reached that far down in the snow.

Figure 3.6 below shows that the snow creep will lead to tensile and shear forces.

! Snow creep will increase when the temperature rises to well above 0ºC in the release area. When combined with precipitation (rain), this can lead to a marked increase in avalanche risk.

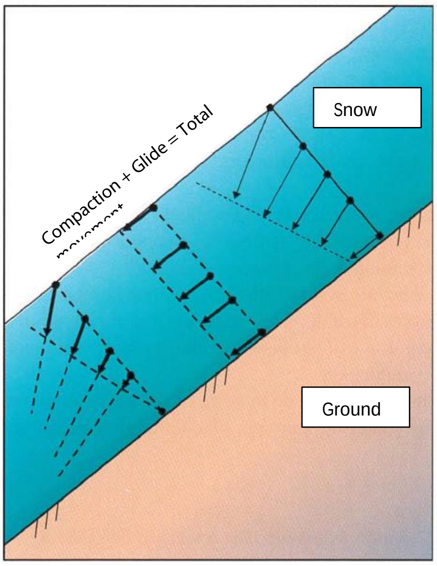


Figure 3.6: Illustration of movement in the snow, known as 'snow creep'
(Source: Lied & Kristensen 2003)

3.4 Remote triggering of avalanches

Under unstable conditions, avalanches can be triggered remotely. Remote triggering is initiated through the formation of a local fracture in a weak layer inside the snowpack, e.g. as a result of a person moving across the snowpack. The overlying slab and the weak layer must have the right characteristics in order for a local fracture to spread as a collapse in the weak layer. This is known as 'fracture propagation'. The weak layer may consist of faceted crystals, depth hoar, snow-covered surface hoar and layers of loose, unbonded snow. The snow crystals in the weak layer will behave like a line of dominoes, where the fracture propagates like a chain reaction.

The slab must have a certain hardness in order for fracture propagation to occur. The collapse often sounds like a rumble or a boom, which occurs when air is forced out of the snowpack. Anyone standing on the snowpack will often be able to feel the collapse, as the snow surface will suddenly sink by up to several centimetres. The collapse can occur when an individual person moves across the snowpack or when the load increases as a result of several people gathering in one place. If the fracture propagation reaches an adjacent slope which is sufficiently steep, an avalanche can be triggered, either to the side, above or below.

As a result, personnel moving across gently undulating terrain with avalanche terrain above them can trigger an avalanche higher up the mountainside. If a person triggers a slab avalanche above them, the likelihood of the person being buried and injured by the snow will be greater than if they are on the upper side or to the side of the avalanche when it is released.

Never approach the foot of steep inclines or enter them when the snowpack is rumbling.

3.5 Slab avalanches in motion

A slab avalanche is the result of a weak or loose layer that fractures, and the overlying slab is then released as a cohesive mass. When a slab avalanche is set in motion down the mountainside, it will accelerate rapidly. Initially, it will have a sliding motion, as the snow slab breaks into smaller blocks of snow that slide like bricks on a smooth surface. In the case of small avalanches, the snow is often deposited as large or small blocks, depending on the slab's hardness, velocity and the run-out length of the avalanche. In the case of larger avalanches, the blocks break up as the velocity increases, and the avalanche changes to a mixture of snow that slides and rolls on the surface, and snow that skips and bounces. If the snow is dry, the avalanche can develop a tall snow cloud consisting of air and snow crystals.

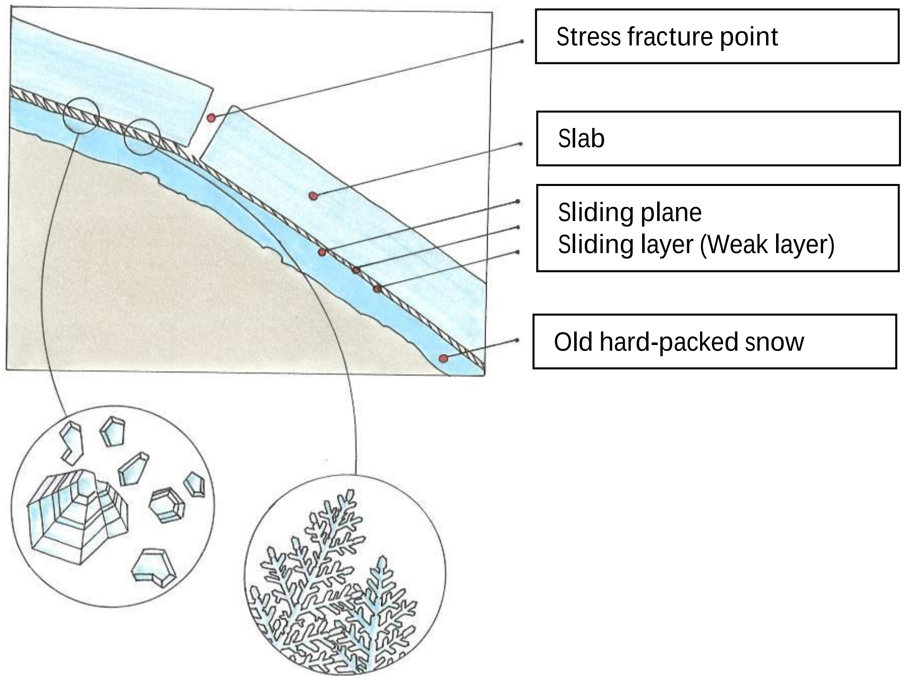


Figure 3.7: Example of layering and avalanche release in a layered snowpack

In order for a slab avalanche to form, the snowpack must consist of a slab and a weak layer and be sufficiently steep.

Figure 3.7 illustrates a slab with a fracture point and a weak layer. A fracture has occurred in the tensile forces in the upper part of the slab where the fracture point is shown. The snow slides like a slab. The slab slides on a weak layer down in the snowpack or along the ground surface. Beneath the weak layer is the sliding plane. The sliding plane often consists of more compact, older snow. The ground can also act as the sliding plane.

Velocity of a dry slab avalanche:	30–60 m/s (approx. 100–200 km/h)
Velocity of a wet avalanche:	10–30 m/s (approx. 35–100 km/h)

The velocity will vary according to the slope angle and the surface. A wet snow mass will have greater friction against the surface and will thus not attain the high velocities of dry avalanches. Avalanches accelerate rapidly and can therefore cause major injuries, even on smaller slopes. Avalanches rapidly freeze and sinter once they have stopped, and the snow will become compact and hard. Such snow is very hard to dig into, and rescue teams may therefore need to use steel shovels. The avalanche mass can form mounds many metres thick if the avalanche stops in a narrow gorge or if the avalanche path has a rapid transition to flat terrain. On level terrain, the accumulation is moved constantly along the avalanche path. If the snow is moist, avalanche debris has a tendency to be deposited in concentrated tongues or mounds.

3.6 Maritime and continental snowpack

Due to differing climates, snowpacks situated near the coast will differ from those found inland, known as maritime and continental snowpack respectively.

Along the coast, snowfalls tend to be more frequent and heavier than inland. Here, the snowpack will be subjected to a greater load, resulting in frequent, but shorter periods with increased avalanche risk, also known as avalanche cycles. Precipitation can often be a triggering factor. High temperatures near the coast cause fresh snow to stabilise more rapidly.

In inland areas, the terrain will normally be more sheltered, and precipitation will not be as high in terms of volume as along the coast. It can also be very cold over longer periods of time, which when combined with a thin snowpack, can lead to weak layers as a result of constructive transformation. These weak layers are considered to be persistent. Periods with increased avalanche risk must therefore be expected to last longer. Such layering also increases the likelihood of remote triggering of avalanches. Low temperatures extend the time that fresh snow takes to stabilise.

4 Avalanche terrain

4.1 Introduction

Small slab avalanches are considered to pose the greatest threat to military divisions. There is particular reason to warn against using stream gorges and small leeward slopes, which units may seek out in order to gain shelter from inclement weather and wind, or to conceal themselves. The threat from large avalanches is considered to be small with regard to military units, as such divisions do not necessarily have the capacity or need to explore extensive mountainsides. On the other hand, large formations can represent a potential threat to roads, terrain axes, bivouac areas and military installations situated in valley bottoms.

4.2 The avalanche area

4.2.1 The various parts of an avalanche

Avalanche areas are divided into:

e) Release area
f) Avalanche path
g) Run-out area

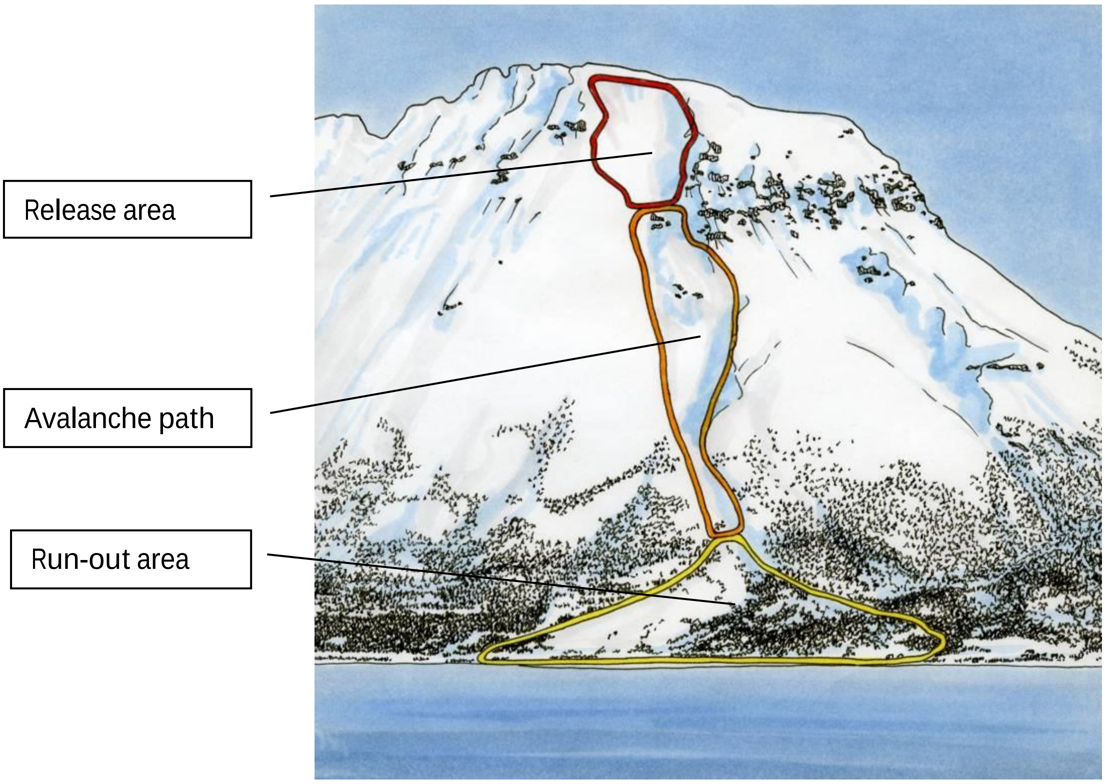


Figure 4.1: The avalanche area

The figure shows a schematic representation of an avalanche area with the release area at the top and the avalanche path and run-out area at the bottom towards the more level areas where the avalanche comes to a halt.

In the case of small avalanches, the release area and the run-out area often overlap, while major avalanches that cover most of a mountainside can have a longer avalanche path, which the avalanche passes through between the release area and the run-out area.

Smaller terrain formations are regarded as the greatest threat to military units, as such formations are used for cover and to avoid extensive areas of avalanche terrain.

4.2.2 Release area

The release area is where the avalanche is triggered. The upper boundary of the release area is delimited by the avalanche fracture line, or the avalanche crown, while the lower limit is the lower part of the slab that slides out. Laterally, the release area is demarcated by the remaining untouched snowpack.
All inclines on a mountainside with a slope angle of between approximately 30° and 60° may represent release areas for slab avalanches, providing there is sufficient snow present and no dense forestation.

Slab avalanches, which are regarded as the greatest threat as regards loss of human life, are usually triggered in terrain steeper than 30°. When the gradient is less than 30°, very unstable conditions will be necessary in order for a slab avalanche to be triggered, because the anchoring forces will normally be sufficient to hold the snow in position. In the case of extremely steep slopes, the snow will not attach itself to the slope, but will gradually slide away as it accumulates. This is the reason why large slab avalanches do not normally occur in terrain steeper than 60°.
Because snow accumulates unevenly on the slope, it may accumulate in such a way that the snow surface is steeper than it appears in the terrain information on a map. Studies of around 500 major avalanches in Norway have indicated that the majority of naturally triggered avalanches are triggered on a terrain gradient of between 35° and 50°. Slab avalanches are triggered when the sum of the forces pulling the slab downslope exceeds the forces holding the slab in position. Surveys of a number of avalanches triggered by skiers indicate that the lower limit for the triggering of a slab avalanche is around 30°.

! Military units must possess specialist knowledge in order to traverse snow-covered terrain steeper than 30°.

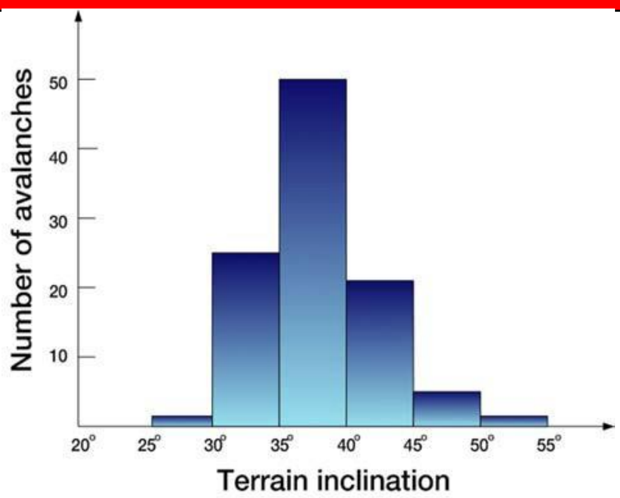


Figure 4.2: Avalanche frequency relative to terrain gradient for major, naturally triggered avalanches
(Lied and Kristensen 2003, p. 23)

4.2.3 Avalanche path and run-out area

Once an avalanche has been set in motion, it will seek out the lowest point, or the line of least resistance. A descending avalanche moves in a very similar way to a river. Prominent ridges and knolls tend to steer the avalanche and will influence the avalanche path. If the snow is dry and the avalanche moving rapidly, the snow mass can still pass over such ridges, even if they are many metres high. The greater the speed and volume of an avalanche, the greater its capacity to move in a straight line. Dry avalanches will usually start to decelerate when the slope of the terrain drops to 15–20°. Large, dry avalanches can extend great distances across level ground and cross valleys that are several hundred metres wide, while smaller avalanches will stop on or close to the slope where they were triggered. This also applies when the snow is damp or wet, mainly because a smaller snow mass is being carried down the avalanche path and these avalanches tend to have a lower velocity. An exception to this is a so-called slush avalanche, which contains such a high volume of water that the avalanche virtually flows like a river and can cross surfaces and have a longer run-out than avalanches that are marked on the Norwegian Armed Forces' avalanche map.

The gradient of the snow surface may be steeper than indicated on the map due to snow accumulation.

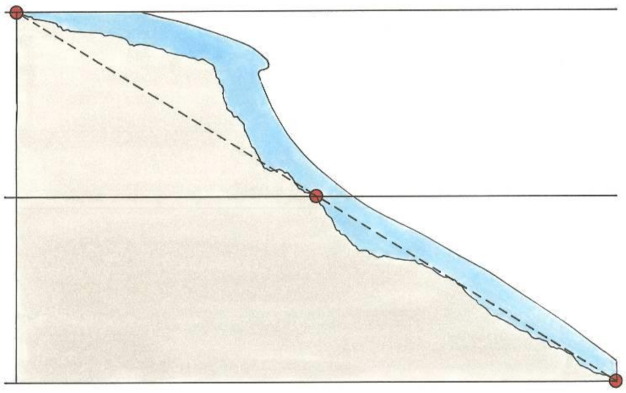


Figure 4.3: The slope of the snow surface (blue colour) in relation to the terrain (light colour) *The contours on the map (red circles and dotted line) indicate the mean slope angle.*

4.3 Exposure

The accumulation of snow must be given strong emphasis when evaluating terrain with regard to avalanche risk. Slopes and mountainsides that are sheltered from the prevailing wind directions during or after snowfall will be most vulnerable to avalanches caused by the wind transport of snow. Exposure describes a given sector where one or more described properties in the snowpack would be expected to occur.

In Northern Norway, precipitation is often brought by westerly or north-westerly winds. Particularly in the coastal regions of Nordland, Troms and Finnmark, strong winds in connection with low pressure from the west and northwest will lead to the accumulation of snow on the leeward side, i.e. mountainsides which face east and southeast. It is worth noting that high pressure situations can cause strong offshore winds and lead to the wind transport of snow onto mountainsides which face west and north.

Western Norway is the most complicated region with regard to the prevailing wind direction. Local conditions, valleys and fjords are determining factors here. Most snow showers are brought by strong south-westerly to north-westerly winds, which would result in northeast- to southeast-facing leeward sides. However, Western Norway can also have prolonged cold winds from the east, which result in snow accumulation on west-facing leeward sides!

East of the watershed divide in Southern Norway, a significant amount of precipitation and wind is brought by low pressure systems coming in from the southeast. This means that in areas with less snow, from the Swedish border to the Dovrefjell Mountains, most snow will usually be present on western and north-western mountainsides. Changes in wind direction following snowfalls can lead to the drifting of snow into other exposures.

In Jotunheimen and more central regions of Eastern Norway, westerly to north-westerly winds will result in leeward sides facing south to southeast.

Nonetheless, in respect of wind directions and wind-drifted snow, it is worth noting local variations in the area in which the unit is operating and the wind directions which have occurred since loose snow accumulated on the ground.

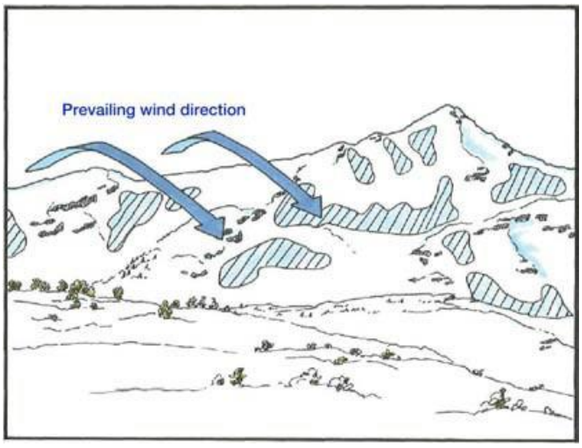


Figure 4.4: Leeward side with snow accumulation

When the wind decreases,
wind-transported snow is deposited on leeward sides.

4.4 Avalanche frequency in diverse terrain formations

According to a survey of around 250 avalanche zones in Western Norway, terrain types in avalanche release areas are divided according to avalanche frequency as follows (Lied and Kristensen 2003, p. 30):

Shape of terrain	Distribution of avalanche frequency in %
Convex areas	29
Deep passes, gorges	27
Glacial cirques	12
Beneath anchoring zones	12
Open hollows, stream valleys	10
Bare rock faces	10

Table 4.1: Avalanche frequency broken down according to terrain type
The table shows the distribution of avalanches in diverse terrain formations.

As the table shows, around 50% of avalanches occur from typical leeward formations such as glacial cirques, passes, gorges and bowl-shaped areas. It is in such areas that wind causes the snow to accumulate and little or no snow is transported away. Such terrain formations often form the starting point for large and very large avalanches.

Convex terrain forms (“roll-over terrain”) also give rise to frequent avalanches. In the table above, convex forms have a frequency of 29 %. On the steepest part of the slope, snow creep will be considerable, and this creates stresses caused by tensile forces in the uppermost part of the slope, in the transition to a thinner snowpack. Avalanches can be triggered naturally or by an additional load, often around the transition between thin and thicker snow cover.

A key factor for wind transport and snow accumulation is whether there is loose snow in the terrain. Where a mountain is capped by a plateau, snow from the plateau may be driven onto the leeward side of the mountain. Such areas are collection areas for snow transport. More snow can accumulate below such areas than in cases where the mountain is shaped like a sharp ridge.

A steep slope does not need to be high before avalanches can become lethal. Skiers have been killed on slopes where the height difference has been between 5 and 10 metres. Many fatal accidents caused by avalanches in Norway have occurred on slopes that are 20–40 metres high. As a rule of thumb, military personnel should not dig themselves in or seek shelter on leeward slopes more than 5 metres high (Norwegian Armed Forces 2018, p. 265). Slopes of 5 metres or more also pose a threat to units on skis or on foot. It is easy to seek shelter in a stream valley during bad weather, but it is also in such areas that slab avalanches first occur. The shape of a stream valley constitutes a terrain trap, and no great volume of snow is required to trap a person at the bottom of such a valley, particularly if they are equipped with a large rucksack, skis and poles. Avalanches in narrow stream valleys will often accumulate at the bottom and thereby bury people to considerable depths. Terrain where the consequences of an avalanche could be particularly serious is known as a 'terrain trap' or 'death trap'. Examples of terrain traps are narrow stream valleys, precipices, slopes above water or rivers and areas where the victims are carried into trees, increasing the risk of mechanical injuries.

Figure 4.5: Avalanches in stream valleys

! Military personnel should not dig themselves in or seek shelter on leeward slopes more than 5 metres high.

The depth of snow across a mountainside may vary from snow that has been completely blown away to snow that is several metres deep.
The weakest part of the snowpack will often occur where it is thinnest. A thinner snowpack presents two challenges. Firstly, thinner snowpacks can give rise to constructive transformation (see section 5.2.5), rendering the snow unstable. Secondly, a thinner snowpack results in a shorter distance down to possible weak layers and less "protection" of weak layers, leading to a greater risk of slab avalanches being triggered from such areas.

4.5 The range of avalanches – the run-out angle

The run-out length of an avalanche can be measured as the angle from the tongue of the avalanche up to the fracture line. This is known as the run-out angle or the α angle (α = alpha). The distance that an avalanche will travel is determined by a number of factors. A clear indication that an avalanche will travel a long way is a significant presence of snow in the release area (large starting volume) and in the avalanche path (large snow mass movement), in addition to the snowpack being dry, not wet. Avalanche paths that have a smooth transition to the valley bottom also result in long run-outs. Wet avalanches (with the exception of slush avalanches) will have a shorter path and range than dry avalanches. Run-out angles as low as 20–25° are not uncommon for avalanches with a relatively long range.

> The α angle is normally just over 30°. Along avalanche paths with a smooth transition to the valley bottom, this angle can drop to less than 20° if conditions for long run-outs are favourable.

4.6 Simple methods for determining the range of an avalanche in the field

A quick and simple method for calculating the maximum range of an avalanche is based on the horizontal distance to the release area of the avalanche. The method is referred to as the "20-degree rule". This means that when the line of sight from a position at the bottom of a valley to the expected avalanche crown is 20º, the avalanche will rarely extend this far. Only 2% of avalanches are considered to extend further than this. The line of sight should therefore form an angle of 20° or less.

Thus, a rough estimate of the range of an avalanche (L) is the vertical drop (H) multiplied by a factor of 3. The 3 x H rule or the 1 : 3 rule, which means that we pass the slope at a horizontal distance which corresponds to three times the height of the slope. This gives a line of sight of approximately 18° and approximates to the 20-degree rule.

Both these methods give a good level of safety against 98% of all avalanches and are simple, fast and safe methods for avoiding the run-out areas of avalanches, particularly when the conditions are uncertain (see the figure below).

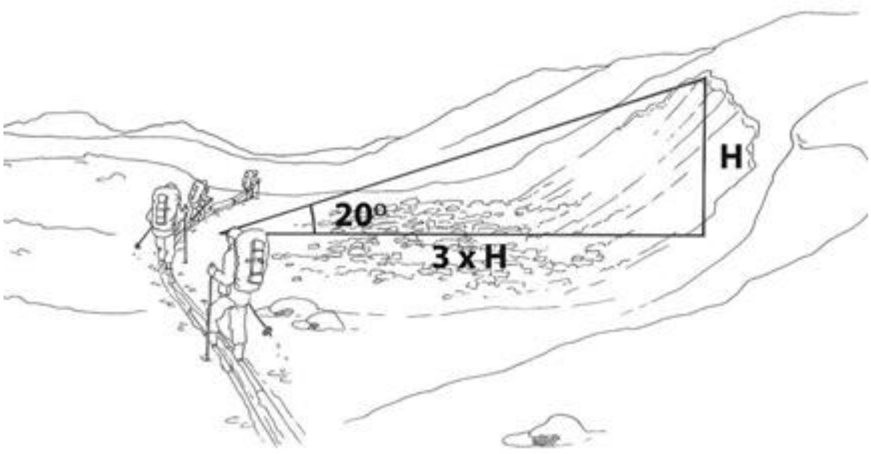


Figure 4.6 The 3 x H or "20-degree rule"

When the avalanche risk is unknown or a fast assessment is needed, the 3 x H or "20-degree rule" can be used to ensure safe passage. H = height from the assumed fracture line to the valley bottom. 3 x H gives a horizontal distance out from the avalanche crown that must be observed in order to avoid most avalanches (~98% of all avalanches). 3 x H gives a light of sight of 18.43º, so that an alpha angle of 20º can be used if a compass or other similar instrument is available to measure the line of sight.

4.7 The Norwegian Geotechnical Institute's topographic model

For many years, the Norwegian Geotechnical Institute (NGI) has mapped and registered several hundred major avalanches in Norway. Through studying these avalanches, NGI has developed a topographic model which forms the basis for the Norwegian Armed Forces' avalanche map production (Lied and Kristensen 2003 p. 84–85).

It has been shown that the maximum range of an avalanche is determined by the angle of the slope and the shape of the mountainside. The slope angle is defined by a line of sight that connects the point on the slope where the terrain gradient is 10° with the top of the release area. The angle of the terrain along this line is described as 'B' (see figure below).

It is possible to determine this 10-degree point using the distance between the contour lines on a map. On the M711 map on which the scale is 1: 50,000 and the equidistance is 20 metres, a 10° terrain gradient equates to a distance of 2.3 mm between contour lines ((20m/tan10)/50m=2.2685 mm).
The 10-degree point is placed on the uppermost of the contour lines where the slope is 10° (between which the 2.3 mm distance has been measured). A simple relationship has been identified between the maximum range of an avalanche (angle A) and the steepness of the avalanche path (angle B):
A=0.96 x B – (1.4°+SD), SD=2.3° and the correlation coefficient, R=0.92.
Using this equation, it is possible to determine the estimated range of a major avalanche (angle A). The map is consulted, the 10-degree point is found and angle B is calculated. Angle B is then inserted into the equation and angle A is calculated. Finally, the height difference H between the release area and the valley bottom is found, and the range L of the avalanche is estimated (Figure 4.7) using the formula L=H/tgA

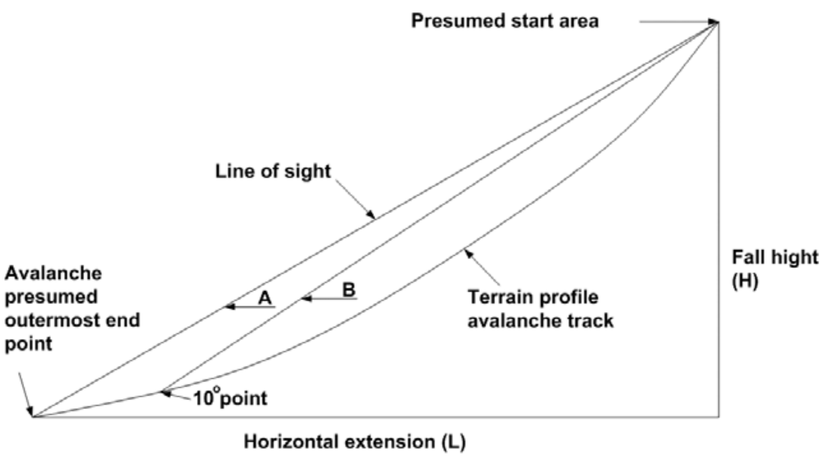


Figure 4.7: The Norwegian Geotechnical Institute's topographic model

Using angle B from the 10-degree point to the assumed release area, it is possible to estimate angle A and the further horizontal extend of avalanche L.

A simplified version of this formula, which is easier to use without special instruments, is A = B – 5º. The same procedure is used to determine angle B. Deducting 5º produces an angle which is approximately equal to the expected run-out angle for an avalanche which extends two standard deviations further than the alpha mean.

Another method that may be applied to the map (M711) is:
Range = 10° + half H.
The 10-degree point is first determined. The fall height from the highest possible fracture line to the 10-degree point is deduced from the map, then half of the fall height is added to the 10-degree point, horizontally. The point in the terrain that is obtained will be the approximate range of a 100-year avalanche. This is how run-out zones can be calculated on an ordinary M711 map if an avalanche map is not available. This method gives shorter ranges than the 3 x H / 20-degree rule and will be well within the NGI's topographic model.
For information on electronic avalanche maps, see section 11.

5 Snow

5.1 Snow in the atmosphere

Precipitation is usually caused by air being forced to rise and cool so that water vapour condenses. Warm air can contain a relatively high amount of water vapour, but when air cools, its capacity to retain water vapour diminishes. When air cools, the relative humidity increases until the air becomes saturated with water vapour. The *dew point* is reached when air has cooled sufficiently for the moisture to condense. With further cooling, the air becomes oversaturated, and water vapour condenses to form droplets of water and ice particles. Even though the air in clouds has a temperature of well below 0°C, it will consist of both ice particles and water droplets. The water droplets are then referred to as being 'supercooled'. The water vapour pressure around the water droplets causes water vapour to be drawn towards the ice particles and be deposited as ice through deposition. Deposition, the opposite of sublimation, is the process where a substance is transformed directly from gaseous form to solid form.

The surplus water vapour condenses and freezes on condensation and freezing cores which consist of small particles, normally salt, dust and soil particles. If the air does not contain any such particles, oversaturation of several hundred percent is required to form water droplets, and ice particles will not form until the temperature drops to -41°C.

At temperatures of around -12 to -16 °C and high air humidity, star-shaped snow crystals are formed. If it is colder, smaller snow crystals are formed, and at temperatures closer to 0°C, the snow crystals will grow to be large. It is the air temperature that determines how rapidly snow crystals will grow, and at low temperatures, snow crystals grow slowly.

Air temperature and water vapour content determine the shape of snow crystals. Once crystals have grown so large that the ascending air currents are no longer able to support them, they will start to descend. The crystals will change shape as they descend, depending on the temperature and moisture content of the air strata they pass through.

If the temperature is below 0°C all the way to the ground, the precipitation will manifest as snow. If the temperature is close to 0°C, several snow crystals will often join together and fall as large snowflakes. However, if it is cold, the snow crystals can take on a needle shape. Hail forms when snow crystals melt as they descend and strong ascending air currents lift them up again, so that ice freezes onto them. This process can be repeated until they eventually fall to the ground as hail and do not melt until they hit the ground.

A special form of snow crystal is graupel ('snow pellets'). These are snow crystals that have collided with supercooled water droplets during their descent. In turn, the water droplets have frosted upon impact with the snow crystals. Such crystals are whitish in colour and are fused together to form a rounded shape. This phenomenon occurs along the coast, often during showery weather and, depending on the wind strength, they can be visible for some distance inland.

Snow crystals have varying shapes. They are classified into nine different primary classifications (see Appendix 1). Each primary classification has its own set of subgroups – a total of 37 different subclasses or snow types. The letter codes for the respective primary classifications and subclasses use the initials of gradings for respective snow crystal types. For example, 'Depth Hoar' has the letter code DH.

A perfect snow crystal in light snow is six-armed with a 60-degree angle between the arms. However, no two snow crystals are ever identical.

In calm, cold weather, snow may be extremely light and airy with a density as low as around 10 kg/m³. However, the average density of dry new snow is 100 kg/m³, i.e. 10% of the density of water (water has a density of 1,000 kg/m³). Thus, we may deduce that 1 mm of precipitation will produce 1 cm of dry new snow.

When the snow has landed, it will either subside or settle. This process will take place more rapidly if the temperature is higher. Persistent cold weather will result in light and airy snow over a prolonged period.

5.2 The snowpack

5.2.1 Fresh snow

The intensity of the snowfall, the temperature during and after the snowfall, in addition to the strength and direction of the wind, will determine how the snowpack accumulates. These conditions will vary and the relationships between the different types of snowfall will cause the snowpack to constantly change. The snowpack will thus be composed of many different layers, with various types of snow crystals and degrees of hardness.

Precipitation particles may be shattered by the wind even during their descent to the ground, or by the wind blowing the crystals along the snow surface. New snow that has fallen in calm and cold weather, often characterised as loose snow, is light and airy. This type of snow has little grip and bonding and, with such snow, loose snow avalanches may occur, providing the terrain is sufficiently steep, i.e. steeper than around 45°. If the terrain is steeper than 60°, the new snow will usually descend continually in many small loose snow avalanches during and after the snowfall. The loose snow avalanches will start after a certain period of time, once the snow crystals have begun to break down. This takes longer in cold, calm weather than if the temperature is higher.

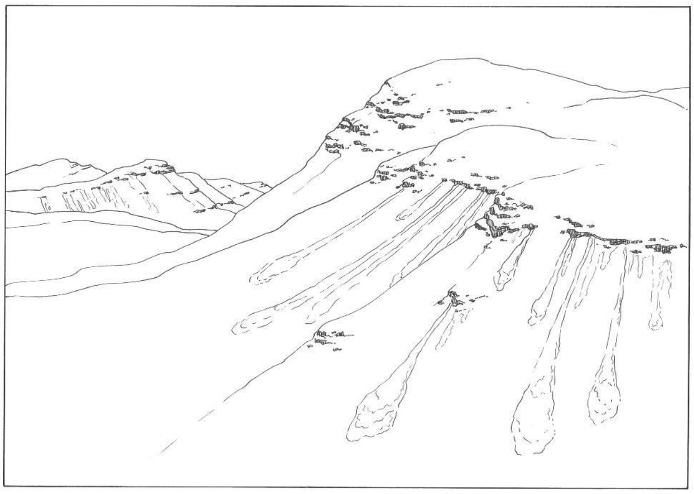


Figure 5.1: Loose snow avalanches in steep terrain

The avalanches are triggered at a single point and increasingly spread out until they stop.

Dry new snow consists of 50–90% air. New snow is subjected to settlement and compaction, which reduces the air content. Over time, these snow crystals will undergo other transformation processes. Mild weather, rain and low temperatures will also influence the snowpack and form snow crust layers and layers with hoar crystals. As the winter progresses, the snowpack will consist of many layers which contain snow or ice with considerable variation in appearance, density and characteristics.

It is the layered composition of snow that is critical in respect of avalanche risk. If there are weak layers in the snowpack and slab formation is occurring, the conditions for triggering a slab avalanche will be met. Certain types of snow crystal will form persistent weak layers that will remain in the snowpack for a long time, while other grain types will alter rapidly, with the result that the weak layer will only remain in the snowpack for hours or days after its formation.

It is therefore important to determine whether there are weak layers in the snowpack. However, it is also important to obtain an overview of the distribution of weak layers, i.e. the heights and cardinal directions of the weak layers. The thickness and depth of weak layers and the magnitude of the force that is required to trigger a fracture can vary greatly over short distances. Persistent weak layers can be a major factor in determining avalanche risk throughout much of the winter and do not normally disappear until they have melted. Once persistent weak layers have been identified, they must be monitored for as long as they exist. For details concerning weak layers and persistent weak layers, see section 7.1.5.

5.2.2 Snow crystal types, dimensions and characteristics

The principal forms of snow crystals, with the exception of artificial snow and ice, are shown below. Appendix 1 contains all primary and secondary classifications.

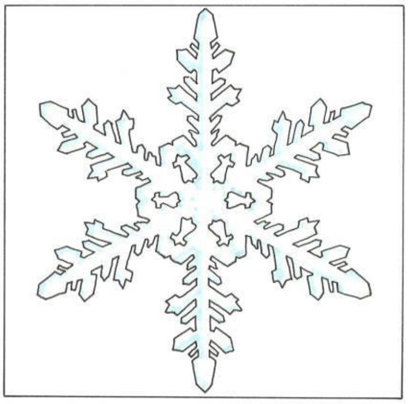


Figure 5.2: Fresh Precipitation Particles, 6-Armed crystals. Primary classification PP, dimension 2–5 mm

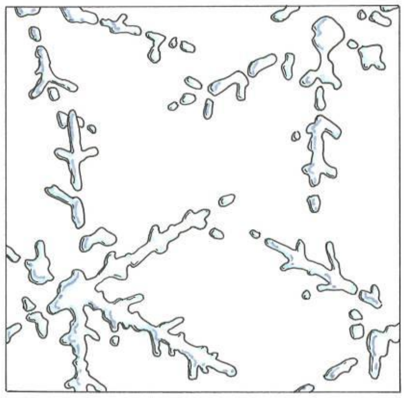


Figure 5.3: Decomposing and Fragmented precipitation particles Primary classification DF, dimension 1–3 mm

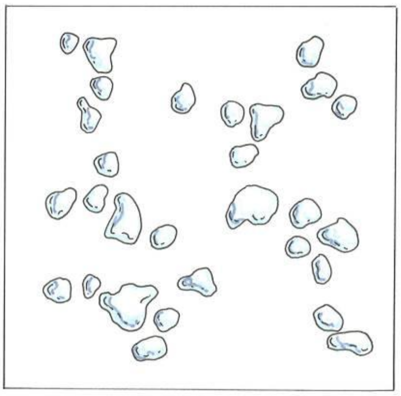


Figure 5.4: Rounded grains Primary classification RG, size 0.1–0.8 mm

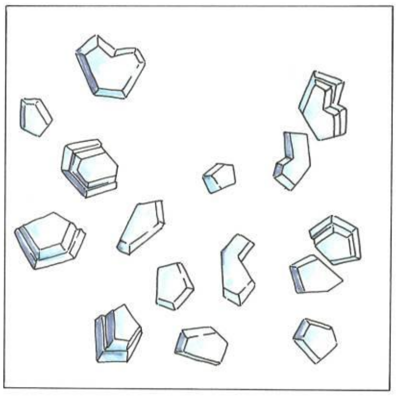


Figure 5.5: Faceted crystal snow

Even surfaces, stripes, lustrous crystals. Primary classification FC, dimension 1.5-4 mm

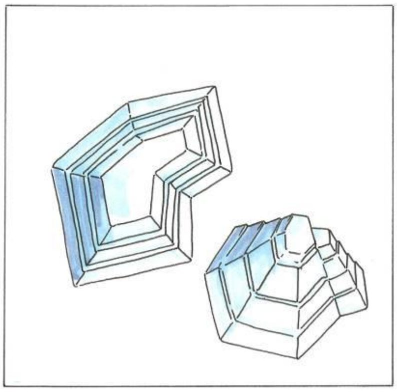


Figure 5.6: Depth Hoar

Primary classification DH, dimension 1–10 mm

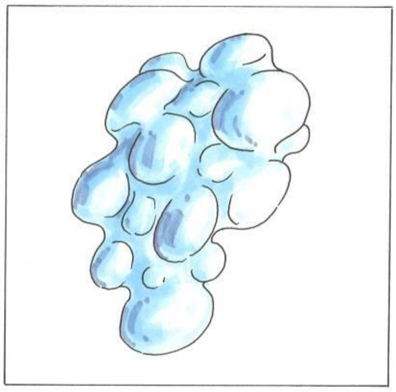


Figure 5.7: Melt forms Primary classification MF, clustered single crystals

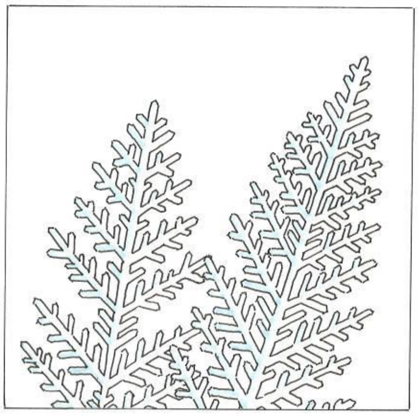


Figure 5.8: Surface hoar

Primary classification SH, dimension 2–100 mm

Digging snow profiles enables us to rapidly identify the differences between recent and older snow. The freshest snow is white in colour, while older snow takes on a greyish colour. This can help us to eliminate many of the primary classifications. The primary classifications PP, DF and RG have a much whiter colour than snow crystals which have undergone melting transformation or constructive transformation. The latter processes give the snow a glass-like or greyish colour.

5.2.3 Destructive transformation (destructive metamorphosis)

Mechanical decomposition

Mechanical decomposition is an external influence on the snow crystals which causes the original shape of the snow crystals to be shattered. Mechanical decomposition can start as soon as the snow settles on the ground. Wind in the atmosphere also contributes to decomposition.

During mechanical decomposition, precipitation particles are eroded and altered from their original shape, PP (Precipitation Particles) or DF (Decomposing and Fragmented), into small fine-grained crystals, RG (Rounded Grains). When this snow settles on the ground, slabs will form rapidly, as rounded grains bond together easily.

Snow which blows along the ground and is eroded is known as snowdrift. The snow crystals in snowdrift are relatively small, often measuring 0.1–0.3 mm. The stronger the wind, the smaller the RG crystals that are likely to be formed. Small RG crystals bond rapidly to form a slab, and the smallest crystals often form very hard slabs if the conditions are right for sintering (ice connections between the crystals).

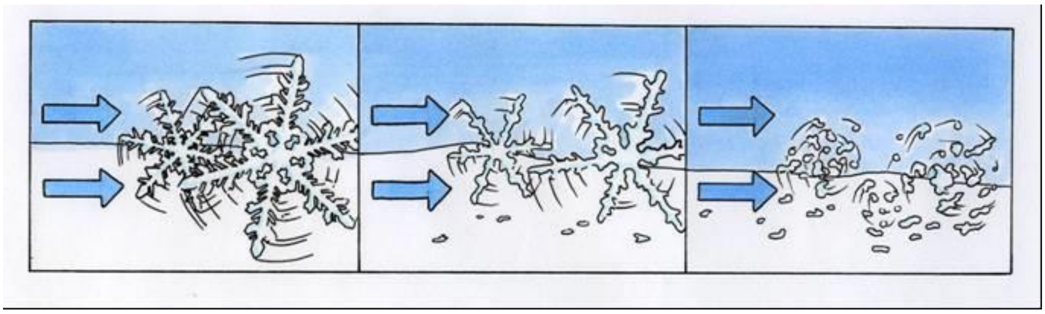


Figure 5.9: Mechanical decomposition of snow crystals
The shape of the snow crystals is altered through mechanical decomposition.

Vapour transport

During destructive transformation, the snow crystals in the snowpack are transformed into small round grains.

If the new snow crystals are not affected by the wind, but remain static, destructive transformation will also occur. This is because the new snow crystals will no longer be in equilibrium with their surroundings. The state of water vapour oversaturation which existed in the atmosphere is not present in the snowpack on the ground. The shape of the snow crystals will therefore start to undergo transformation. On the ground, the large new snow crystals will attempt to take on a balanced shape which combines the greatest possible volume with the smallest possible surface area. There is a higher vapour pressure between the molecules over convex areas compared with concave areas on the snow crystals. Because of the difference in vapour pressure, water vapour will migrate from convex to concave areas. In other words, ice from projecting areas will be converted into water vapour through *sublimation*, and settle as ice on the centred, concave areas of the snow crystal through *deposition*. *Sublimation* is a process where ice is transformed into water vapour, skipping liquid form as an intermediate stage. *Deposition* describes the opposite process, where water vapour settles as ice on the snow crystal. Sublimation is often used to describe both processes.

The destructive process will first destabilise the fresh, loose snow due to the decomposition of the crystal arms. Once the decomposition has progressed further, the bonds in the snow will in turn strengthen due to the process of sintering, which will be described later. Through destructive transformation, the shape of the ice crystals is altered into smaller, rounded shapes. When the crystals disappear, a compact snow crystal of the type RG is formed. The RG crystals will normally range from 0.2 to 0.8 mm in size. It is important to be aware that this process takes place without any melting, i.e. the temperature is below 0ºC. Destructive transformation occurs more rapidly, the closer the temperature is to 0ºC. Close to 0ºC, the process will only take a few hours, while at -20ºC, the process will take between a few days and several weeks. It will therefore take longer before the snow bonds and forms slabs after snowfall in cold weather than when the temperature is closer to 0ºC.

This form of destructive transformation is known as thermodynamic decomposition.

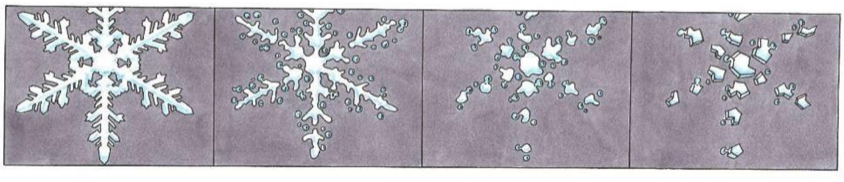


Figure 5.10: Destructive transformation
The snow crystals are gradually broken down into smaller particles.

The destructive transformation causes the snowpack to sinter and form a slab.

5.2.4 Sintering

When small, round snow crystals come into close contact with each other, they also fuse together through the creation of small ice bridge connections at the contact points. This process is known as sintering and is caused by water vapour moving towards lower pressure. This is the same as what happens through thermodynamic decomposition, where water vapour moves from higher saturation pressure over convex areas, to lower saturation pressure over concave areas. During the sintering process, the water vapour is deposited at the contact points between the snow crystals, where the water vapour condenses and ice bridges form. The transfer of molecules also occurs on the surface of snow crystals towards the contact points between the crystals. Both of these processes occur faster, the closer the temperature is to 0ºC. The smaller the crystals, the more ice connections are formed. This results in the snow sintering together to form a solid slab, which will tolerate relatively high tensile, compressive and shear loads.

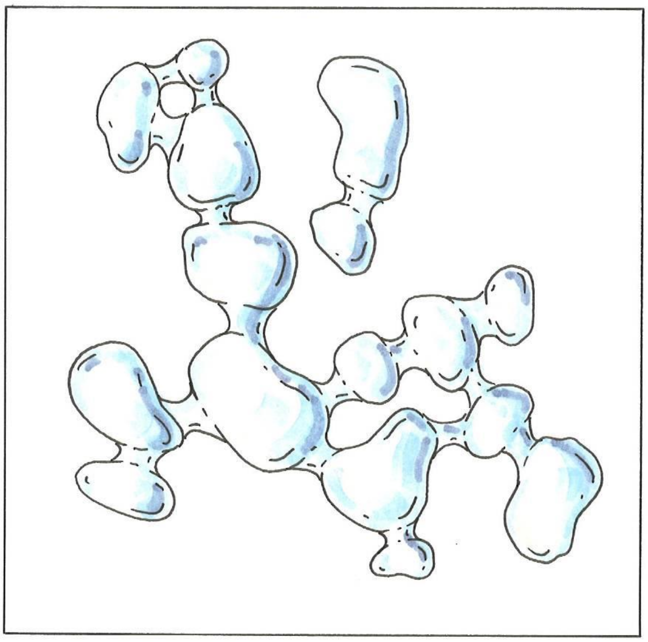


Figure 5.11: Sintering
The snow crystals fuse together at the contact points through the formation of ice bridges. The process stabilises the slope and leads to slab formation.

Sintering is of great significance to the snowpack; Before sintering commences, the snowpack has minimal strength, particularly in calm weather. When sintering develops ice bridges, the strength of the snow increases, i.e. it requires a greater force to displace the crystals in relation to each other. This has two contradictory consequences in relation to avalanche risk: The snow becomes more compact and capable of tolerating greater loads before an avalanche occurs. However, when the snow becomes more compact, coherent slabs form which can transfer forces and spread a fracture over a larger area. If there are weak layers in the snowpack, the overlying slab can contribute to the propagation of a fracture across the entire slope, from so-called 'super weak points'. Such release points may occur where the snowpack transitions from thick to thin, or around prominent rocks, ridges or bushes where there may be weaknesses following the formation of large crystals from constructive transformation (see the next section).

Snow containing RG crystals and well-developed sintering in coastal areas can have a density of up to 500 kg/m³, but will usually be around 300 kg/m³. Layers of sintered RG crystals will be white in colour, but can develop a lustrous, sparkling reflection as the snow ages.

The sintering process bonds the snow crystals together and causes the snow to form slabs.

5.2.5 Constructive transformation (constructive metamorphosis)

Constructive transformation creates persistent weak layers of faceted crystal snow and depth hoar. According to research conducted in Switzerland, these snow layers account for around 35% of all avalanche accidents.

The temperature difference between the snow surface and the ground causes excess water vapour on the ground to move upwards into the snowpack. Water vapour moves from warmer areas with high vapour pressure to colder areas with lower vapour pressure. When this water vapour reaches snow layers with lower temperatures, it condenses on the surfaces of the snow crystals, causing the snow crystals to grow and change shape. Water vapour molecules also move from snow crystal to snow crystal upwards within the snowpack and condense. The conditions for constructive transformation are more favourable when the snow is looser and the temperature change in the snow is greater. The temperature difference in the snow is described as the 'temperature gradient'. This must be greater than 1ºC per 10 cm or 10ºC per metre in order for constructive transformation to occur.

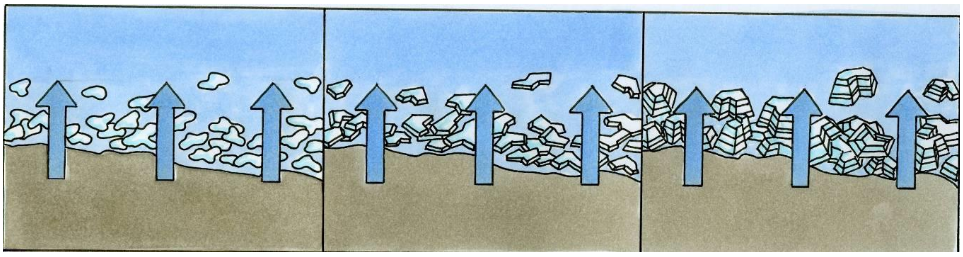


Figure 5.12: Constructive transformation

The crystals gradually increase in size, becoming faceted crystals, and eventually depth hoar.

! A thin snowpack and prolonged cold weather result in rapid constructive transformation and the development of persistent weak layers.

The snow crystals develop into larger snow crystals, with even surfaces and sharp edges. The snow crystals become coarse-grained, lustrous and faceted with a dimension of 2–3 mm or larger. The contact surface between the snow crystals diminishes. The snow crystals grow in size, and the strength of the layer decreases, as there are fewer ice bridges and more air between the ice crystals. There are also fewer crystals sharing any loads, making the layer less stable than before. The shape is described as faceted crystal snow and belongs to the primary classification FC (Faceted Crystals, also known as facets). It should be noted that RG crystals and MF crystals (Melt Forms) can undergo constructive transformation for as long as the temperature gradient is sufficiently large (>1°C per 10 cm snow). Crystals in the initial phase of constructive transformation are often encountered. As regards classification, FC must then be selected to indicate that the process has begun and that the process is expected to continue. It is important to identify this process, and even small faceted crystals can form unstable weak layers.

When conditions permit a high temperature gradient, faceted crystals will develop further. Their surfaces will gain stripes, the crystals will become hollow and the walls will form 120° angles to each other. Once the snow crystals have become hollow, they are known as depth hoar, which is given the primary classification DH (Depth Hoar). These crystals can grow up to 10 mm in size according to the literature, although it is possible to find larger depth hoar crystals. Depth hoar crystals are stacked on top of each other with the opening facing downwards, and the instability of the layer can be compared to a house of cards. During prolonged cold spells, particularly when the snowpack is thin, thick layers of depth hoar can form in the snow.

Layers of faceted crystals and depth hoar are weak and unstable. If there is an overlying slab which is sufficiently strong to transfer forces and disperse a fracture, layers with faceted crystals and depth hoar can cause an avalanche to be triggered remotely. Remote triggering occurs when a fracture occurs in the snowpack, resulting in subsequent collapse which spreads across a slope which is steep enough for a slab to slide out. Remotely triggered avalanches can often be traced back to long cracks, often called 'shooting cracks', which reveal how the collapse has spread.

Faceted crystal snow and depth hoar can also develop as thinner layers just a few millimetres thick higher up in the snowpack. This occurs where there is an ice or snow crust layer buried in the snowpack which acts as a vapour barrier. When the temperature gradient is sufficient, constructive transformation will occur rapidly beneath the snow crust. If the snow crust is sufficiently thick, it can act as a protective layer in the snowpack. As winter progresses, this process will eat away at the snow crust layer, and the layer of faceted crystal snow will become more unstable. The load imposed on the snowpack as a result of the accumulation of more snow may eventually become so great that the snow crust layer fails.

Studies have shown that the growth of snow crystals during constructive transformation depends on the density of the snow in the layer in which the process is taking place. In the case of high-density snow, there have been observations of snow crystals becoming faceted without any marked increase in size. With lower densities, there is more scope for the crystals to increase in size.

The impact of the faceted crystal layer on stability will largely depend on the thickness of the overlying snow crust layer. If the snow crust is sufficiently thick, the crust will help to stabilise the layering by preventing loads from reaching down into the weak layer (Habermann et al.).

The growth of facets over snow crusts requires a more detailed explanation. Facets over snow crusts pose a greater danger than those beneath snow crusts (Jamieson). Laboratory studies of snow-covered snow crust layers have shown that deposition beneath the snow crust and sublimation above the snow crust are the main causes of facet formation. Local temperature gradients measured over very short distances can be several tens of times greater than is measurable using a thermometer in the field, and thereby represent a greater driving force than we are able to register (Hammonds et al.).

Snow crusts and facets over a snow crust layer can also be formed simultaneously when wet snow is covered by dry snow. Rapid freezing of the wet surface occurs, giving rise to the formation of a snow crust. During the freezing process, latent heat is given off, which can give rise to a sufficient temperature gradient for facets to form above the newly formed snow crust layer (Colbeck and Jamieson). The wet, snow-covered layer represents a moisture source which, when combined with high temperatures, contributes to a high growth rate. During freezing of the moist snow, latent heat is continually given off, which in turn helps to maintain a high temperature gradient.

Near surface facets

Near surface facets is the formation of faceted crystals in the upper part of the snowpack.

Substantial variations in incoming thermal radiation during the daytime and negative outgoing radiation during cold nights can lead to the formation of strong, fluctuating temperature gradients which help to provide the right conditions for constructive transformation.

During cold, clear nights, a high temperature gradient occurs due to high levels of long-wave radiation from the surface of the snow. During the day, the snow will warm up, but it is still cold down inside the snowpack. A negative temperature gradient develops, water vapour transport reverses, and further constructive metamorphosis of the snow crystals occurs (Birkeland 1998, Tønnesen 2013). Low-density snow provides the best substrate for this kinetic growth, which is called 'diurnal recrystallization'. The term 'diurnal' refers to the daily temperature variation between low temperatures at night and higher temperatures during the day.

The result of diurnal recrystallisation is facets close to the surface without any overlying snow crust. The growth of facets of 1 mm has been observed over the course of 36 hours as a result of this process. The process is limited to the upper 15 cm of the snowpack (Birkeland et al.). Facets close to the surface are known as 'near surface facets' and only become a problem once they have been covered by further layers of snow.

A snow crust near the surface can increase the effect of temperature variations between night and day and the fluctuating temperature gradient. Depending on the direction of water vapour transport, either sublimation or deposition will occur on the upper and lower sides of the snow crust, with associated faceting. Sublimation can create more pore space, facilitating the faceting process (Greene 2006, Greene et al. 2007, Tønnesen 2013).

Near surface facets can also be formed by two other processes: *radiation recrystallization* and *melt-layer recrystallization*. Radiation recrystallization occurs in the uppermost centimetres of the snowpack and is caused by strong incoming solar radiation (short-wave), which is absorbed just below the surface. The temperature of the snow rises, and a melt layer can develop. The surface also loses energy through long-wave radiation and becomes colder. This can create a strong temperature gradient at the surface and cause the rapid faceting of snow crystals. Strong incoming solar radiation will melt this weak layer, causing it to disappear. The process is most common on south-facing slopes, at lower latitudes and high up in mountainous areas.

Melt-layer recrystallization occurs with the aid of incoming solar radiation or rain, which creates a layer of wet melt crystals. Colder, new snow falls on the wet snow, and a strong temperature gradient develops between the wet snow, which is at a temperature of 0°C, and the colder, overlying snow. The thinner the layer of fresh snow and the lower the density of the fresh snow, the stronger the temperature gradient will be. The wet snow gradually freezes to form a crust with near surface facets on the upper side. The process will be reinforced if it is caused by a downpour or cold clear weather on the following night or a combination of these factors.

Stability evaluation

Studies of unstable and stable slopes show that the thickest layers with facets or depth hoar do not necessarily result in the worst stability. The studies assume that slopes with skier-triggered avalanches are unstable. The findings of one study indicate that persistent weak layers less than 10 cm thick pose a greater danger than layers which are more than 10 cm thick (McCammon I and Schweizer J, 2002). Another study showed that the correlation between the thickness of the weak layer and stability/instability is equal (Jamieson and Schweizer, 2002). The thickness of the weak layer is therefore as well-represented on stable slopes as it is on unstable slopes. These studies show how difficult it is to establish absolute tolerance limits based on observations of weak layers in the snowpack.

> ! Danger signs: Rumbling in the snow is primarily caused by persistent weak layers collapsing. The rumbling noise is caused by air being forced out of the layer as it collapses.

5.2.6 Other types of crystals

Surface hoar

After one or more nights of cold, clear weather, surface hoar will form – Primary classification SH (Surface Hoar). Surface hoar resembles feathers growing on top of the snowpack. Its dimensions usually vary from a few millimetres up to 50 mm. Under favourable conditions, surface hoar can measure up to 100 mm. Surface hoar forms because on clear nights the snow surface will be colder than air, as there are no clouds to reflect radiation back to earth. This phenomenon is called ‘negative radiation balance’ or ‘negative radiation’, and is a result of long-wave radiation (infra-red radiation) not being reflected back to earth, but disappearing out into space. This causes the snow surface to emit energy, cool and become colder than the overlying air layer. In such cases, the temperature of the snow surface can be 10°C colder than the air temperature. When the warmer air comes into contact with the cold snow surface, moisture in the air condenses, forming surface hoar.

This surface hoar is extremely slippery; however, it poses no threat until it is buried by other snow. The surface hoar layer is often destroyed by wind, melted by the sun or higher temperatures. If a surface hoar layer is buried without being destroyed, the crystals will often lie flat, turning into a thin layer. The layer can be well below 1 mm in thickness. It can form a dangerous sliding layer which is difficult to see with the naked eye and is defined as a persistent sliding layer.

In a small number of cases, as a result of new snow not being compacted or because the surface hoar crystals are not blown over, the surface hoar layer may remain in the snowpack and contain a lot of air. Hoar layers such as these can cause rumbling in the snow and the remote triggering of avalanches.

When influenced by the wind, surface hoar can accumulate in pockets in depressions in the terrain. Surface hoar crystals can then be difficult to identify, as they only exist across limited areas, but the accumulation of surface hoar crystals in pockets can result in the triggering of avalanches on individual slopes. Consequently, it is difficult to monitor the formation of surface hoar, the development of surface hoar layers and the impact of the weather, in order to make any conclusions regarding the existence and distribution of the layer.

Surface hoar layers are not a particularly stable form of snow crystal. Surface hoar crystals are easily destroyed. The briefest exposure to sun or temperature rise can destroy the crystals, and wind has a tendency to shatter the crystals.

Graupel

During the winter, especially in coastal climates, layers of graupel may occur. Closer examination will reveal that it is whiter in colour than regular lustrous ‘summer hail’. Graupel is a form of new snow with the primary classification type PP, but in subclass gp, i.e. graupel is described as PPgp. Graupel can vary in size, from approx. 1–12 mm. The layers will usually be relatively thin, but thick layers of graupel can also occur if the wind causes the grains to accumulate in smaller hollows and depressions in the terrain. Graupel can behave like pellet layers, creating very localised and unstable conditions where little or no extra load is required to trigger an avalanche. Graupel often occurs during showery precipitation and can fall intensively for shorter periods of time. Graupel is often found mixed in a layer of new snow. Graupel which is well mixed with new snow crystals poses less of a danger than layers which consist entirely of graupel. Graupel is the subject of varying attention in the literature. This is likely because the phenomenon is linked to coastal areas and therefore does not occur frequently in all areas where avalanches are relevant. As Norway has a long coastline, and strong onshore winds can carry graupel reasonably long distances inland, it is not possible to exclude graupel as a component in an avalanche problem.

5.2.7 Melting transformation (melting metamorphosis)

When snow has warmed up to 0°C, it will start to melt. Snow crystals which are affected by melting belong to the primary classification MF (Melt Forms).

The onset of melting transformation is characterised by the snow becoming ‘sticky’. The snow crystals fuse together because of the presence of a thin layer of water which surrounds them. Further melting will result in the snow pores gradually filling with water. When the moisture content exceeds 8%, the water may be forced out of the snow, and when it reaches 15%, the water will drain out of the snow without any external influence (Lied and Kristensen, 2003, p. 55). When snow particles melt, the strength of the snow will also diminish because the bonds between the snow crystals weaken and eventually disappear altogether. In spring, this is often described as ‘rotten snow’. When the water eventually drains away, the snow will become more compact again.

When the snow becomes wet or starts to melt, the avalanche risk will increase due to increasing snow creep and diminishing surface friction. After a period of time, the avalanche risk will decrease as the snow settles and the snow crystals fuse together because of the capillary forces in the water membrane around the snow crystals. If the snow becomes soaked and saturated with water, the stability of the snowpack will be further reduced and the risk of slush avalanches will increase, particularly if there has been heavy rain and significant snow melt.

If it becomes cold and the moist snow freezes, the avalanche risk will diminish, and the snowpack will stabilise. If the entire snowpack becomes damp and freezes again, the snowpack will return to being stable.

6 Weather that increases avalanche risk

6.1 General

Typical weather conditions which increase avalanche risk are precipitation falling as snow combined with wind, and strong winds following a snowfall. It is the intensity of snow accumulation on leeward slopes that is the most critical factor in respect of increases in avalanche risk. Temperature rises also play an important role in increasing avalanche risk. In summary, the three most important weather factors which impact on avalanche risk are as follows:

- Precipitation (intensity)
- Wind
- Temperature rise

6.2 Snowfall and wind

In Norway, the heaviest precipitation usually occurs when large low pressure systems move in across the country from the sea in the west. These are often followed by showery weather that can cause heavy precipitation to fall along the coast and in the mountains to the west of the watershed. In Eastern Norway, it is the Langfjellene mountains of southern Norway which block weather systems coming in from the southeast and east, and cause precipitation to fall in this region.

Air which is forced to ascend over terrain formations will produce precipitation if it contains sufficient moisture. The content of water vapour in the air is temperature-dependent, and warm air is able to hold more moisture than cold air.

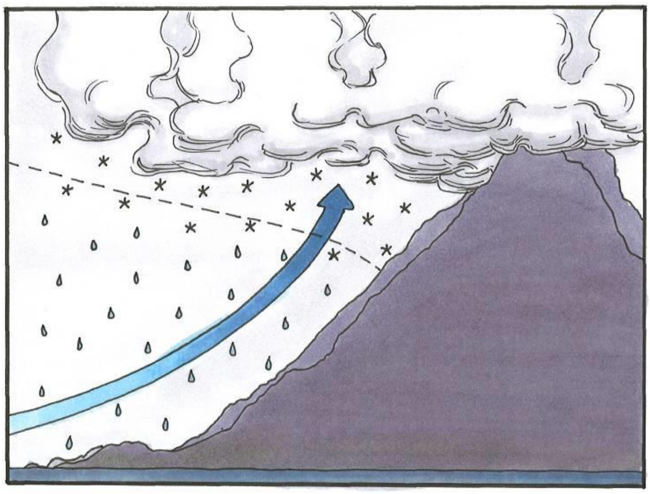


Figure 6.1: Low pressure meets a coastal mountain range; snow in higher areas

When low pressure from the sea moves in across a coastal mountain range, the air is forced upwards. In the case of air which is near-saturated with water vapour, the air temperature will drop by 0.6°C per 100 m of elevation. With dry air, the temperature will decrease by up to 1°C per 100 m

of elevation. When the air is cooled, it becomes oversaturated with water vapour, resulting in the formation of clouds and precipitation (orographic precipitation). As a result of this, large quantities of precipitation fall west of the watershed near the coast. If the temperature is sufficiently low at ground level, the precipitation will fall as snow.
Once the air has crossed the mountains, it will descend again and its temperature will rise. The air temperature rises because of increasing pressure and density. As the air has released moisture on the windward side, it will be drier and warmer when it descends again on the leeward side. Less precipitation will fall on the leeward side than on the other side, giving rise to the term 'rain shadow'.

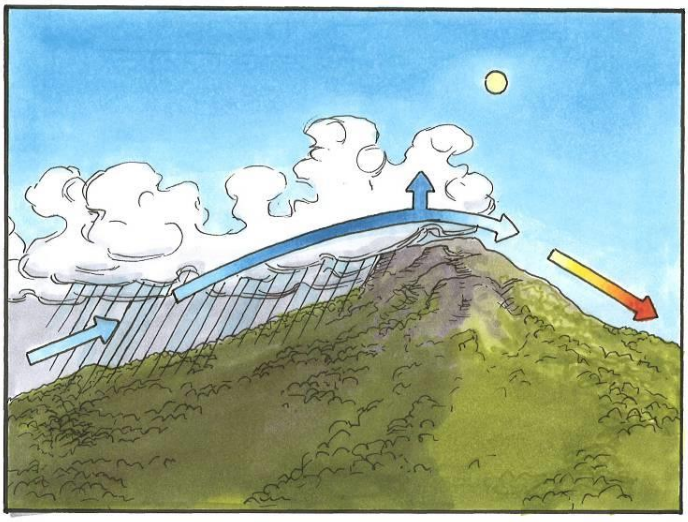


Figure 6.2: Rain shadow
The windward side receives precipitation; the leeward side little or no precipitation.

It is difficult to provide general guidelines in respect of the wind strengths and precipitation levels that would be necessary to increase the avalanche risk. Stability and avalanche probability are linked not only to additional loading and temperature, but also to layering and the properties of the layers. The terrain gradient is also of significance.
It is the amount of new snow that is of greatest significance to the development of stability. The amount of new snow measured in millimetres has been shown to correspond closely to avalanche probability. Lied and Kristensen (2003, p. 95) found that 10 mm of precipitation over the course of three days leads to a 5 percent increase in avalanche probability, while 90 mm of precipitation will almost certainly result in the triggering of an avalanche. As 1 mm of precipitation produces approximately 1 cm of new snow, 90 mm of precipitation will produce 90 cm of snow and a high avalanche risk.
The relationship between the depth of new snow and the likelihood of a naturally triggered avalanche is shown schematically in the table below.

Increase in snow over 3 days	Probability of naturally triggered avalanches, and avalanche type
Up to 10 cm	Rare, very localised snow movement (primarily loose snow avalanches)
10–30 cm	Some local slab avalanches. Frequent loose snow avalanches
30–50 cm	Frequent local slab avalanches, primarily on steep mountainsides
50–80 cm	Widespread slab avalanches, also in less steep terrain. General risk above tree line. Some larger avalanches into the valley bottom

80–120 cm	Frequent major avalanches into the valley bottom. Also occasionally outside of known avalanche paths
Over 120 cm	Possibility of rare and, up to now, unknown avalanches, both in new locations and also beyond old avalanche paths and risk maps (Zone 2)

Table 6.1: Thickness of new snow fall and the probability of naturally triggered avalanches
The table applies with wind speeds up to 5 m/s. With stronger and more persistent winds, the risk may increase by one or two levels.

Snow is often referred to as *the avalanche's building material* and wind as *the avalanche's builder*. The wind transports the snow, accumulates it and distributes it on leeward slopes. At temperatures below 0°C with a relatively soft snow surface, snow transport will commence at wind speeds of 5 m/s, and even at 10 m/s there will be a strong ground storm, known as snowdrift.
Generally, when the wind speed doubles (2), its potential to transport snow increases to the third power (2^3) (Lied and Kristensen 2003, p. 97). This means that the amount of snow accumulated per hour on the mountainside must be multiplied by 8 (or 2^3) when the wind speed doubles. With 10 cm accumulation of snow per hour on a leeward slope and a wind speed of 5 m/s, a doubling of the wind strength would lead to 80 cm (10 cm x 2^3) accumulation of snow on leeward slopes per hour. A trebling (3) of the wind strength to 15 m/s could lead to the accumulation of snow on leeward slopes of 270 cm per hour (10 cm x 3^3). At wind speeds of around gale to strong gale force (20–25 m/s), the wind can transport large amounts of snow, and several metres may accumulate on leeward sides in the course of a few hours. The amount of loose snow that is accessible for wind transport will also determine how much snow is transported. However, it should be noted that at wind speeds of 14–16 m/s, strong snow crust layers will be torn up and hard-packed snow will begin to move.

! A rule of thumb is that avalanche risk will increase in strong winds in the mountains over several hours if snow is available for wind transport.

Weather forecasts at yr.no give mean lowland wind speeds. Experience suggests that, for exposed areas above the tree line, the forecast wind speed can often be doubled. Another challenging factor to be taken into account is that measurements are not available from a sufficient number of weather stations in Norway. This means that evaluations of measured and forecast temperature, precipitation and wind speed in mountainous regions are uncertain.
Precipitation is usually measured in mm and indicates how much water is produced when snow has melted. 1 mm of rain is approximately 1 cm of snow (density: 1 m^3 = 100 kg). Accumulated snow is most easily measured by placing a board measuring 1x1 metre on the ground at a location not affected by wind. The amount of precipitation is then measured on the board daily.
Without any wind, the intensity of precipitation must be 2–2.5 mm per hour or more in order for the probability of an avalanche to be affected to any great extent. This is because the load on the snowpack increases faster than the strength of the snowpack increases. It must be noted that substantial local variations will occur in precipitation quantities and intensities during showery weather, which also produces the highest precipitation intensity.
Providing no persistent weak layers are present, the risk of naturally triggered avalanches after snowfall and wind will diminish, but the risk of avalanches triggered by human activity will remain.

! Following snowfall and wind, the risk of naturally triggered avalanches will diminish quite rapidly, provided no persistent weak layers are present. **However, the risk of avalanches triggered by human activity will remain.**

6.3 Rain

It is not only snowy weather that can act as the source of avalanches. Rain on top of snow increases the load on the snow, and the higher temperatures also gradually weaken the bonds between the snow crystals and reduce the friction both between the layers and against the ground. It is on the first occasion that the snowpack becomes saturated that an immediate increase in avalanche risk occurs. Rain will also cause an increase in the weight and load on the snowpack. The temperature will also rise during wet weather, which will generally increase the rate of snow creep and weaken the bonds in the snowpack.

In the absence of a simultaneous sharp rise in temperature, more than 5–10 mm of rain per 24-hour period must fall in order to significantly increase the avalanche risk. Rain on the snowpack will initially be absorbed by the surface. Further rainfall will then filter down through the layers. The water can be prevented from draining vertically through the snowpack by layers of ice or impermeable snow crust. Layers of small RG crystals form capillary barriers, absorb the water and prevent it from draining further down into the snowpack. This reduces the strength of the RG layer. The stresses in the snowpack also increase due to the accumulation of water and an increase in snow creep. This diminishes the strength of the snowpack.

Once the snowpack is saturated, the stability will increase again. The bonds between snow crystals in wet snow deteriorate, but the water membrane around the snow crystals fuses them together, increasing stability. The consistency of snow is a significant factor, and rain on new snow more readily results in an avalanche than rain on an old snow surface.

Heavy precipitation in the form of rain can lead to slush avalanches. A risk of slush avalanches arises when the snowpack is oversaturated with water. The accumulation of water is often apparent as a change in the colour of the snowpack, with the snow becoming blue or grey in colour. In such cases, it is important to keep away from depressions in the terrain and channels where the slush could flow downhill, even on gentle slopes. Dealing with the problem of slush avalanches is a matter of *timing*, with the additional load caused by a skier being of little significance as regards the triggering of avalanches. In such cases, oversaturation of water in the snow will be the triggering factor.

6.4 Snowpack temperature

The temperature is a significant factor in determining the stability of the snowpack. At low temperatures, destruction transformation of the new snow crystals and sintering will occur slowly. Prolonged spells of cold weather are also of significance as regards the constructive transformation of snow crystals. Low snow surface temperature combined with a relatively thin snowpack (high temperature gradient) will cause the transformation of snow crystals into faceted crystal snow or depth hoar crystals. A prolonged cold spell with a thin snow layer, followed by new snow and wind transport, will often result in extremely unstable conditions that may persist throughout the winter. Persistent weak layers must normally undergo melting transformation in order to disappear from the snowpack.

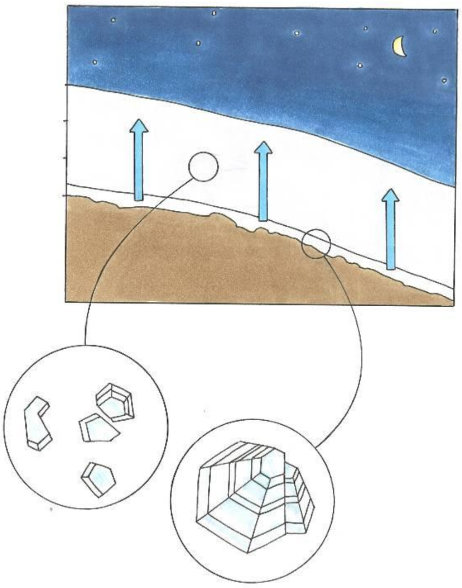


Figure 6.3: Constructive transformation during spells of cold weather and a thin snowpack
Water vapour rises through the snow and condenses on snow crystals that it encounters.

It is also known that variations between day and night temperatures can lead to diurnal recrystallisation, which is the faceting of snow crystals close to the surface. This process leaves behind facets, which form a weak layer when buried (see near surface facets).
When the temperature rises, the sintering process will accelerate, but when the temperature of the snowpack approaches 0°, the snow will become sticky and damp, and the ice bridges between the snow grains will diminish in strength and eventually disappear altogether. Settlement in the snowpack will also occur more rapidly. Snow creep will increase as a result of weakening of the bonds between the snow crystals and increased settlement in the snowpack. This reduces the stability of the snowpack. If the snowpack is exposed to low temperatures, ice bridges will form and the snowpack will stabilise.

6.5 Solar heating

As spring progresses, the sun will increasingly gain more of a hold and radiation will heat the snowpack. The amount of solar energy that accumulates on the snow surface depends on the nature of the snow and the angle of the snowpack relative to the sun. The closer to 90° that the solar radiation hits the snowpack, the stronger the effect of solar heating will be. New snow which has not been contaminated will reflect up to 90 percent of incoming solar radiation. Older snow will reflect significantly less radiation, causing it to heat up more rapidly and become moist. The moisture will seep down into the snowpack, and stable bonds will be dissolved. This can occur even if the air temperature is below 0°C. Thus, strong solar radiation during the spring heightens the avalanche risk. If it becomes so cold during the night that the entire snowpack freezes, the snowpack will stabilise. During the early part of the winter, when sunlight does not emit as much energy, solar heating will usually have little effect on the snowpack.

6.6 Convection – air humidity and wind

As air moves across the surface of the snow, either heat or cold is applied through convection. Warm air which is applied to the snow surface can cause extensive snow melt. The air humidity is an important factor as regards snow melting. Water vapour in the air condenses to form water droplets as the snow cools the air. This results in the release of a lot of heat, which in turn accelerates the snow melting. With a wind strength of 5 m/s and an air temperature of 5°C, as much snow melts as with a wind speed of 12 m/s and a temperature of 2°C, assuming the relative air humidity is 100 percent. This occurs as a result of the increasing ability of the air to retain moisture at higher temperatures.

During mild weather when snow melt is expected to take place, moist winds will significantly increase the snow melt, thereby further reducing the stability of the snowpack.

6.7 Weather forecasts and meteograms

6.7.1 Weather forecasts

The weather is a major factor in determining the accumulation of the snowpack and changes in avalanche risk. When evaluating changes in snowpack stability, certain factors are more important than others. The most common factors to consider are temperature, precipitation and wind. It must be stressed that the structure and layering of the snowpack will always be the decisive criteria as regards whether stability will be affected by external factors.

Low temperatures can give rise to constructive transformation, but this process takes place over time and is not as critical for the impending day. With regard to low temperatures, it is more important to consider the historical weather patterns in an area in order to determine whether the snowpack has been exposed to low temperatures over time. Yr.no enables the weather situation to be viewed retrospectively as regards temperature, wind and precipitation (see *været som var* at yr.no).

A more time-critical factor linked to temperature is rapid temperature rises. If the temperature rises to well above 0°C in the release area over the course of a few hours, this will affect the stability of the snowpack. Snow creep will accelerate and tensile forces will increase. It can be difficult to assess the impact of temperature on avalanche risk. The anticipated effect is often exaggerated, resulting in less avalanche activity than expected being observed. It is difficult to predict the elevation at which mild weather will affect the terrain and the depth in the snowpack that the rise in temperature will reach. The structure and layering of the snowpack are also decisive as regards the effect of the temperature rise. There is no definitive answer to this question. It is therefore important to build up experience of temperature fluctuations and to monitor the effects of these fluctuations in order to reduce the level of uncertainty. A sound knowledge of local weather situations and their effects is an important additional skill in understanding local developments in avalanche risk.

Cold weather leads to the slow stabilisation of fresh snow, while temperatures up to 0°C accelerate the stabilisation process.

Another important factor for avalanche risk warnings is precipitation. The amounts of precipitation, in the form of either rain or snow, which impact on avalanche risk, have been described previously (see Weather that increases avalanche risk). When evaluating avalanche risk, it is necessary to consider whether the additional load and possible weakening of bonds in the snow that may be caused by the forecast precipitation would significantly affect the stability of the snowpack. Different layering structures will react to precipitation in different ways, so it is also difficult to determine the expected consequences of forecast precipitation in this case. Normally, heavy precipitation will always increase the avalanche risk through the increase in additional load that it causes. A layer of new snow may be unstable in itself, in addition to constituting an additional load. Precipitation falling as rain can diminish the bonds in the snowpack, as well as forming an additional load. If an additional load or weakening of bonds in the snowpack is expected to increase the avalanche risk as a result of forecast weather, this will be reflected in the avalanche forecast through an increase in the degree of risk.

Forecast wind strengths, particularly if strong winds are forecast, must be evaluated in relation to their impact on avalanche risk. Remember that double the expected wind strength can often be expected in mountainous areas compared with the forecast wind strength. To evaluate the impact of the wind, it is necessary to consider the forecast precipitation and the amount and distribution of snow in the terrain which is available for transport. The evaluation must consider whether it is likely that sufficiently large quantities of snow can be transported to leeward slopes in order to increase the avalanche risk. It is necessary to know the existing layering in order to deduce what additional load the snowpack will tolerate. Strong winds will usually increase the avalanche risk, but this will of course be dependent on there being sufficient snow available for transport.

One difficult aspect of the task of avalanche forecasting is reducing the hazard level. Persistent weak layers normally only stabilise through avalanche activity or a melting process. Weak layers which are not persistent stabilise over time, and the rate at which they stabilise will depend on a number of factors, including temperature. Ongoing investigations of the snowpack help to determine whether or not the snowpack is stabilising.

6.7.2 Meteograms

Many weather forecasting services are available, one of the most popular being www.yr.no, for which the Norwegian Meteorological Institute provides the meteorological data. It is also possible to download meteograms from this website. The Norwegian Meteorological Institute also provides custom weather services to the Norwegian Armed Forces through the HALO service. Information from the weather forecasts can be downloaded from https://halo.met.no. Personal user names and passwords are issued for the service. To access this service, it is necessary to contact the METOC coordinator at the Norwegian Military Geographic Service (FMGT). FMGT will need the user's full name, position, e-mail address for an unclassified e-mail and telephone number in order to grant access to HALO. The e-mail address will be used as a user name.

The Java meteograms contain a number of parameters:

a) Temperature
b) Precipitation
c) Wind symbol
d) Wind speed and direction
e) Weather symbol
f) Air pressure
g) Cloud cover
h) Dew point temperature

Below the meteogram, it is possible to select the parameters that are to be displayed. Note that meteograms are produced automatically using data models. The text forecast is prepared by a meteorologist. Meteograms can therefore differ from the text forecast. The text forecast for the area concerned should therefore always be checked.

The Norwegian Meteorological Institute also provides detailed weather forecasts for areas for which avalanche forecasts are issued at varsom.no. This weather forecast can be found linked to the avalanche forecast for the various regions. The forecast mountain weather takes account of local effects which occur in the mountains.

7 Snow profile and stability tests

7.1 Snow profile

7.1.1 Introduction

A snow profile consists of a cross-section of the snowpack which should normally be excavated down to the ground through the entire snowpack. The purpose of a snow profile is to study the layering in the snow. If one is not familiar with the snowpack in an area, it is important to excavate the profile all the way down to the ground. The characteristics of slabs and weak layers will be of particular interest, and observations must be documented during the excavation. Stability tests are used to obtain an indication of the additional load that the snowpack will tolerate, the layers in which fractures will occur and whether the snowpack has the characteristics that will be required in order to bring about fracture propagation. The documented snow profile provides a written or graphical presentation of the findings in the snow profile. A completed snow profile can either be drawn by hand or prepared electronically using a suitable application.

7.1.2 Location

Stability tests should be performed in locations that are as representative as possible of the areas in which we wish to assess the avalanche risk. This also involves choosing the right exposure and height above sea level.

A snow profile should be carried out above the tree line, as the snow here is particularly affected by wind transport and slab formation. Snow profiles can also be carried out below the tree line; however, the challenge below the tree line can lie in finding areas where slab development is sufficiently advanced for there to be a risk of a slab avalanche being triggered. Loose, unbonded snow is often found below the tree line, with the exception of certain exposed areas where the wind has affected the snow.

Stability tests have clear limitations, as there are substantial local variations in the accumulation of the snowpack. A few metres away, the profile may be very different, and the tests may give completely different answers. It is therefore important to carry out a number of stability tests with similar exposures in order to look at variations. Several stability tests can also be carried out adjacent to each other in the same snow profile in order to compare results.

The choice of location should always be based on the general rule that it is safe for the individual(s) performing the tests. This includes an evaluation of the size of the slope, the consequences of an avalanche being triggered, terrain traps, and the scope for rescue if necessary. The slopes being tested should be 5 to 10 metres high and be representative of the area. Even if certain tests have been documented as being reliable in low angle terrain, profiles in terrain with slopes of up to 30° should be excavated wherever possible. In the event of any uncertainty concerning the prevailing conditions or if it proves difficult to find low, safe slopes of 30°, profiles and tests can be carried out in more gently sloping terrain. It is important to be aware that the outcome of tests can be less clear in gently sloping terrain than in steep terrain.

As a general rule, one should not enter slopes from below. If there are persistent weak layers in the snowpack, or if rumbling and shooting cracks have been observed in the snowpack, it will normally be necessary to find terrain gentler than 30° in order to reduce the risk of being caught by an avalanche.

7.1.3 Design

A snow profile is produced by digging a pit around 220 cm wide across the fall line of the slope, as shown in Figures 7.5 and 7.6. When investigating an unfamiliar snowpack, it is necessary to dig right down to the ground. This will ensure that any weak layers close to the ground are detected. Once the snowpack is known in more detail and no weak layers have been identified at the base of the snowpack, it will be sufficient to dig down to the older stable snow through the upper layers. It will be most appropriate to find locations where the snowpack is not too thick and the snow profile is no more than around 1.5 m deep. This will save time and make the tests easier to perform. It will also enable the snowpack to be tested to a greater extent at depths where the weight of a person can be expected to affect it.

7.1.4 Layering and hardness

Layering in the snow must be documented, the type and size of the crystals in each layer determined, and the hardness of the respective layers measured using a simple hardness test.

The force that is used in the hardness test is about the same as pressing the tip of your nose until it feels unpleasant, or around 1.5 kg / 15 N force.

The test is started by pressing a clenched fist with the knuckles first into the snow, and then four straight fingers, one straight finger, the blunt end of a pencil and finally a knife. If it is pure ice, this is recorded as *hardness ice*. The purpose of the test is to determine the respective hardnesses of the various layers. Hard layers form slabs, while loose layers can form weak layers. Ice or snow crusts can provide the right conditions for faceting on the upper or lower side. The transition between hard and loose layers is an interesting topic for further study.

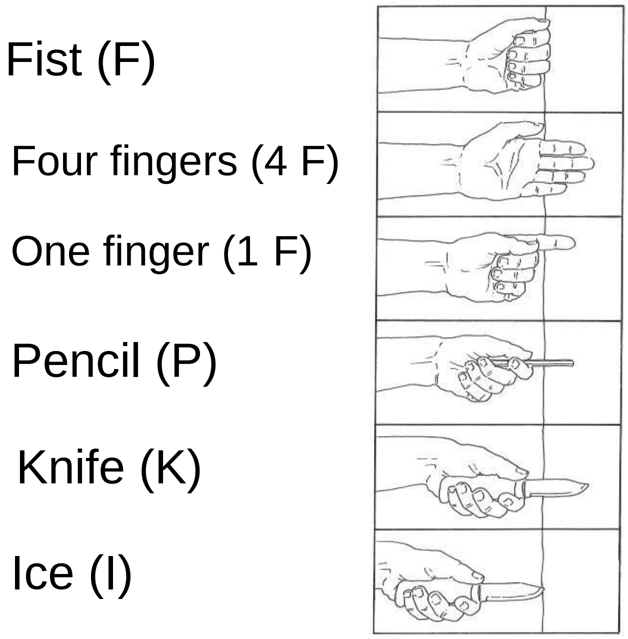


Figure 7.1: Values for measuring hardness

! The location where a snow profile is to be produced should always be safe for the personnel who are intending to study the snowpack.

Hard layers which form slabs above loose layers are of particular interest for further evaluation!

7.1.5 Weak and unstable layers in the snowpack

The purpose of a snow profile and stability tests is to identify weak layers and sliding layers in the snow. The objective is therefore to identify snow-covered layers of loose, unbonded snow, layer transitions, surface hoar or graupel layers that could act as sliding layers, and layers of faceted crystal snow or depth hoar that could collapse easily and are poorly bonded. In 80% of avalanches triggered by people, the fracture (cause) occurs in weak and unstable layers, 47% in layers of buried surface hoar, 26% in layers of faceted crystal snow and 8% in layers of depth hoar (Brattlien 20014, p. 48).

Persistent weak layers consist of surface hoar, facets or depth hoar. Persistent weak layers do not generally stabilise until they have undergone a melting process. The layers can also collapse and the crystals freeze together, causing the properties of the layers to change and the snowpack to become more stable. This primarily applies to facets and depth hoar. In such cases, one will recognise the crystals and the persistent weak layer, but see that the crystals have frozen together. Snowpack tests will then also not indicate instability.

Weak layers which are not persistent stabilise over time, depending on the snow crystal type and weather conditions. Such weak layers are often snow-covered layers with loose, fresh, unbonded snow. The fresh snow will stabilise over a few hours or days, depending on the temperature.

Changes in wind strength and direction can lead to layering in the snowdrift which is perceived as sliding layers. Such layers will also stabilise within a relatively short period of time.

Wet transitions can also form, which become weak layers. This occurs when the snowpack becomes saturated with water and the water accumulates in specific layers, e.g. layers with small crystals with good absorption properties. If the overlying slab does not slide out, wet layer transitions will eventually dissolve and allow the water to seep further down into the snowpack, causing the snowpack to stabilise again.

7.1.6 Snow profile form

All snow profile observations must be recorded in a field logbook, so that this can be registered electronically upon returning from the field. Appendix 3 contains a simple form for recording a snow profile. In this form, it is possible to choose whether to record the profile layer by layer, or to sketch the layers. The form is also available in the Instruction in Field handbook - Avalanche Forecasting .

If appropriate, the snow profile can be recorded directly in the field on an electronic profile form such as Snowpilot (available online), Ullr's Mobile Avalanche Safety Tools (Android and IOS app) or AvyLab (IOS app). It is also possible to draw the profile by hand and record the tests on this profile. The documented snow profile is like a combat log for the avalanche forecaster. The log will make it possible to review the condition of the snowpack several days earlier, enabling its development to be studied. The documentation will also be important if a situation should arise which requires written documentation and later review. An example of a snow profile form is enclosed as Appendix 2.

7.1.7 Classification of snow on the ground

The various types of snow crystals are divided into primary types, each of which has its own subgroups. Some of these will be of interest, as they indicate the stage in the development of a snow crystal and the direction in which the development is taking place. All subgroups are specified in Appendix 1. This is an international classification (ICSI 2010) which is also used by the Norwegian Armed Forces (UNESCO 2009). The crystal types in the individual layers should be entered on the snow profile form.

The table below shows the main types of snow crystals and their associated abbreviations and symbols. See Figure 5.2 to Figure 5.8 for illustrations.

Primary shape	Primary classification	Symbol
New snow; the crystal is the same as or similar to its original shape, as well as hail	PP (Precipitation Particles)	+
Transformed new snow; irregular rounded shapes with branches, first stage of destructive transformation, partially decomposed	DF (Decomposing and Fragmented precipitation particles)	/
Rounded snow; rounded individual crystals, the final stage of destructive transformation, mechanically decomposed crystal shapes	RG (Rounded grains)	•
Faceted crystal snow; crystals with even surfaces and stripes; first stage of constructive transformation	FC (Faceted Crystals)	□
Depth hoar; hollow crystals, even surfaces with stripes, final stage of construction transformation	DH (Depth Hoar)	∧
Melt forms; wet crystals, may be frozen together, polycrystals, slush	MF (Melt Forms)	O
Surface hoar; surface hoar or cavity hoar, feather-like crystals	SH (Surface Hoar)	∨
Ice; pure ice layer in which the crystals are no longer visible	IF (Ice Formations)	■
Machine-made snow	MM (Machine Made snow)	◎

Table 7.1: Primary shapes of snow crystals with abbreviations and symbols

7.1.8 Snow crystal transformation schematic

Snow crystals will continually be in the process of transforming into a new shape until the crystals melt and turn into water. Figure 7.2 shows how snow crystals can be transformed through constructive transformation, destructive transformation, stagnation or melt processes. The figure illustrates this through the addition of energy in the form of heat or cold. The green arrow also shows the slow rounding off of snow crystals, which takes place through thermodynamic decomposition.

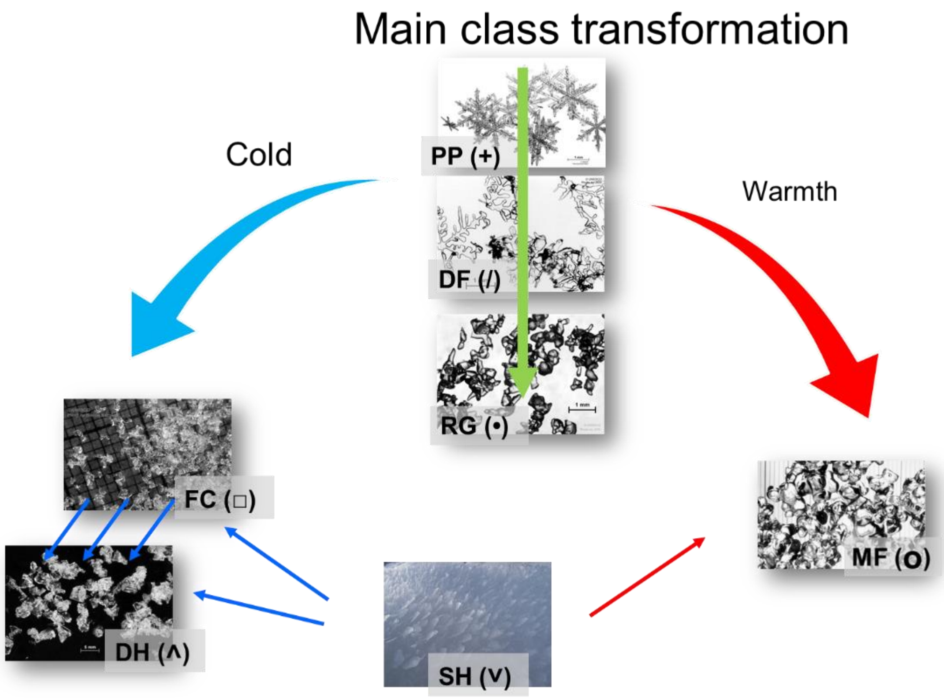


Figure 7.2: Transformation cycles of snow crystals
The figure shows the direction in which the various snow crystals develop as a result of the transformation processes.

All crystals can be transformed through melting into melt forms (MF). Through a process of destructive transformation, the new snow crystals (PP) will transform into decomposing and fragmented new snow (DF). Through further destructive transformation, DF will be transformed into fine-grained rounded crystals (RF), which is the end product of the destructive transformation.

With a low density and a high temperature gradient on the snow surface, PP and DF crystals can be transformed directly into small faceted (FC) crystals during fine cold weather over a prolonged period with a thin snowpack. Substantial differences between incoming solar radiation during the daytime and low night temperatures can also lead to the formation of facets (FC) in the upper part of the snowpack through diurnal recrystallisation (see section 5.2.5 Near surface facets). No forms of snow crystal will revert to new snow forms PP or decayed and fragmented crystals DF. Fine-grained, rounded crystals (RG) can be transformed into facets (FC) through constructive transformation and facets (FC), and can develop into depth hoar (DH), which is the final stage of the constructive transformation process. Surface hoar SH can develop further into facets (FC) and depth hoar (DH).

7.2 Shear quality and energy

The purpose of the various stability tests is to attempt to trigger a fracture in the snowpack and analyse how the fracture occurs, and the properties of the fracture surface. Shear quality (Q) is critical to avalanche risk. Shear quality is an indication of how slippery the surface is where a fracture/slippage occurs, as well as how easily the fracture occurs. On most occasions when a fracture or collapse occurs, the block that is situated above the fracture behaves sluggishly. On some occasions, the block of snow emerges as if it were spring-loaded, almost shooting out. When we interpret test results, there is a correlation between the amount of energy and a high avalanche risk. Shear quality is used to describe the properties of the fracture surface in the stability tests which are discussed later.

Fracture surface quality is divided into Q1, Q2 and Q3. Q1 indicates a smooth sliding surface and stored energy in the snowpack. Q2 indicates a smooth sliding surface but without the release of energy. Q3 indicates an even fracture surface, which in some cases also occurs as a step-shaped fracture. The table below specifies shear quality.

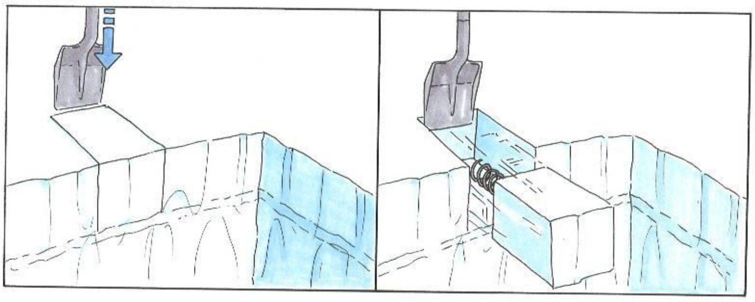


Figure 7.3: Shear quality Q1: *The 1-block shoots out as if it were spring-loaded.*

Shear quality	Description of slip plane	Remarks
Q1	The block almost shoots out.	NB: Indication of substantial energy in the snowpack and high avalanche risk
Q2	Slip plane is smooth, but with little energy	Large, loose crystals does not mean that the surface is rough
Q3	Slip plane is uneven	Good attachment between layers, or fracture in a homogeneous layer

Table 7.2: Subdivision of shear quality

! Q1 is a clear indication of unstable conditions.

7.3 Shovel test

The shovel test is not a stability test, but a method to identify layers of surface hoar and other potentially critical layers that may be difficult to locate. A buried layer of surface hoar can be less than 1 mm thick and be difficult to locate in a profile. However, the overlying block will slide on this layer when a shovel test is performed. The test is carried out in combination with other tests and creates space for sawing and release of the other tests.

The procedure involves sawing a 30 x 30 cm column of snow or the equivalent width of the shovel. At the rear edge, a cut is made in the snowpack corresponding to the length of the snow saw. The shovel is then inserted vertically down behind the column in the slit which has been sawn out. With the shovel inserted vertically behind the column, the shovel is pulled horizontally downwards in order to apply a tensile force on the block and thereby identify weak layers.

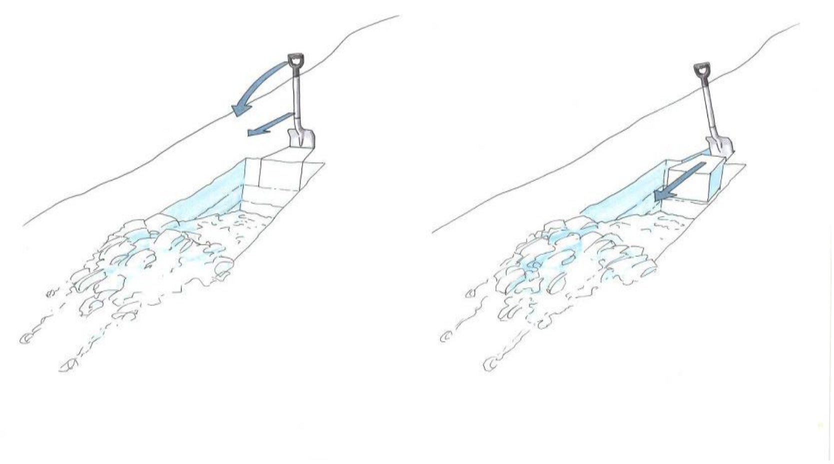


Figure 7.4: Shovel test

The shovel must not be used like a crowbar, but pulled downwards in a steady movement.

NB! The shovel test helps to identify sliding layers, which may be difficult to detect.

7.4 Compression test (CT)

A compression test (CT) is a stability test of the snowpack. The test helps to identify weak layers in the snowpack and gives an indication of the vertical load that is required before the snowpack collapses. The test is also relatively quick to perform.

The load is applied vertically to the top of an isolated column of snow, which has been released from the surrounding snow on all four sides. The top of the column must be cut flat so that the load applied to the shovel is applied vertically downwards, rather than at an angle to the top of the column. The shovel is placed on the top of the column, with the front of the blade facing down towards the column. The load is then applied with light “strikes”, first using the hand, then the forearm and finally the whole arm. ‘Strikes’ means the deadweight of the hand, the forearm or the whole arm dropping from the vertical position. The fractures are observed on the front of the column, ideally using a colleague as an observer.

The procedure involves isolating a snow column measuring 30x30 cm measured horizontally, at a depth that passes through the potentially weak layers. It is important to decide on how deep into the snowpack the column should be cut free. On layered winter snow, the lower part of the snowpack often consists of hard, frozen and stable snow. If one consistently cuts down through the old snow to looser layers close to the ground, the weight of the column can cause it to collapse and produce artificially “high” values during the tests. In the event of uncertainty, two consecutive tests can be performed, where the columns are isolated to different depths in the snowpack.

Performing a shovel test first makes it easier to isolate the column that will subsequently be used during the compression test. The column is isolated by cutting into the rear face and cutting out a wedge-shaped section from the side facing away from the shovel test, so that the column is not in contact with the sides.

The sides of the column must be smooth and even to ensure that any fractures will be clearly visible. The column must not be so high that it starts to topple, i.e. usually around 1 m. If a layer fractures during isolation of the block or when the shovel is placed on top of it, this should be recorded as ‘Compression Test – Very easy’ (CTV).

Up to 10 'strikes' should then be applied using the deadweight of the hand. The load should not exceed the force that is applied by lifting the hand with the fingers pointing upwards and then letting it drop onto the spade without impacting. If a layer fractures after seven 'strikes', for example, this must be recorded as CT 7, or alternatively CTE (7). See Table 6.4 for more examples. The snow must then be removed down to the layer which fractured, the shear quality is assessed, and the test continues with 'strikes' no. 8, 9, 10, etc. From 11 to 20 'strikes', the whole forearm should be used, and from 21 to 30 'strikes' the whole arm with a flat hand or clenched fist, but still without applying more than the deadweight of the arm. The test is concluded after 30 'strikes', and CTN (No fracture) should be recorded in the event that no fracture or collapse occurs. If the snow under the shovel is crushed, the force of the strikes will not be transferred to the underlying layers. Crushed snow must therefore be removed during the test. The test must then be continued on the new surface.

The test is not valid for weak layers situated at depths greater than 100–120 cm. In such cases, the overlying snow must be removed and a shorter column loaded. The Canadian Avalanche Association uses a test (known as a Deep Tap Test) where the overlying snow is removed down to a height of 15 cm above the weak layer. On the new surface, the compression test is then performed as described above. Care must be taken when interpreting the results of a test in such cases, as some of the snowpack will have been removed. After the removal of some of the snow, layers that were previously protected by a thick layer of snow can cause lower test results and appear to be more unstable than they actually are. We also know that deep layers which are difficult to release can cause bigger avalanches than layers which are not as deep. In such cases, it is necessary to find a location where the weak layer occurs at shallower depths in the snowpack instead. The number of 'strikes' as an additional load for this test has not been verified against artificially triggered avalanches, but the shear quality can be interpreted in the same way as with an ordinary CT test.

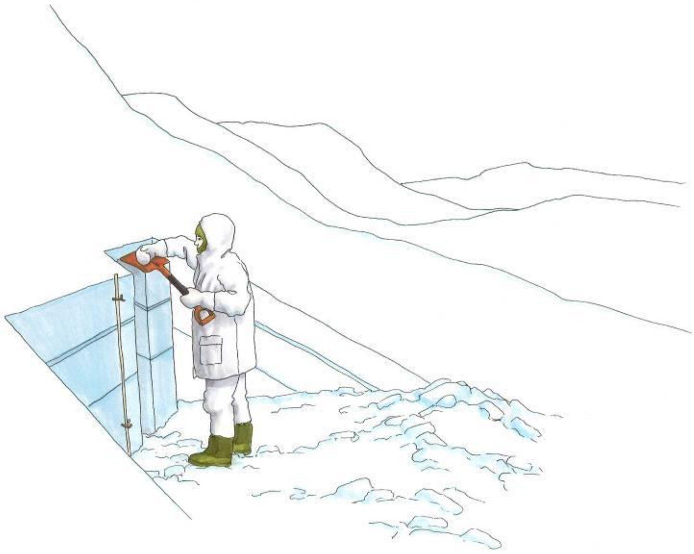


Figure 7.5: Compression test

A 30 x 30 cm column is isolated and then loaded through vertical "strikes" with the hand, forearm and finally the deadweight of the whole arm as a "loading" of the snowpack.

Result	Explanation	Description
CTV	Very easy	Fracture when column is isolated
CT 1-10/CTE	Easy	Fracture from strike 1 to 10
CT 11-20/CTM	Medium	Fracture from strike 11 to 20
CT 21-30/CTH	Hard	Fracture from strike 21 to 30
CTN	No fracture	No fracture

Table 7.3: Recording the results of a compression test (CT)

Interpreting the results of a compression test

A section of snow measuring 30 x 30 cm does not provide sufficient basis for drawing conclusions about the snow conditions. The most important finding that can be taken from a compression test is whether it is possible to trigger a local fracture in the snowpack by applying a small or large load. If a fracture occurs, we may have to carry out the ECT test (see below) in order to evaluate whether the snowpack possesses the properties that are necessary in order to propagate the fracture. In the event of uncertainty regarding the quality of the compression test, further tests must be carried out. As a general rule, conclusions must be based on as many tests and observations from varied exposures and different heights as possible.

7.5 Extended compression test (ECT)

The Extended Column Test (ECT) is a test which produces relatively reliable results viewed in relation to the ability of the snowpack to propagate a fracture, which the test is designed to evaluate. The ease with which a fracture propagates in the snowpack is linked to the ease with which an avalanche can be triggered. It would be natural to perform this test if a fracture is produced during the compression test (CT). If a compression test indicates a relatively stable snowpack, there would be little reason to assume that an Extended Column Test (ECT) would produce any results. Subject to the development of new tests, the ECT has so far proven to be the most reliable individual test for assessing the ability of a snowpack to propagate a fracture.

Instead of isolating a snow column of 30x30 cm, a 90x30 cm column is isolated in this case, with the 90 cm section being the width of the column. The shovel is applied to one corner of the column and loading of the column is applied in the same way as in the compression test: Initially, 10 'strikes' with the hand from the wrist are applied, followed by 10 'strikes' with the forearm and, finally, 10 'strikes' with the deadweight of the whole arm.

When a fracture/crack appears in the snow column, the number of 'strikes' should be recorded, as well as whether the fracture spread across the whole column. If fracture propagation occurs on the same 'strike' as that which caused the initial fracture, the test must be recorded as follows: ECTP 6. The depth must also be recorded as "@ X cm".

If fracture propagation does not occur on the same strike as the initial fracture, the test must be recorded as "No Propagation", i.e. ECTN 6. The method used to record test results has been updated on a number of occasions (Snow, Weather and Avalanche Guidelines, American Avalanche Association, SWAG 2010, SWAG 2016), and the developers of the test also believe that shear quality values, i.e. Q values, obtained during tests should no longer be recorded (SWAG 2016). The Norwegian Armed Forces recommends that shear quality continues to be documented, as this parameter can provide critical addition information for use when determining how readily a fracture can propagate through the snowpack.

The important part of the ECT test is when fracture propagation occurs in relation to the initial fracture. If the fracture does not propagate on the same strike as the initial fracture, this is considered to be a clear sign of danger, i.e. the strength of the snow, combined with the characteristics of the weak layer, has resulted in unstable conditions. This test is not as suitable in situations where the initial fracture is not identified and fracture propagation occurs on a later strike. The test may then be interpreted incorrectly and recorded as an ECTP result.

The test is not valid for weak layers situated at depths greater than 100–120 cm. If the weak layer is deeper, the column must be reduced in height. This leads to the same reservation as regards interpretation of the test results as for the compression test. In such cases, it is necessary to find a location where the weak layer is not as deep in the snowpack instead, in order to render the tests valid.

Interpreting the results of an ECT

As with all other tests, it is difficult to interpret the results of an ECT test on the snowpack in relation to actual stability. However, the results can provide an impression of the characteristics of the slab and the weak layer. If an initial fracture propagates over the entire column on the same 'strike', the snowpack has a strong ability to propagate fractures. This corresponds to relatively unstable conditions. If no fracture occurs or if the fracture does not propagate, the ability to propagate is not as good, and the snowpack is likely to be more stable. This information must be taken into account in further investigations of the slab and the weak layer. In the event of doubt over the test results, one or more additional tests must be carried out.

Figure 7.6: Extended compression test (ECT)
A 30x90 cm column is loaded with up to 30 'strikes', as for the compression test.

! In the event of slippage/collapse of CT 0–10 and initial fracture and fracture propagation occurs on the same strike during the ECT, this can be taken as a relatively certain indication of unstable conditions in the snowpack.

Result	Description
ECTPV	Fracture propagates over the entire column upon release. (Fracture propagates during isolation)
ECTP#	Fracture is initiated and propagates over the entire column after # strikes. (Fracture with propagation)
ECTN#	Initial fracture occurs, but no fracture propagation after # strikes. (No Propagation)
ECTX	No fracture occurs during the test. (No fracture during test)

Table 7.4: Recording the results of an ECT test
The method used to record the results takes account of the changes from SWAG2016.

7.6 Propagation Saw Test (PST)

A more recently developed test is the Propagation Saw Test (PST), which in the same way as ECT has been developed to test the fracture propagation properties of the snowpack. PSTs are carried out when we wish to test an identified weak layer and the overlying slab. The test is performed on a 30 cm wide column which extends 100 cm up the slope. The entire column is isolated, and the depth must extend down to the weak layer that is to be tested. If the weak layer is situated deeper than 100 cm, the length of the column must be extended corresponding to the depth of the weak layer. Wherever possible, the test must be carried out in locations where the weak layer is situated at a depth of less than 1 m.

Once the column has been isolated, the weak layer must be tested by inserting the blunt side of the saw from below and up into the slope through the weak layer. The outcome of the test gives an indication of the critical fracture length that is required before fracture propagation occurs. The principal weakness of the PST is that the test can be time-consuming if a sufficiently long saw is not available. A further weakness is that the test gives no indication of the load that is required in order to cause the column to fracture.

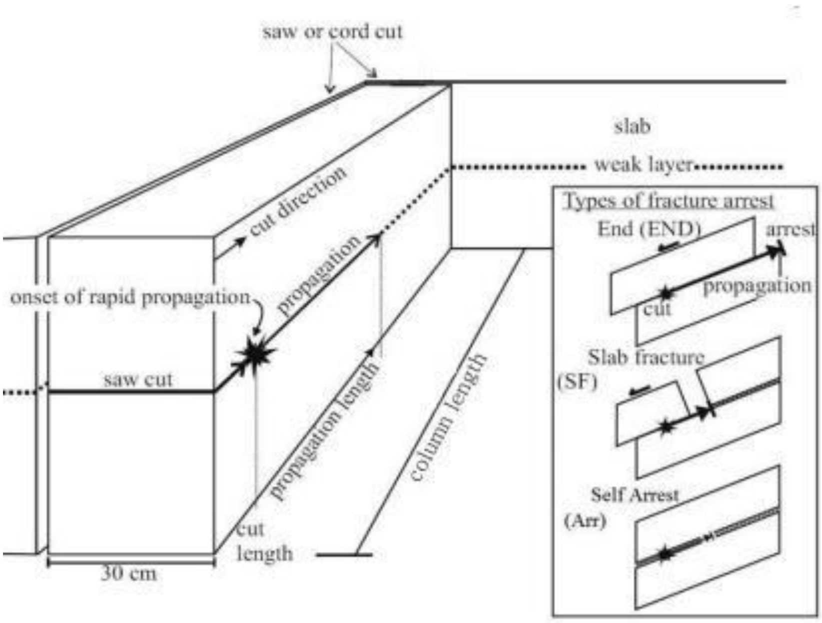


Figure 7.7: Propagation Saw Test (PST)

PST has been designed to measure the proportion of the weak layer which must be affected (critical fracture length) before fracture propagation occurs.

Result	**Explanation**
PST X/Y End or Arr Z cm Example: PST 45/100 End 33 cm	X = position of the saw in cm when the fracture propagates (0–100 cm) Y = length of the column (100 cm or more) “End” is recorded if the fracture propagates over the entire column “Arr” is recorded if the fracture does not propagate over the entire column “SF” is recorded if the slab fractures (slab fracture) Z = depth of the weak layer, measured vertically

Table 7.5: Recording the results of a PST test

Interpreting the results of a PST

As mentioned previously, the results of a PST test give no indication of the additional load that is required in order to trigger an avalanche in the snowpack. The test describes what proportion of the weak layer beneath the column must be removed, i.e. the critical fracture length, in order to bring about fracture propagation. In other words, the test examines the resistance of the weak layer to fracture in the proximity of a crack.

Comparison with other tests on skier-triggered slopes suggests that a critical fracture length of 50% of the column length or less can be interpreted as unstable. Results with values of 50% are to be considered unstable.

7.7 Rutschblock test

The rutschblock test is a direct test of the stability of the snowpack using an increasing vertical load. Arutschblock takes around 25–40 minutes to excavate. This is labour-intensive relative to the amount of information that is obtained.

The test area is 3 m². When the snow is loose, it may be difficult to test the uppermost layers (20–30 cm). There is also uncertainty as to whether this method provides a true picture of weak layers situated at depths of more than 1 metre beneath the surface.

A vertical wall is dug in the snow to a length of 2.5–3 m and a depth of 1.5–2 m. In order to isolate the 3 m² block, 1.5 m long trenches are dug on either side. The upper or rear long side is cut using an avalanche cord or snow saw, if it is long enough.

Special long saws and cords are available for cutting the sides instead of having to dig them out.

If a saw is used on the sides, the block must be cut trapezoidally in order to prevent it from jamming.

Once the block has been isolated, it should be loaded in seven stages with increasing loads, until it eventually slides out in a weak layer, in accordance with the scale in Table 7.6.

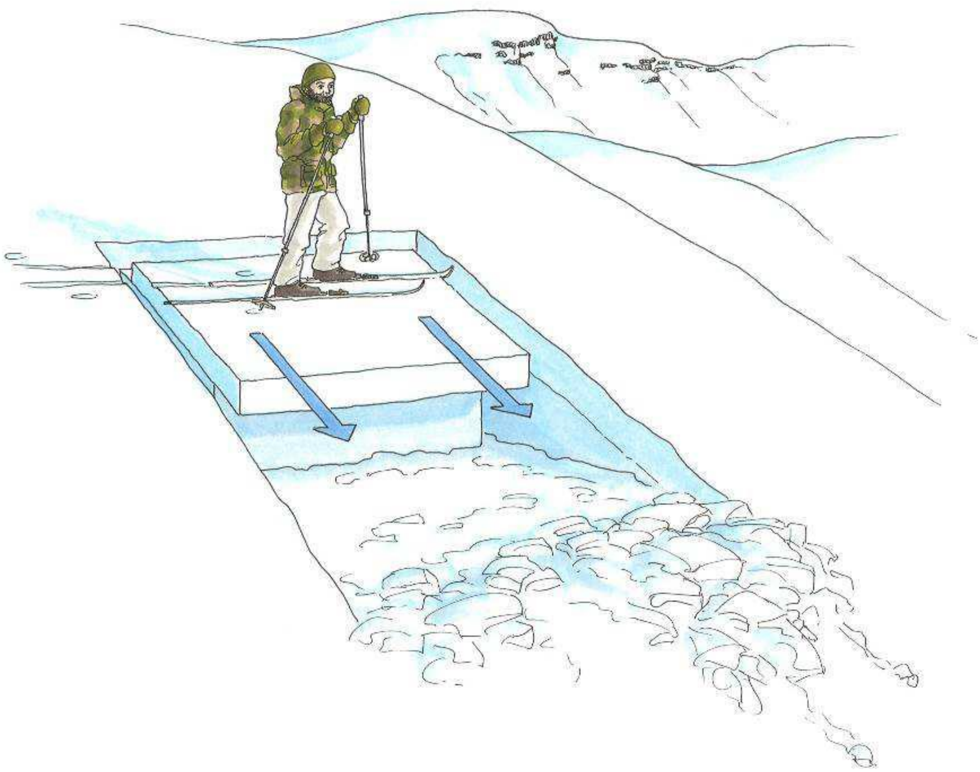


Figure 7.8: Rutschblock

Step	Loads that cause the block to slide out
RB 1	Excision without additional load
RB 2	A skier cautiously moves onto the block (on the upper half of the block, 30–40 cm below the upper edge)

RB 3	The skier performs a rocking motion without raising the heels or the skis
RB 4	The skier jumps and lands in the same place
RB 5	The skier jumps again in the same place
RB 6	Jump without skis in the same place. If the snow is loose, descend to the middle of the block wearing skis, rock once and then jump three times
RB 7	None of the preceding stages result in a clean fracture

Table 7.6: Recording the results of a rutschblock test

The above table shows the American rutschblock classification. The Swiss classification differs slightly.

7.8 Validity of stability tests

All of the stability tests referred to above are performed on columns which have been isolated (sawn or excavated) from the surrounding snow. None of the stability tests take account of the protective and stabilising effect of hard slabs overlying weak layers when they are not sawn through. This could for example be compact wind-drifted snow over a layer of faceted snow, particularly when there is a snow crust above the weak layer. Under such conditions, tests can give results upon sawing (ECTPV/CTV), even though it is possible to jump on the snowpack on the same slope without triggering a fracture or fracture propagation. On the other hand, it is sometimes possible to obtain results indicating that the snowpack possesses stable characteristics, even though skiers can still trigger an avalanche on similar slopes. This could for example be the case where the weak layers are situated deep in the snowpack.

The most important factor as regards the validity of these tests is spatial variation in the snowpack. Such variations have been demonstrated in numerous studies and mean that a particular test can produce very different results when the test is repeatedly performed on the same slope (including: Campbell and Jamieson 2004), see Figure 7.9). The results of a single test should therefore not be trusted, and it is necessary to verify the results on several occasions in order to determine the characteristics of the snowpack.

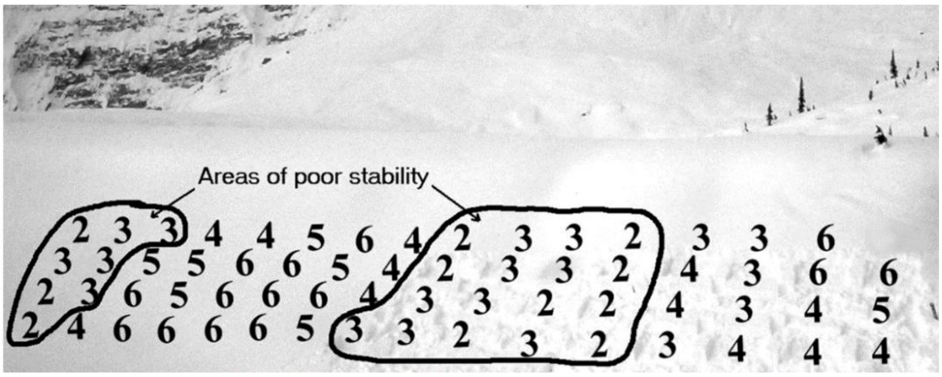


Figure 7.9: Spatial variation

The illustration shows the extent to which rutschblock tests (RB) varied across a slope. The numbers refer to RB values obtained from the tests (Cam Campbell and Bruce Jamieson 2004).

Over and underestimation of stability can also be attributed to the design of the tests. There are no tests which completely simulate the natural triggering of an avalanche or the effect of the loads caused by a skier on the snowpack. The results of tests on snowpacks must therefore be interpreted accordingly, and the answers that are obtained will not necessarily correspond with reality.

Stability tests on snowpacks are the only way of obtaining information on fracture initiation and propagation with minimum risk for human life and health. The results of the tests are indications of stability or instability. In order to compare the various tests with the stability of the snowpack, the tests have been conducted on both skier-triggered slopes and slopes which have not been triggered (Schweizer and Jamieson 2010). During these tests, the following limit values were set in order to define the outcome as unstable: fracture during CT upon < 14 strikes/Q1, fracture propagation during ECT maximum of 1 strike following fracture initiation and fracture propagation during PST with values of less than 50/100.

Schweizer and Jamieson concluded that ECTs offer the best average accuracy of all the tests. ECTs and PSTs have larger surfaces in the weak layer compared with CTs, and are therefore better suited to evaluating the characteristics of the weak layer. The tests also assess the ability of the snowpack to propagate fractures. For all tests, performing two or more tests enables more reliable results to be obtained compared with just a single test.

According to Schweizer and Jamieson (2007), threshold values are correct in 60–75% of cases. Stability assessments and the crossing of avalanche terrain therefore require a thorough knowledge and careful weighting of the various factors and their interrelationships. Observations from a wider area, improvised tests, an understanding of the distribution of weak layers and underlying processes must be accorded weight. This requires experience and frequent practising of the skills required. It is also necessary to assess the impact of the weather on the snowpack (see Chapter 6 for details).

7.9 Fracture line inspection

Inspecting the fracture line, or the avalanche crown, where a recent avalanche has occurred can provide valuable information. The purpose of such inspections is to study the characteristics of the slab and the weak layer, and thereby attempt to understand the unfavourable properties of the snowpack. Fracture line inspections can provide valuable experience of the various tests. This gives us the opportunity to compare test results with the instability of a snowpack where an avalanche is known to have been triggered. Before walking up or down an avalanche path, the safety of the slope must be assessed. This is particularly important in run-out zones with parallel avalanche paths which could represent a hazard. An assessment must also be made as to whether sufficient new snow has accumulated along the avalanche path for there to be a possibility of further avalanches being triggered.

Avalanche paths where an avalanche has recently been triggered are normally safe areas. It is unlikely that the remaining snow will be released when the tensile forces in the snowpack are released. The forces acting on the slab on the upper side of the fracture line have been dissipated and the terrain above the fracture line is often too gently sloping to constitute avalanche terrain. In order to define an avalanche as safe, there must be no other slopes higher up which could present a risk.

Fracture line inspections are carried out as an ordinary snow profile followed by stability tests. The profile should be excavated above or to the side of the fracture line in virgin snow which has not fractured or been affected by the fracture.

7.10 Free moisture content in the snowpack

Free moisture content describes the content of water in the snow as a volume percentage. Free moisture is only present in snow that has a temperature equal to 0°C. Dry gloves or mittens are required to test the moisture content of the snow. Before starting to test for free moisture content, the surface layer in the profile wall must be removed in order to reach layers that have not been affected by the air temperature or solar radiation. The moisture content is determined by squeezing the snow with a glove or mitten to ascertain the degree to which it becomes sticky, or whether water can be squeezed out of the snow. The table below specifies the qualitative and quantitative gradings for the moisture content of snow.

Numeric code	Grading	Properties	Corresponding moisture content in %	Graphic symbol
1	Dry	Snow temperature (T) is below 0°C. The snow is difficult to shape.	0	None
2	Moist	T = 0°C. Free moisture is not discernible but the snow is sticky and may be shaped.	<3	|
3	Wet	T = 0°C. Free moisture between some snow grains can be observed through a magnifying glass but it is not possible to squeeze the water out with moderate pressure.	3–8	||
4	Very wet	T = 0°C. Water can be squeezed out with moderate pressure but the snow pores still contain an amount of air.	8–15	|||
5	Soaked	T = 0°C. The snow is soaked with water and contains little air.	>15	||||

Table 7.7: Evaluation of free moisture in snow

The moisture content of the snow is a factor that must be assessed in an analysis of the snowpack. A high moisture content will weaken the bonding between the snow crystals, while an increase in moisture content following rainy weather will contribute to increasing the additional load on the snowpack. However, extremely wet snow or slush will help to stabilise weak layers.

In the event of weather situations which result in wet or moist snow, it can be useful to assess how far down into the snowpack the moisture has penetrated and how quickly this has occurred. It is difficult to predict the effects of mild weather and rain on the snowpack or the avalanche risk. It is therefore important to gain experience of this when the weather conditions result in the presence of moisture or rain on the snowpack. It is also important to investigate developments in order to determine when the snowpack will stabilise again following mild weather or rain, in order to gain experience of decreasing avalanche risk.

7.11 Temperature in snow layers/temperature gradient

The temperature of the air should be measured at a height of 2 metres above ground level, along with the temperature of the various snow layers. The air temperature and surface temperature must be measured in the shade. This can be done by covering the area that is to be measured with a shovel. It is important to give the surface time to cool before taking the measurement.

The spacing of temperature measurements may depend on the conditions, but an interval of 20 cm is normal, except for the three uppermost measurements. The first measurement should be taken on the snow surface (0 cm), then at 10 cm, 20 cm, 40 cm, 60 cm, etc. If the snowpack is isothermal (0°C) throughout, not all the intervals need be recorded. If there are potentially weak layers in the snowpack, the temperature can be measured on both the upper and lower sides of the weak layer. If a snow crust is present close to the weak layer, the temperature can be measured immediately above and below this crust. Detailed measurements around weak layers can help to determine temperature gradients over short distances.

It is recommended that a digital thermometer be used to measure the temperature of the snow, as such thermometers normally adjust rapidly to changes in temperature. It should be possible to insert the thermometer's sensor 15 cm into the snow in order to avoid any influence from the air temperature.

The purpose of measuring the temperature of the snow is to determine whether any temperature gradients are present in the snowpack. If the temperature drops by more than 10°C per metre, or by 1°C per 10 cm, a temperature gradient is considered to be present which is sufficient to trigger constructive transformation. This means that weak layers are continuing to develop and could become even weaker. In the uppermost layers, where solar radiation and mild weather can have an impact, the bonds in the snow may be weakened and snow creep may increase, but when it freezes, this will lead to better stability. Fluctuations between cold night temperatures and solar heating can lead to the faceting of crystals at the top of the snowpack (near surface facets) through diurnal recrystallisation. This faceting can create a persistent weak layer once it has been buried by snow.

Remember that all thermometers must be calibrated by checking them in ice slush, which is always at around zero degrees (0°C).

8 Safety of personnel involved in avalanche risk assessment

8.1 Competence level and equipment

Military personnel who are to carry out avalanche risk assessments and cross avalanche terrain must have completed the avalanche assessment course (UD 2-1, section 5.13.6.1 p. 266 (2018–19). Military personnel who are to lead small units in avalanche terrain must have completed the course entitled *Ferdsel i skredutsatt terreng (Crossing avalanche terrain)* (UD 2-1, section 5.13.7 p. 267 (2018–19). The scope of these courses is set out in curricula prepared by the Norwegian School of Winter Warfare. According to standard procedures, buddy rescue equipment must be carried when crossing avalanche terrain, and the personnel must have completed training in buddy rescue.

Personnel intending to work with avalanche risk assessment in the field should always work in pairs.

Personnel should carry a means of communication in order to report any avalanche-related accidents.

Avalanches do not distinguish between avalanche experts and less knowledgeable people!

8.2 Route planning in connection with avalanche risk surveys in the field

Before a patrol leaves to make observations and carry out an avalanche risk assessment, it is recommended that a plan be drawn up which details their movements. The plan should take account of current avalanche hazards, and the terrain to be crossed must be linked to relevant avalanche problems. The plan must be made available so that other people are aware of where the patrol is at all times. If several patrols are carried out simultaneously, an overview may be drawn on a map showing the patrol plan for the day.

When moving across a slope to produce a snow profile, it is important that only one person enters the slope at a time. One person must remain on safe ground in order to observe the movements of the first person to enter the slope. Other personnel can enter the area once the first person has completed initial investigations and is certain of the stability of the slope where the profile is to be excavated.

Slopes more than 5 metres high can contain sufficient snow to bury a person. It is therefore vital to assess the consequences of an avalanche being triggered. In the event of an avalanche being triggered, it would be advantageous to be as high up the slope as possible, i.e. you should always enter a slope from above and never from the base. If you enter the slope at the base of the mountainside or slope, the avalanche will flow over you and it is very likely that you will be completely buried.

You should also be aware that it is possible to trigger avalanches on gentler terrain through remote triggering. In addition, a release area can spread outwards into slopes of less than 30°. You should also be aware that the snow slope may be steeper than 30° even if the map indicates that the slope angle is less than this (see Figure 4.3).

! Always enter a slope as high up as possible.

Terrain traps

Terrain traps are terrain formations which will exacerbate the consequences in the event of an avalanche being triggered. Examples of this are cases where the avalanche path enters a forest or passes over cliffs, and avalanche channels with visible rock formations and stream gorges. Avalanche channels containing terrain traps should be avoided during avalanche risk assessments. It is not without reason that terrain traps are often referred to as death traps.

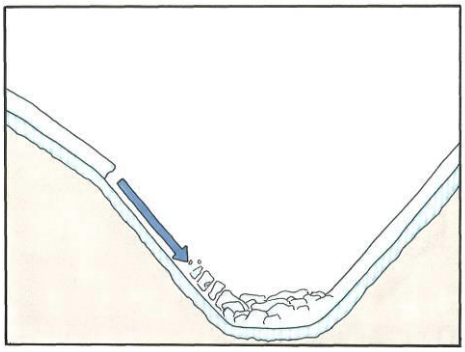


Figure 8.1: Terrain trap in a river gorge

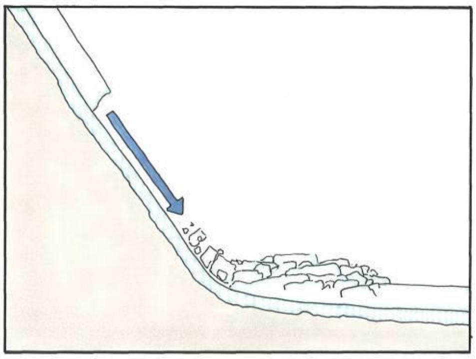


Figure 8.2: Terrain trap down into flat terrain

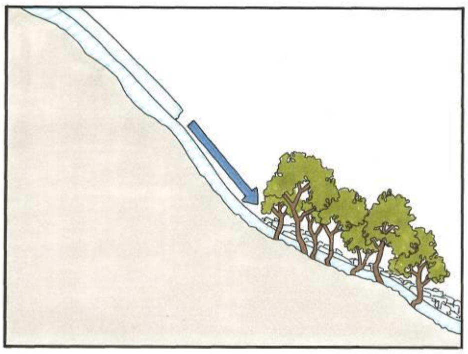


Figure 8.3: Terrain trap into a forest

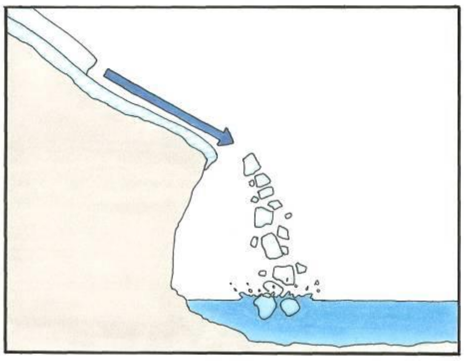


Figure 8.4: Terrain trap over cliff/ into water/frozen lake

9 Assessing avalanche risk

9.1 The Military Avalanche Danger Scale

The Military Avalanche Danger Scale was revised with effect from 1 November 2008. Since 2018, the Military Avalanche Danger Scale has taken into account changes in the size of avalanches. The scale is identical to the European Avalanche Danger Scale, except for the supplementary military regulations which stipulate movement rules relating to avalanche risk and the Norwegian Armed Forces' avalanche map.

The Military Avalanche Danger Scale (updated 2018)			
Degree of risk	**Snowpack stability**	**Avalanche probability**	**Military regulations**
5 **Very high** 	The snowpack is generally weakly bonded and very unstable.	Many very large, in some cases extremely large, naturally triggered avalanches are expected, even in moderately steep terrain*. Remote triggering very likely.	Movement in zones 1 and 2 is not permitted. Avalanches may have longer run-outs than indicated on the avalanche map.
4 **High** 	The snowpack is weakly bonded on most steep slopes*.	Triggering is probable even with low additional loads** on many steep slopes*. Under certain circumstances, many large and some very large naturally triggered avalanches are expected.	Movement in zones 1 and 2 is not permitted.
3 **Considerable** 	The snowpack is moderately to weakly bonded on many steep slopes*.	Triggering is probable, particularly with high additional loads** on steep slopes*. Under certain circumstances, some large, occasionally very large, naturally triggered avalanches are expected.	Movement in zone 1 is not permitted. Movement in zone 2 is permitted but only far out in the zone. Long pauses and bivouacking are not permitted in zone 2.
2 **Moderate** 	The snowpack is moderately well-bonded on some steep slopes*. Otherwise, it is generally well-bonded.	Triggering is possible, particularly with high additional loads** on steep slopes*. Very large naturally triggered avalanches are not expected.	Movement in zone 1 is not permitted. Movement in zone 2 is permitted, but long pauses and bivouacking should take place more than half way out in zone 2.
1 **Low** 	The snowpack is generally well-bonded and stable.	Triggering is generally only possible with high additional loads** on very few extreme slopes*. Only small or medium-sized naturally triggered avalanches are possible.	Movement in zone 1 is not recommended. Zone 2 is expected to be safe.

*Terrain slope:

Moderately steep terrain <30°, steep slope 30–40°, extreme slope – slope with particularly high avalanche risk >40°
** Additional load:
High additional load = group of skiers, snowmobile or similar Small additional load = one skier

Table 9.1: The military avalanche danger scale

The military avalanche danger scale is based on the European Avalanche Danger Scale. Rules for movement in terrain exposed to avalanches for military divisions are given in the right-hand column "Military regulations".

9.2 Factors to be considered

Preparing an avalanche forecast is rather like doing a jigsaw puzzle with many pieces missing. Assessing avalanche risks in a limited area may appear to be a relatively straightforward task; however, assessments normally have to be carried out over more extensive areas within which the conditions vary considerably, and the forecast must also apply into the future. Avalanche forecasts can also cover areas where no tests or profiles have been carried out, and where assumptions must be made based on observations made elsewhere. It is also necessary to take account of observations of natural signs which cannot necessarily be quantified, but which provide important supplementary information. There may have been recent avalanche activity in the area, rumbling in the snowpack or fracturing and/or slippage in the snowpack.

Factors that must be assessed when preparing an avalanche forecast:

- What the winter has been like generally, and the specific weather conditions in recent days
- Where has the snow accumulated in the relevant areas, what variations are there in the snowpack, what has the accumulation of snow and the weather been like during the winter so far
- Layering, slabs, persistent weak layers, as well as the thickness and depth of weak layers
- Results of stability tests
- Other observations: avalanche danger signs in nature
- What type of weather is expected over the next 24–48 hours and how it will impact on the snowpack

! Remember that you will not be aware of all the factors that could impact on the avalanche risk.

9.3 Avalanche problems

EAWS's five avalanche problems

There is an international consensus regarding the definition of a snowpack and the snow conditions in the form of different avalanche problems, in addition to how the degree of risk should be determined. It is normal to focus on the most important avalanche problem; however, two or three avalanche problems may be included in a forecast. The avalanche problem with the highest probability of being triggered must be presented as the main problem. The association European Avalanche Warning Services (EAWS) has agreed a set of five avalanche problems. Describing the snowpack in the form of avalanche problems makes it easier for those who want to define the avalanche risk and in particular those who will read the forecast, as avalanche problems provide a good illustration of the challenges associated with the layering.
Avalanche problems create a clear, common understanding of layering. It may be necessary to determine the conditions in specific valleys or exposures which are safer than other locations for personnel who have to reach higher elevations. Using avalanche problems also makes it easier to discuss the present situation and future changes in the avalanche risk with other personnel with avalanche expertise. An overview is presented below of the avalanche problems (NVE 2018):

- New snow – loose snow avalanche and slab avalanche

- Wind-drifted snow
- Persistent weak layer
- Wet snow – loose snow avalanche and slab avalanche
- Gliding avalanche

It is important to note that the avalanche problems 'new snow' and 'wet snow' are divided into loose snow avalanches and slab avalanches, so that in practice seven different descriptions of the snowpack can be forecast.

Military avalanche forecasts during major exercises are issued via daily safety bulletins (UD 2-1, 2018/2019 section 5.13.2). The scope of avalanche forecasts will be limited to some extent by the template that is used for safety bulletins and the scope to issue bulletins with graphic content. It may therefore be necessary to describe the avalanche problem, instead of using graphic symbols. Units requiring more information on the snowpack can contact the avalanche forecasting personnel.

A detailed description of the avalanche problems is presented below:

<u>New snow – loose snow avalanche</u>	 **Figure 9.1:** EAWS symbol for the avalanche problem New snow – loose snow avalanche
Characteristics	Caused by recent snowfall. Starts at a point and increases in width as it travels downhill. Normally small, but can increase considerably in mass on large, steep slopes. Drop-shaped. Can trigger larger slab avalanches if there are weaker layers deeper down in the snowpack.
Spatial distribution and terrain type	Generally widespread. Usually released in steep terrain (steeper than 40°).
Release mechanism	Loss of cohesion/binding between the snow particles inside the new snow.
Duration	Rapidly stabilise following snowfall, normally within a couple of days, depending on temperature and radiation.
Identification	Fairly easy to recognise in the terrain. The danger signs are new snow on steep cliffs and recent avalanche activity.

New snow – slab avalanches	 **Figure 9.2:** EAWS symbol for the avalanche problem New snow – slab avalanche
Characteristics	Caused by recent snowfall. New snow usually arrives in combination with wind and in such cases, leeward sides will be the most exposed. New snow slabs are normally soft, easy to release and easy to underestimate with regard to their size. Varies in size from small to extremely large. The critical amount of new snow is often around 30–50 cm; however, this will depend on a number of factors such as temperature and the age of the snowpack.
Spatial distribution and terrain type	Generally widespread. Typically released on steep slopes of around 30° and steeper. Can be released in all types of terrain, but these avalanches are often the largest and most frequent above the tree line.
Release mechanism	Bonding processes in the new snow lead to the formation of soft slabs (wind, radiation, temperature). Accumulation leads to the formation of a fracture in the weakest layer.
Possible types of weak layer	Snow-covered weak layers of new snow. Weak bonding between smooth crust and new snow.
Duration	Rapidly stabilise following snowfall, normally within a couple of days, depending on temperature and radiation.
Identification	New snow is easy to recognise in the terrain. Danger signs: - New snow bonds and forms soft slabs - Cracking of the snow - Recent avalanche activity

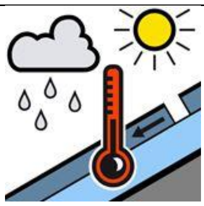
Wind-drifted snow	 **Figure 9.3:** EAWS symbol for the avalanche problem *Wind-drifted snow*
Characteristics	The problem occurs when wind moves loose snow along the ground. Avalanches caused by wind-drifted snow vary in size and hardness, depending on wind strength and the amount of loose snow available in the terrain.
Spatial distribution and terrain type	Highly variable depending on wind strength and the amount of snow that is available for transport.

	Released on steep leeward sides and hollows filled by wind-drifted snow (typically steeper than 35°). Often limited to leeward areas created by the terrain, e.g. behind ridges and in gullies and hollows.
Release mechanism	The wind-drifted snow forms hard or soft slabs in leeward areas. Accumulation leads to the formation of a fracture in the weakest layer.
Possible types of weak layer	Weak bonding between layers in the wind-drifted snow. Snow-covered weak layers of new snow.
Duration	Stabilises relatively rapidly, normally within a couple of days, depending on temperature and moisture.
Identification	Fairly easy to identify with good visibility and sufficient knowledge. Often recognisable based on the nature and changes in hardness of the snow surface. Danger signs: - Signs of strong winds on the surface of the snow. - The snow surface bonds and forms soft or hard slabs - Shooting cracks - Rumbling (rare) - Recent avalanche activity

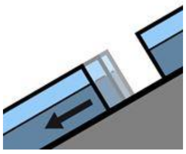
<u>Persistent weak layers</u>	 **Figure 9.4:** EAWS symbol for the avalanche problem *Persistent weak layers*
Characteristics	Leads to slab avalanches, which can become extremely large. The weak layer is formed during spells of cold, clear weather. Can result in fractures/avalanche release in several layers deeper inside the snowpack. May continue to exist in terrain pockets after most other areas have stabilised. Often have “dormant” periods and are “reawakened” when the weather changes. Often triggered remotely and can be released on top of those who triggered them.
Spatial distribution and terrain type	Can often be linked to specific elevations, cardinal directions or areas. Typically released on slopes between 30° and 40°.
Release mechanism	Fracture in weak layer occurs due to accumulation and/or weakening of the slab lying on top of the weak layer.
Possible types of weak layer	Snow-covered surface hoar Snow-covered faceted snow Faceted snow above crust layer Faceted snow beneath crust layer Faceted snow on the ground Depth hoar
Duration	Stabilise slowly, have a tendency to persist for several weeks, sometimes months.
Identification	Danger signs:

	- Rumbling - Shooting cracks - Remotely triggered - Recent avalanche activity is typical Sometimes, little or no evidence for skiers/snowmobile drivers. Absence of avalanche activity and danger signs are not reliable indicators of stability. Stability tests can reveal persistent weak layers (if one looks in the right place).

Wet snow – loose snow avalanche	 **Figure 9.5:** EAWS symbol for the avalanche problem *Wet snow – loose snow avalanche*
Characteristics	Avalanche starts at a point and increases in width as it travels downslope. Drop-shaped. Normally small, but can increase considerably in mass on large, steep slopes.
Spatial distribution and terrain type	Generally widespread where the snow is sufficiently soft. Usually released in steep terrain (steeper than 40°) and often near cliffs.
Release mechanism	Loss of cohesion/bonding within the wet snow. Occur due to warming of the snowpack. Possible causes include incoming solar radiation, temperature rise, rain or absence of night frost.
Duration	Hours or days, depending on temperature and radiation.
Identification	Fairly easy to recognise in the terrain. Danger signs: - Wet and soft snow surface - Recent avalanche activity - Rolling snowballs/snow wheels

Wet snow – slab avalanche	 **Figure 9.6:** EAWS symbol for the avalanche problem *Wet snow – slab avalanche*
Characteristics	Can vary in size from small to extremely large. Can extend a long way with a high moisture content. Presuppose a clear layered snowpack. Upon the initial saturation of a dry layered snowpack, the probability of wet slab avalanches will be greater than if the snowpack has previously been wet.

	It may be difficult to predict when the avalanches will be released. It takes time for the water to penetrate down into the snowpack and weaken it sufficiently for the avalanche to be triggered. Normally self-triggered (naturally triggered).
Spatial distribution and terrain type	Generally widespread, particular in connection with rain and temperature rises. In connection with incoming solar radiation, limited to specific cardinal directions and elevations.
Release mechanism	Warming of the snowpack leads to the melting of bonds and weakening of the snowpack. Rain will cause weakening in addition to the additional loading of critical layers. Possible causes include incoming solar radiation, temperature rise or absence of night frost.
Possible types of weak layer	Accumulation of water in/over layers in the snowpack Snow-covered surface hoar Snow-covered faceted snow Faceted snow above crust layer Faceted snow beneath crust layer Faceted snow on the ground
Duration	Hours or days, depending on temperature and radiation.
Identification	Readily identifiable. Danger signs: - Wet and soft snow surface - Recent avalanche activity

<u>Gliding avalanche</u>	 **Figure 9.7:** EAWS symbol for the avalanche problem *Gliding snow*
Characteristics	Entire snowpack glides on the ground. The snow gradually creeps on smooth ground such as smooth rock zones or grassy slopes, and distinct glide cracks usually become visible before release. The snowpack is wet on the ground. Gliding snow avalanches are more frequent in mild winters with high levels of precipitation where the ground has not frozen before snowfall.
Spatial distribution and terrain type	Limited to areas where the snowpack rests on smooth rocky zones or steep grassy slopes. Variable steepness.
Release mechanism	The snowpack creeps and glides on the surface under the force of gravity. Releases when the friction against the surface which is holding the snowpack in place becomes less than the force of gravity.
Possible types of weak layer	Moisture on the ground/melting on the ground.
Duration	Days to months.

	It is very difficult to predict when a gliding snow avalanche will release. This will depend on the amount of water that is present, the weight of the overlying snowpack and the strength of the snowpack.
Identification	Readily identifiable. Danger signs: - Glide cracks - Recent avalanche activity

9.4 Method for obtaining observations of the snowpack – from observations to forecasting

9.4.1 Introduction

Evaluating the snowpack

When one is unfamiliar with the snowpack in an area, evaluations must always be based on complete snow profiles through the entire snowpack down to the ground, in addition to other observations and the weather forecast, in order to issue an avalanche forecast. Once one has become familiar with the local snowpack and built up extensive experience of snow awareness, it will be possible to focus more on the upper part of the snowpack and the number of tests on the snowpack, and determining the distribution of weak layers. In this way, it will be possible to increase the number of investigations and observations, whilst at the same time obtaining information from across much of the terrain.

Location of profiles

Snow profiles should be located so that the snowpack is as representative as possible of the exposures that are to be evaluated. This applies to elevation, cardinal direction and snow quantity. Safety is paramount, and the location chosen for a snow profile must of course be safe given the avalanche risks. Profiles must be no more than approximately 180–200 cm deep. The ideal depth for a snow profile is between 120 and 150 cm. When choosing locations for snow profiles, use an avalanche probe to find the most suitable locations. It is also not desirable to dig down into uniform snowpack, such as wind-drifted snow and accumulated snow. Small terrain formations offer safe locations for excavation, but may sometimes not have the same layering as the main snowpack we want to investigate. Distinct, loose and weak layers can often be felt using an avalanche probe, which can help when searching for the best locations for profiles. Thick layers of wind-drifted snow can also be identified using an avalanche probe in order to avoid digging there.

Follow the weak layer

If a weak layer is identified in the snowpack, it is important to follow the layer and obtain an impression of its distribution (see 9.4.3.2 Distribution). Once detailed knowledge of the snowpack and the avalanche problems has been built up, the scope of full profiles can be reduced, enabling the focus to be placed on specific tests of the weak layer and associated slab. This can be done through simplified profiles and improvised tests (see below).

Simplified profiles

To save time and increase the number of observations, a focus can be placed on simplified profiles. In the case of simplified profiles, excavations are dug down to just below the weak layers. This will enable the distribution of the weak layers to be determined, enabling testing to be focussed on these layers. Simplified profiles can be documented using simple sketches showing the key characteristics, such as layer thickness, hardness, snow type, size of snow crystals, etc., and the tests that have been carried out. When using simplified profiles, it is important to be sufficiently familiar with the snowpack, so that one can be certain that the are no unstable or weak layers deeper in the snowpack.

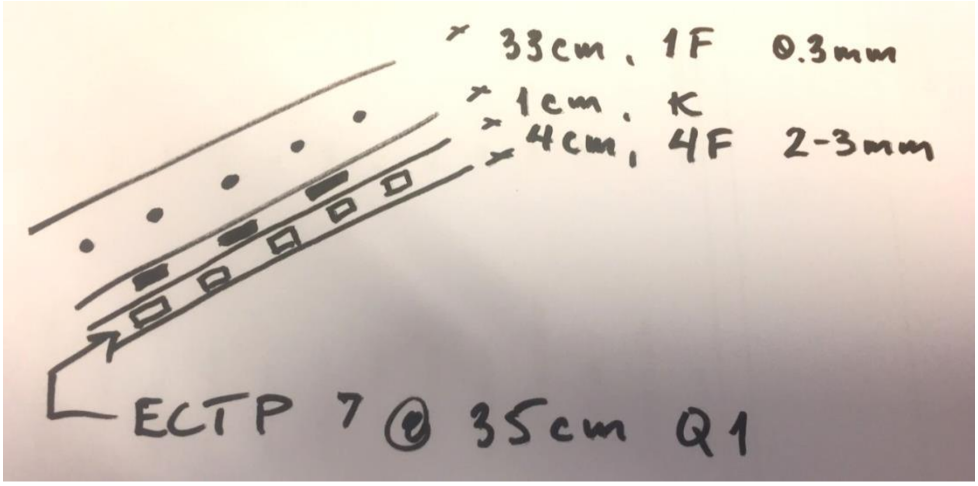


Figure 9.8: Example of a simplified profile

Characteristics of the slab and the weak layer have been recorded, and the weak layer has been tested. Many such tests can be carried out in different locations in order to test the weak layer effectively. It will also enable a good impression to be built up of the distribution of the weak layer. Elevation and exposure must also be recorded!

Improvised tests

Improvised tests are carried out to quickly test the weak layer in many places and evaluate both the distribution and variations in stability of the snowpack. The number of observations is increased and we build up a better general picture of the snowpack. It is important to note that each test that is used which differs from standard tests will have to be interpreted accordingly. These tests must be considered for what they are, i.e. simplified tests, rather than internationally acknowledged, standardised tests. Nevertheless, simplified tests can provide useful feedback and, when we make important observations, they can be tested through full profiles and standard tests.
Examples of improvised tests:

- Drive a snowmobile/ski across small, safe test slopes
- Increase the additional load on small, safe slopes (from small to large)
- Place two snowmobile or ski tracks a short distance apart to see whether the slab between the tracks glides out.
- Reduced ECT (approx. 60–70 cm wide) down to the weak layer. This test can be carried out using a short saw and shovel, and time can be saved by not using a wire saw. The test gives an impression of the ability of the snowpack to propagate fractures. If a sufficiently long saw is available, the original size of the column should be retained.

During movement, we look for changes in the snowpack by carrying out the following:

a) stamping on the snowpack
b) inserting a ski pole into the snowpack
c) digging into the snowpack by hand

All indications that the snowpack has changed, particularly in the case of changes which suggest a more unstable snowpack, should lead to more thorough investigations being instigated to evaluate the layering and stability.

Edge forces

When carrying out tests on test slopes, it is important to select small terrain formations to ensure that no one is caught by snow masses which are sufficiently large to bury a person in the event of misjudgements being made. On the other hand, the forces in small formations act differently than on larger slopes. Edge forces which hold a slab in place become less important as the size of the slab increases. When a slope increases in size, the surface area of the slab will increase at a faster rate than the area of the edge around the slope which holds the slab in place. The relationship between these two areas will determine the importance of the edge forces as regards whether the snow masses will remain stationary. This means that, when attempts are made to disturb a slab on a short slope, it will take a lot more to exceed the forces – the edge forces – that are holding the slab in place. The stability of the small test slope will be perceived as being better than it might be on larger slopes.

Examples of the importance of edge forces:		
Area of slab	**Area of edge**	**Ratio between area and edge forces**
10 x 10 m = 100 m^2	1 m thick: 40 x 1 m = 40 m^2	2.5
100 x 100 m = 10,000 m^2	1 m thick: 400 x 1 m = 400 m^2	25
1000 x 1000 m = 1,000,000 m^2	1 m thick: 4000 x 1 = 4000 m^2	250

Table 9.2: Ratio between the area of a slab and the edge which is holding the slab in place
Edge forces are of greater importance in small slabs than in larger slabs.

9.4.2 Procedure

9.4.2.1 General

A description is presented below of the procedure for obtaining the maximum amount of high-quality information on the snowpack. The same description is thoroughly elaborated upon in section 9.4.3.
As a basis for our forecast, information on the snowpack is obtained based on *structure*, *strength* and *energy*, as well as *the distribution of the avalanche problem (see section 9.3 for avalanche problems)*. We also obtain observations concerning *natural signs and signals*.

9.4.2.2 Structure

The following steps must be followed in order to evaluate an unfamiliar snowpack in a particular area:

a) excavate to the base,
b) identify the layering,
c) evaluate exposures and elevations

The key questions that must be asked are:

- Is there a weak layer present?
- Is there a slab above the weak layer?

9.4.2.3 Strength

The question that must be asked is whether it is possible to trigger an avalanche in the layering. Tests are carried out on the snowpack to determine whether the weak layer could fail and whether the local fracture could propagate to other parts of the slope (CT, ECT, PST).
The key questions that must be asked are:

- Are local fractures created in the snowpack where there is a risk of fracture propagation?
- Do the characteristics of the slab and the weak layer result in a risk of the fracture propagating to other parts of the slope or across the entire slope?
- What additional load will the snowpack tolerate? Natural triggering, small additional load or large additional load?

9.4.2.4 Energy

Shear quality and energy are investigated through tests on the snowpack. The weak layer can give rise to a fracture which is smooth and is easily achieved. Tension in the snowpack can result in a fracture with the consequent release of a large amount of energy, i.e. the fracture is triggered suddenly and with great force.

If a fracture occurs during the tests, the shear quality and the energy in the fracture must be evaluated: Q1, Q2 or Q3 (see Figure 7.3).

9.4.2.5 Distribution

What we are attempting to determine is how widespread the weak layer is.
Once a weak layer has been identified, it must be followed and investigated further. By understanding the processes that lie behind the formation of the weak layer and the information that has been obtained, we are attempting to describe the distribution of the problem, the exposures and elevations that are most exposed and the number of slopes in which the problem exists.

9.4.2.6 Avalanche danger signs

In addition to investigating the snowpack through excavation and testing, we must make observations before, during and after we have been in the terrain. Observations can either reinforce the impressions that have been gained or be used as a basis for locating snow profiles and carrying out tests on the snowpack. The following danger signs must be monitored particularly closely:

a) Shooting cracks
b) Rumbling
c) "Hollow sounds" in the snowpack
d) Recent avalanche activity, small slides, open cracks
e) Wind-drifted snow, wind-affected snow, leeward sides, waves in the snow, sastruga
f) Heavy snowfalls
g) Rapid temperature rises
h) Rain on the snowpack
i) Long spells of cold weather, particularly on thin snowpack, or in windy, exposed locations
j) The formation of surface hoar, any intact layers of surface hoar which are being covered by snow

9.4.3 Detailed description of the procedure

A description is presented below of the procedure for preparing a detailed avalanche forecast.

9.4.3.1 Structure

Dig down to the base of the snowpack!
Once one has become familiar with the snowpack in a particular area, it is necessary to dig down to the ground in order to identify the layering. This also means that it is necessary to familiarise oneself with the layering on all exposures and at different elevations.

Identify the layering in the profile!
The layers must be recorded and analysed. Tests must be recorded in a logbook or electronically. The decisive questions are as follows:

- Is there a weak layer present?
- Is there a slab over the weak layer?
  - How hard is the slab? (More than one degree difference in hardness between layers leads to greater weakness)
- How big are the snow crystals and how hard (softness) is the weak layer?
  - When the crystals exceed 1 mm in size and the layer is loose, we can assume that the layer will fracture readily and that the fracture will propagate
  - The hardness of the weak layer will often be in the range 4 F to F.

Factors linked to the duration of the layers which are of particular interest:

- Snow crystals produced through constructive transformation (facets, depth hoar, surface hoar) are persistent in the snowpack and considered to be persistent weak layers.

- These persistent weak layers do not normally stabilise until they are subjected to a further process (melting, collapse).
- Layer transitions in wind-drifted snow and snow-covered loose unbonded snow are considered to be weak layers, but they often stabilise over the course of a few days.

Different types of weak layers

Persistent weak layers consist of large, recognisable snow crystals, such as facets, depth hoar and surface hoar. These crystals form through constructive transformation.

Weak layers can consist of snow-covered, unbonded loose snow. Such layers tend to stabilise quickly. It is assumed that it takes between one and a few days to stabilise snow-covered, unbonded loose snow, depending on the temperature. At temperatures of around 0°C, the process can take place rapidly, while at lower temperatures, e.g. 20–30 degrees below zero, it can take several weeks.

Layer transitions in wind-drifted snow also constitute weak layers. These are formed by temperature differences, changing wind directions and/or wind strengths. Layer transitions in wind-drifted snow stabilises rapidly, taking anything between a few hours to a few days.

Weak layers can also constitute a layer transition in the snowpack with high moisture content and weak bonds. Such a layer transition often forms a boundary between large and small crystals. Layers of small crystals can absorb large quantities of water (like a sponge) and form such a layer transition. Stable layer transitions can become weakened. The unstable conditions will last from between a few hours to a day or two, and are therefore not persistently stable.

Graupel which is formed during showery precipitation can form weak layers. Graupel often slides or is blown away, or becomes mixed with other types of snow crystal and therefore does not constitute a risk. If distinct, concentrated layers or pockets of graupel are identified, these will constitute weak layers in the snowpack and may persist for an extended period of time.

In order for the snowpack to represent a threat, a slab must be present above the weak layer. The snow must be bonded in order to constitute a slab. If the snow is not bonded, the snow will still be loose and not lead to any risk of a slab avalanche. Wind-drifted snow bonds rapidly (minutes to hours). Wind-affected snow can also bond rapidly. This may be snow which has not necessarily been transported to leeward slopes, but where the surface has been affected by the wind, and the snow shows a clear tendency to form slabs.

New snow bonds take between a few hours and a few weeks to form, depending on the temperature. As soon as the snow shows a tendency to bond, slab formation begins to occur. If it is cold, it will take longer than when it is warmer. During cold weather, loose, fresh snow can take several weeks to bond.

To test whether loose snow has begun to form a slab, a shovel can be loaded with snow and shaken carefully. If the snow does not disintegrate and remains in a block, it has started to form a slab and could therefore be released as a soft slab. A slab which is very hard will protect the underlying weak layer to a greater extent, enabling it to support more weight and reducing the effect of the additional load on the snowpack. It could facilitate the accumulation of a lot of snow on the slab before it eventually fails and results in a larger avalanche. Large avalanches often involve slabs with a hardness of up to 'knife'. If the layer is softer, the additional load will penetrate down into the weak layer more readily, but if the slab is too soft, the fracture may not have the characteristics to propagate. This can be felt when crossing the terrain on skis or on foot.

People on foot will sink further down into the snowpack than those on skis, increasing the risk of affecting a weak layer and fracturing occurring.

9.4.3.2 Strength

When testing the snow, the aim is to determine the strength of the snowpack and whether the layering could facilitate an avalanche.

Tests of the snowpack determine whether it is possible to cause a localised fracture in the snowpack. A further aim is to determine whether the localised fracture could propagate to other parts of the slope. The compression test (CT) gives an indication as to whether the layer could fail. A low test score in a CT test indicates that a fracture could readily occur. An extended column test (ECT) gives an indication of the characteristics of the weak layer and the ability of the slab to propagate a fracture. A low test score in an ECT test indicates that fracture propagation could readily occur.

The PST test tells us that if fracture propagation occurs before 50/100, the result will be considered to be unstable, and that a fracture could propagate and lead to an avalanche.

It must be remembered that a test gives an indication of the stability of the snowpack at this limited position – a tiny fraction of a large landscape. Layers can vary considerably in thickness across a single slope. Where the snowpack or overlying slab increases in thickness, the overlying slab can "protect" the weak layer to a greater extent than where it is thinner. The snowpack is often thinner towards the edges and towards the top of a slope. The transition from thick to thinner snowpack can form the weak "trigger point", from where the release of an avalanche is possible. The transition from soft to hard or vice versa can be a critical point in the release of an avalanche. The snow at the surface could be very soft at the bottom of a slope, but towards the top of the slope, wind may have affected the snow and begun to form a slab. This can lead to the triggering of an avalanche as a person approaches the top of the slope.

Additional load

Testing of the snowpack gives an indication of the load that the snowpack will be able to tolerate at the site of the test before an avalanche is triggered. Tests that result in low test scores indicate that only a small additional load will be required to trigger an avalanche. It is difficult to give any absolute or critical limit values for the test results that correspond to a small or large additional load, as the tests only simulate an additional load on the snowpack. However, it can be assumed that the snowpack is unstable where test results are triggered during sawing, preparation or just a few strikes. This can be interpreted as indicating that an avalanche could be triggered with a small additional load. Higher test values are an indication that triggering of an avalanche would require a larger additional load. A snowpack which is capable of tolerating a large additional load indicates that a snowmobile or a group of people would have to cross the slope in order to trigger an avalanche. If the snowpack tolerates a small additional load, it will take more than one person on skis before it is likely that an avalanche will be triggered.

When testing very hard slabs, particularly with ice and crust layers, the results of stability tests will often be exaggerated. One or more very hard slabs "protect" the weak layer to a greater extent than softer slabs. When cutting above such slabs, particularly ice layers, it is likely that the test results will exaggerate the degree of instability. Such hard layers in the snowpack reduce the depth to which the stress load extends down into the snowpack, thereby protecting weak layers. On the other hand, hard slabs which reduce the load imposed on weak layers can cause the avalanche that is eventually released to be large. This takes place because more snow can accumulate on the slope before an avalanche is released.

NOTE: A person on foot without skis or a person who falls while skiing could constitute a substantial additional load.

Number of observations

In addition to the standard tests, a series of improvised tests can be carried out on the snowpack. Improvised tests are often quick and simple investigations, which make it possible to determine the capacity of the layering to fracture and propagate fractures over a wider area. Improvised tests do not replace full profiles and recognised tests, but they can provide an effective method for covering a large area and following an avalanche problem which is already known.

9.4.3.3 Energy

In the event of fracture initiation and propagation, it is important to determine the shear quality of the weak layer and the energy in the fracture. This is done by classifying the fracture surface from Q1 to Q3. The Q value gives an indication of the amount of energy in the snowpack.

It is necessary to determine whether the fracture is smooth, or whether the surface is rough and uneven. If fracture propagation occurs, it is necessary to look for dissipated energy by seeing

whether the block slides out readily during testing. Shear quality is described using the codes Q1, Q2 and Q3. See Chapter 7, Figure 7.3 for more details concerning shear quality and energy in the snowpack.
Note that if the tests are carried out on gentle slopes, it may be difficult to distinguish between Q1 and Q2.
The stresses in the snowpack originate from within the snowpack. Gravity causes the creep, and the upper layers of the snowpack will creep more than the base. Stresses often occur between the layers in the snow. Creep also increases the compressive forces at the bottom of the slope and the tensile forces at the top of the slope. In the event of mild weather or heavy precipitation, for example, creep can increase, thereby also causing an increase in stresses in the snowpack.

9.4.3.4 Distribution

Once the necessary investigations have been carried out into *structure*, *strength* and *energy*, we must reach a conclusion regarding the distribution of the avalanche problem. Distribution can be determined through a combination of further investigations and an understanding of the process behind the formation of the weak layer and the slab. What must be determined is the proportion of the terrain across which the avalanche problem exists. Distribution must describe the exposures and elevations where the avalanche problem exists. The number of slopes where the layering exists (a few, some or many slopes) must also be described. There are primarily two ways of evaluating distribution:

1) following the weak layer:
   When collecting information on the snowpack, we investigate whether the weak layer is widespread across many slopes, several exposures and at many different elevations. The avalanche probe is used to identify suitable locations to investigate the snowpack without having to dig profiles which are either too deep or too shallow (see Location of profiles). As many observations as possible must also be obtained. Once the snowpack is known in detail, the number of investigations can be increased by only digging down through the known weak layers, if these layers are not at the base of the snow.
2) process approach/cause:
   Once a weak layer has been identified, it is possible to reach certain conclusions concerning the process behind the formation of the weak layer. It is necessary to ask whether the process has led to the formation of this layer across much of the mountainside, or whether it is limited to isolated slopes, in addition to specific elevations of the weak layer.

Different processes behind the formation of weak layers result in different distributions. If there has been a prolonged cold spell, for example, surface hoar will be formed across much of the mountainside. The surface hoar may have subsequently been destroyed by wind, sun or temperature on certain exposures. Wind direction and strength can be investigated for the most recent period, sun conditions, whether the weather in the area has been mild or damp, and how high the 0-degree isotherm (the boundary between snow and rain) has been. The problem can be limited to specific elevations, the shady or the sunny side, based on whether the sun, wind or temperature has "neutralised" parts of the mountainside, so that the avalanche problem only remains in sheltered exposures.

Some examples of how weak layers arise are given below:
Surface hoar is formed during calm, cold weather across an entire area, resulting in widespread distribution. Wind on one side of the mountain may have destroyed the surface hoar layer, while the layer on the leeward side may have been preserved. On occasions, surface hoar can occur in lower-lying terrain (cold hollows), but not at higher elevations. Local knowledge of cold distribution would be a major advantage in this context. Sunlight often "eats into" surface hoar during the daytime on slopes which are affected by the sun. Precipitation in the form of rain may

have destroyed the surface hoar layer across the entire mountain. Mild temperatures may also have neutralised the surface hoar layer across the entire mountain. A fresh snowfall may have buried the surface hoar layer across some or all of the mountain and cause the surface hoar layer to remain in situ as a persistent weak layer.
Rain can create weak layers, i.e. a transitional layer between wet and drier layers. Rain can also result in an increase in creep in the snowpack, which can give rise to wet slab avalanches and, in the worst case, slush avalanches. It is necessary to assess the distribution of the wet weather by demarcating it geographically and in terms of elevation. Rain and mild weather strike in all cardinal directions at the elevation at which they occur. If the snowline is known, it is possible to demarcate the problem of influence from rain in terms of elevation.
The formation of layers of depth hoar and faceted snow is often widespread. Or they can form on windblown mountainsides or on parts of the slope where there is less snow, following prolonged spells of cold weather. An understanding of the distribution of snow in the terrain during the cold spell will help to understand the distribution.
Different types of crust (ice, rain, snow crust) can have different distributions, particularly in the case of sun crust. Sun crust can only be found on slopes which face the sun. Ice and rain crust is caused by wet and mild weather, and can be limited in terms of the elevation at which it occurs, but it will otherwise be distributed across all exposures. Crust layers can subsequently be covered by snow at certain elevations and exposures, depending on the transport of snow by the wind.
Graupel often occurs during spells of weather with heavy showers near the coast. Graupel will therefore be limited to areas where the showers occurred. Graupel can later be transported by the wind and accumulate on a few slopes or pockets across limited areas of the mountainside. In the case of strong winds and showers, it is not uncommon to find graupel some distance inland.

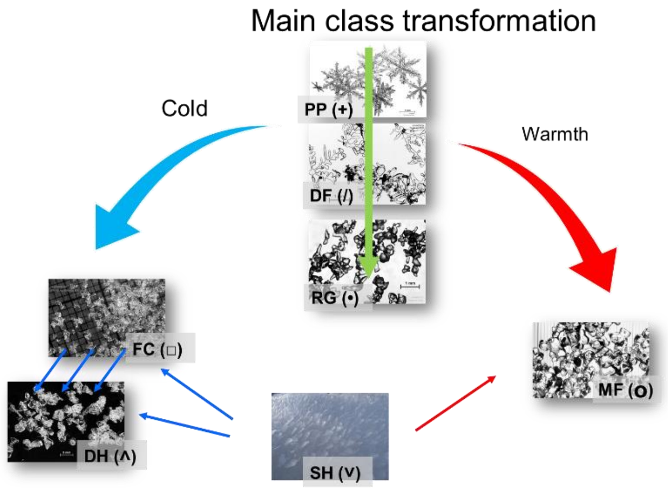


Figure 9.9: Process approach/cause
The figure shows the transformation processes affecting the various crystal types.

Explanation of the process approach (Figure 9.9)
Figure 9.9 shows the transformation processes affecting the various types of snow crystals. Mechanical decomposition (green arrow) is shown through the new snow crystals (PP) being transformed into partly decomposed snow crystals (DF) and then into rounded crystals (RG). Thermodynamic decomposition follows the same development process, but occurs through water vapour transport from convex to concave parts of the snow crystals caused by differences in vapour pressure. Thermodynamic decomposition occurs while the snow crystals are buried in the snowpack.

When heat (red arrow) is applied, all snow crystals transition to melt forms (MF) through the melt-transformation process.
When cold is added (blue arrow) to the crystal types PP, DF, RG and MF, faceted crystals (FC) can be created through constructive transformation. If cold continues to be applied, FC also develop into depth hoar (DH). Constructive transformation occurs as a result of an active temperature gradient, i.e. a temperature drop of 1°C per 10 cm or more down through the snowpack. Surface hoar (SH) can also develop into facets and depth hoar when it is subjected to an active temperature gradient.

9.4.4 Summary of unfavourable conditions

The following points summarise various factors which impact unfavourably on snowpack stability.

- Layering which can readily fracture, i.e. tests produce a fracture during sawing or light tapping or give a Q1, is unfavourable to stability.
- Thin weak layers fracture more readily than thick layers. In addition to thin surface hoar layers, thin layers of depth hoar and faceted snow can be unfavourable. Thick layers of depth hoar crystals/facets are sometimes encountered where the test results do not indicate particularly unstable conditions.
- Large crystals resulting from constructive transformation are unfavourable. A limit of 1 mm is often set, but care should be taken as soon as it becomes apparent that the snow crystals have undergone a low degree of constructive transformation.
- If a weak layer is situated deep in the snowpack, it is more difficult to influence than if it is situated closer to the surface. A limit of 1 m is often set as regards how far down into the snowpack a skier will be able to influence a weak layer. A fall while skiing, a group of people, a person not wearing skis or a snowmobile could affect weak layers further down in the snowpack.
- Wind-drifted snow on top of loose new snow gives unfavourable layering.
- Solid new snow or wind-drifted snow over loose old (faceting) snow can give rise to an unstable snowpack.
- Cold snow over warm snow, particularly if the latter is wet, is not favourable. This can lead to constructive transformation due to the presence of moisture (latent heat) which is buried in the snowpack.
- Compact, old snow over faceted crystal snow or depth hoar provides a basis for an unstable snowpack.

9.4.5 Avalanche danger signs

When traversing terrain in order to evaluate stability, it is important to include as many observations as possible in the overall evaluation. Below is a summary of various avalanche danger signs. If rumbling occurs and shooting cracks and avalanches are observed, it can be assumed that the avalanche hazard level is 4.

Rumbling in the snowpack

If rumbling is heard in the snowpack, it is important to dig down into the snow in order to find the weak layer that collapsed, and not simply assume that it occurred in a particular layer. In some cases, rumbling can occur on flat ground (boggy areas with a lot of bushes or thickets), without any weak layer having been identified on slopes.
Rumbling is a sign of weak layers collapsing, and is caused by air being forced out of the snowpack from persistent weak layers in the form of surface hoar layers (vertical surface hoar), faceted snow or surface hoar. Faceted snow and surface hoar in particular contain a lot of air, because they consist of large crystals surrounded by air-filled pores. The air is forced out of the layer when the layer collapses. In many cases, it is also possible to feel the collapse on the body, and a height difference often occurs between the upper and lower sides of the crack as a result of the collapse.
Rumbling has been observed with the following hazard levels (specified as % of the number of days with a given hazard level):

1) 13% with hazard level 1,
2) 22% with hazard level 2, and
3) 63% with hazard level 3 or higher.

Note that on more than one third of days on which rumbling was observed, the degree of risk was not as high as 3, so rumbling alone is not sufficient to draw any conclusions (Schweizer 2010). According to Schweizer, if avalanche activity and rumbling are observed, there is an 84% probability that the avalanche hazard level is 3 or higher.

Shooting cracks

Shooting cracks are another sign of instability. If shooting cracks are observed, it will be necessary to immediately dig down to identify the layer that caused the cracks. The cracks occur because of stresses in the snowpack and unfavourable layering. If the conditions do not facilitate avalanche triggering, e.g. because the slope is not sufficiently steep, the crack will not lead to an avalanche. In other cases, the crack can propagate across a slope some distance away and cause a remotely triggered avalanche.

The cracks indicate a collapse in a weak layer, and a small height difference can often be seen on either side of the crack, which indicates how much the snowpack settled.

The hazard level linked to shooting cracks is as follows (specified as % of the number of days with a given hazard level):

1) 2.6 % with a hazard level of 1,
2) 1.6 % with hazard level 2, and
3) 41% with hazard level 3.

If rumbling occurs and shooting cracks and avalanches are observed, it can be assumed that the hazard level is 4.

Naturally triggered avalanches

Fresh avalanches which are triggered naturally provide direct feedback on the avalanche hazard level. Large, naturally triggered avalanches will not be expected if the hazard level is low. Fresh avalanches indicate large stresses and unfavourable layering in the snowpack, which leads to a high degree of instability.

Observations of avalanche activity compared with a forecast hazard level have been analysed by Schweizer et. al (2018). The number of naturally triggered avalanches increases (non-linearly) with increase in the forecast hazard level. From hazard level 2 to hazard level 3, the number of naturally triggered avalanches doubled in dry snow. In the case of wet snow, there is a three-fold increase.

The number of days (specified as % of the number of days with a given hazard level on which avalanche activity was observed) is as follows:

1) 7.2 % with hazard level 1,
2) 22 % with hazard level 2,
3) 50 % with hazard level 3, and
4) 99 % with a hazard level 4.

Small slippages

Small slippages are another sign of instability. Small slippages indicate that there are stresses present in the snowpack which can trigger avalanches and that little or no additional load will be required to trigger an avalanche. It will be necessary to assess whether the slippages are limited to small slabs only, or whether there is potential for larger avalanches to be triggered. An assessment must also be made of the elevations and exposures where the danger occurs.

Hollow sounds in the snowpack

Hollow sounds emanating from the snowpack when walking on or striking the snowpack are a sign that the snowpack consists of a hard slab with a looser, underlying weak layer. The hollow sound is caused by an increase in the volume of air between the crystals in the weak layer. The increase in the volume of air may be caused by settlement in the snowpack, constructive transformation or destructive transformation. The combination of a slab and a weak layer with a high pore volume (air) is unfavourable and can be unstable.

Signs of wind transport

The accumulation of snow, wind-affected snow, leeward sides, waves in the snow and wind accumulations are all signs of wind and snow transport. It is important to note where the snow has accumulated (which are the leeward sides) and to assess the stability of the leeward slopes. The wind can also blow across a slope and cause the cross-loading of snow. Cross-loading can give rise to unstable slopes in gullies and hollows, even without a lot of snow in the terrain, and do not always appear as potential leeward slopes. It is important to observe wind transport which is in progress and to assess the consequences of this as regards the distribution of snow in the terrain, layering and the stability of the snowpack.

Fresh snowfall

Heavy snowfalls increase the load on the snowpack and will normally result in an increase in the avalanche hazard level until the snow stabilises again. A fresh snowfall will increase the load on weak layers down inside the snowpack by increasing the load on the snowpack, and by increasing creep. The stresses in the snowpack will increase as a result. The increased stresses will persist until they are either dissipated or the snowpack stabilises again. In theory, persistent weak layers will remain in the snowpack until they melt or until they collapse and an avalanche is released. Weak layers, such as layer transitions (poor bonding/different hardnesses) and snow-covered new snow will stabilise within a few hours or days, depending on the temperature. It will take longer in very cold conditions.

Loose snow avalanches can occur a few hours after a snowfall. The snow crystals will immediately bond to each other relatively well, but the risk of naturally triggered loose snow avalanches will increase once destructive transformation weakens the strength of the snow crystals' structure. The challenge with fresh snow is to predict when the snow has formed a slab and represents a threat in the form of a slab avalanche. As long as it concerns a loose snow avalanche, it is less likely that humans will trigger an avalanche or that infrastructure will be damaged. Loose snow avalanches are largely naturally triggered.

Rapid temperature rises

Rapid temperature rises increase creep in the snowpack and thereby increase stresses, which can ultimately result in the triggering of an avalanche. The temperature must rise to well over 0°C in the release area in order for the avalanche hazard level to increase. What can be challenging is to predict how far down in the snowpack the temperature change will reach. Some experience will be necessary to understand the effects of rapid temperature rises. It is therefore important to monitor the effects of temperature rises when they occur. It is primarily the increase in snow creep which impacts on the avalanche risk, rather than how far down inside the snowpack the temperature rise reaches. Avalanche release may therefore occur deeper inside the snowpack than the temperature rise has reached.

If windy conditions occur during spells of mild weather, the effect on the snowpack will increase. If the air humidity is also high, the impact of the mild weather and the wind on the snowpack and snow melt will increase further. The cold snow surface cools the moist air, resulting in an increase in the condensation of moisture on the snow and thereby leading to an increase in the moisture content of the snow. The condensation releases heat, further increasing the melting effect of the warm, moist air. An increase in the moisture content of the snow causes an increase in the melting effect due to the high thermal conductivity of the water. When meltwater seeping through the snowpack freezes to ice on the snow crystals, heat is given off, causing the temperature of the snow to rise. During the spring, this will eventually lead to the snowpack reaching a temperature of 0°C (isothermal snowpack).

Dry, warm air, e.g. a Foehn wind, requires stronger winds and higher temperatures in order for similar melting to occur, compared with moist air. Dry air causes the snow to sublimate (transition from ice to vapour), and the heat of vapourisation draws energy from the snowmelt heat. This results in a decrease in snowmelting, and dry snow can occur on the surface, even though the temperature is high and a wet snow surface would be expected. The effect of the wind on the snowpack, by applying warmth or cooling, is known as 'convection'.

Rain on the snowpack

Rain in the release area leads to an increase in the load on the snowpack, but also causes the bonds to become weaker. Both these factors lead to an increase in creep in the snowpack, and to stresses being generated in the snowpack. Once the stresses become sufficiently large, fractures can occur in the layering, followed by avalanche release. It is the risk of wet, or partially wet, slab avalanches that initially poses the greatest threat. An increase in avalanche risk due to rain is particularly relevant for the first rainfall. An increase in avalanche risk due to wet weather will persist for a few hours before the risk diminishes again. The increase in avalanche risk depends on the precipitation being sufficiently heavy. Small amounts of rain are often absorbed by the upper part of the snowpack without any impact on the avalanche risk.

When the bonds in the snowpack weaken due to an increase in moisture content, the snowpack will eventually settle. The moisture content in the snow causes the snow crystals to stick together due to the capillary forces in the water membrane around the snow crystals. It is this process which causes the snowpack to stabilise again and the risk of slab avalanches to diminish.

Further smelting or wet weather can increase the risk of slush avalanches. If the moisture content is sufficiently high, oversaturation of free water in the snowpack will occur, impacting on the risk of slush avalanches.

If the temperature drops below freezing point after the snow has become damp, the wet snow will freeze and the snowpack will stabilise.

Prolonged cold weather

Long spells of cold weather, particularly on thin snowpack and in exposed locations, lead to constructive transformation, which results in large, unstable crystals. Depth hoar and faceted snow, along with surface hoar, form persistent weak layers. The thinner the snowpack that is subjected to low temperatures, the faster the transformation will occur. The transformation process accelerates as the temperature drops. In order for constructive transformation to take place, the temperature in the snowpack must increase towards the ground. This is called a 'temperature gradient', and it must be greater than or equal to 1°C per 10 cm (the snow is colder towards the surface than at ground level). The temperature gradient should be monitored around crust layers, as constructive transformation usually occurs just below or above crust layers.

Variations between night and day temperatures – diurnal recrystallisation

It is also necessary to remember that the difference between day and night temperatures creates positive and negative temperature gradients at the surface, which can lead to the formation of *near surface facets*, i.e. the formation of facets close to the surface. This process is known as diurnal recrystallisation. The name refers to the fluctuations between day and night temperatures. This process does not produce such large facets as those which are found beneath crust layers. Nevertheless, when the facet layer is covered by a slab, a new avalanche problem arises, as a result of the presence of facets between the fresh slab and the older snow. Near surface facets can be identified in the snow profile and through stability tests (see near surface facets).

Surface hoar

The formation of hoar on the surface is caused by a combination of low temperatures, still air and frequently high air humidity. Surface hoar is the crystal type which represents by far the greatest threat and results in most fatal accidents of all the snow crystal types. It is important to monitor the formation of surface hoar, but it is often destroyed by wind, sun or high temperatures before it is buried by snow. It is therefore important to monitor the weather conditions after the surface hoar has formed.

The hoar often lies flat on the snowpack, making it difficult to see with the naked eye. It is therefore important to pay close attention when performing tests on the snowpack and to check all fracture surfaces. Surface hoar can also be buried vertically in the snowpack, which makes it easier to see. Always verify slip planes in the snow profile in order to see whether surface hoar is present.

Falling temperatures during snowfall

Cold snow falling on a wet surface leads to a buried moist layer. The wet snow cools and latent heat is given off when the wet snow freezes, and the wet snow acts as a source of moisture. If the temperature gradient is sufficient, this can, when combined with the moisture, lead to high growth rates and thereby faceting. The result is the formation of facets above the newly formed crust layer (Colbeck and Jamieson, Jamieson, Tønnesen). The situation described above is a typical example of fresh snow which does not bond well with the snow on the surface and can lead to an avalanche risk.

9.4.6 General considerations regarding avalanche forecasting

An avalanche forecast is a process which involves the processing of large quantities of information of widely varying quality and accuracy. There will very probably be numerous error sources and a certain degree of uncertainty. We already know that there is considerable *spatial variability* in the snowpack. This means that the results of investigations and tests can vary significantly on an individual slope. The methods behind producing avalanche hazard forecasts are based on research, and there will be variations and inaccuracies in the collected data that forms the basis for the research. By analysing large quantities of data, researchers often propose different parameters of instability based on values such as mean, median, etc. This means that the outer limits (max./min. values) are not accorded the same importance. The thickness of a weak layer or the size of crystals in a weak layer is often defined using given threshold values for instability.

For example, investigations have been carried out into the size of snow crystals in weak layers on slopes where avalanches have occurred. These findings are then compared with slopes where no avalanches have occurred. A link has been found between snow crystal sizes of >1.25 mm and unstable slopes. Snowpacks with weak layers consisting of snow crystals which are smaller than this are "defined" as being less unstable. The same can be done with the thickness of weak layers, where tests indicate that 10 cm is the upper limit for the thickness of a persistent weak layer in terms of an unstable snowpack. The limit values do not mean that the snowpack is stable outside the critical values. People have lost their lives in avalanches where the crystals have been smaller than 1.25 mm, and also when the weak layer has been more than 10 cm thick. Instead of using the critical values as absolute values, it is necessary to use them as reference values and be particularly alert when the conditions approach these values.

As regards the properties that should be assessed, there are also differing opinions regarding the different recommendations and research results. When a test indicates a correlation between the thickness of the weak layer and slope instability, other tests have indicated that this correlation also applies to stable slopes. In other words, different research results alternate between assessing the thickness of the weak layer as a threshold value and disregarding the thickness completely.

However, there is no doubt of the fundamental parameters which lead to instability. The following factors are noted:

- Unstable snowpacks are layered.
- The layering consists of at least one weak layer.
- Above the weak layer is a slab.
- The slab must have a certain hardness in order to propagate fractures, but it must not be too hard or too soft.
- A thin snow crust can fracture due to an additional load without the overlying snow being sufficiently hard to be called a slab.
- Persistent weak layers consist of larger crystals caused by constructive transformation or surface hoar and often has a certain looseness.

- A weak layer can also consist of unbonded snow in the form of new snow, a layer in wind-drifted snow, wet snow or a smooth crust.

9.4.7 Systematic structure of an avalanche forecast

Summary – Strength, Energy and Danger signs

The table below collates various results and provides us with an indication of the level of danger indicated by our observations, before the weather forecast for the forthcoming day is taken into consideration. Strength is evaluated on the basis of the tests. Energy is evaluated on the basis of the shear quality. The number of danger signs is based on the various danger signs that have been obtained while observations were being made.
The danger signs that are used here are Yellow Flags (Jamieson B, Schweizer J, 2005); depth to weak layer (20–85 cm), hardness of the overlying slab > 1F, snow crystal type (persistent), difference in hardness > 1, crystal size > 1 mm, difference in crystal size between the layers > 0.5 mm.
The table below divides test results into red, yellow and green colour codes.

	Strength	Energy	Number of danger signs
RED	CT 0–5 ECTPV ECTP	Q1	4–5
YELLOW	CT 5–20 ECTN	Q2	2–3
GREEN	CT 20–30 ECTX	Q3	0–1
Remarks	Wide spatial variation	Less spatial variation	Less spatial variation

Table: 9.3: Summary of test results

When test results are summarised, it is apparent from the table that the evaluations end up in the red, yellow or green zone, where red indicates the highest degree of instability.

Weather forecasts

Once a good overview of the current situation in the snowpack has been obtained, the weather forecast must be taken into consideration. The forecast weather for the next 24 hours could impact on the stability of the snowpack.

It is necessary to evaluate whether the forecast weather would cause an additional load on the snowpack, and whether the stability of the snowpack will be affected by this. An increase in the load on the snowpack can be caused by precipitation or wind accumulation, an increase in tensile forces due to mild weather or the decomposition of bonds due to rain or snow melting. It can be difficult to decide whether the anticipated effects will occur during the impending period covered by the avalanche forecast. It is therefore important to monitor the effects of different weather situations in order to gain experience of the impact of the weather on the snowpack. For more detailed information on the impact of the weather on the snowpack, see Chapter 6.

Avalanche size

In order to use various aids and produce an avalanche forecast, it is necessary to evaluate what sizes of avalanche would be expected to occur. Avalanche sizes are divided into a 5-step scale with associated descriptions. The scale is based on avalanche sizes which have been agreed upon by the European avalanche forecasting services.

AVALANCHE SIZES			
Size	**Description**	**Run-out classification**	**Volume**
1 **Small**	Low risk of being buried (risk of slippage)	The avalanche stops on the slope itself	<100 m^3

2 **Medium**	Could bury, injure or kill a person	The avalanche stops at the foot of the slope	<1000 m^3
3 **Large**	Could bury or damage cars, damage trucks, small buildings and forests	The avalanche could extend beyond the foot of the slope and up to 50 m out into gently sloping terrain (much gentler than 30 degrees)	<10,000 m^3
4 **Very large**	Could bury or damage trains and large trucks, many buildings and forest areas	The avalanche could extend across gentler terrain (much less than 30°) over distances of more than 50 m and reach all the way to the valley bottom	<100,000 m^3
5 **Extremely large**	Can damage the landscape Catastrophic damage possible	The avalanche reaches the valley bottom Largest known avalanche	>100,000 m^3

Table 9.4: Subdivision of avalanche sizes

This 5-step scale for the subdivision of avalanche sizes is used by the European forecasting services.

The subdivision of avalanche sizes is used both to calculate avalanches which have already occurred and to determine the anticipated size of an avalanche which could be released. An avalanche which has already occurred and which has a mean fracture line of 0.5 m and a released slab measuring 70 x 50 m, has a volume of 1,750 m3. This avalanche is designated as being size 3.

To specify the anticipated size of a potential avalanche, it is necessary to determine the thickness of the slab which could be released (the depth of the weak layer) and the ability of the slab to propagate fractures. It is difficult to predict how large an avalanche could become, but using information from the snowpack, it is possible to distinguish between small, local avalanches with thin slabs and avalanches with thick slabs which are expected to propagate across a large slope and become a large avalanche.

9.4.8 Decision-making support for the issuing of avalanche forecasts

Various aids can be used to determine avalanche risk based on all observations and available information on the snowpack and the forthcoming weather. The sub-sections below present certain tools which summarise the decision-making basis and support our decisions.

ADAM

ADAM is an abbreviation for Avalanche Danger Assessment Matrix, which has been developed by NVE's avalanche forecasting service (NVE 2019 Skredfarevurdering). To determine the degree of risk, the probability of avalanche release must first be determined. This probability is defined by the sensitivity of the snowpack to avalanche release and the distribution of the avalanche problem.

The descriptions and explanations of the terms used in ADAM are summarised below table 9.5.

Sensitivity to triggers		Slopes		
Natural release	Triggered	Few	Some	Many
Extreme loading/ weakening		C	E	E
Heavy loading/ weakening	Very easy to trigger/ touchy	B	D	E
Moderat loading/ weakening	Easy to trigger/ reactive	B	C	D
Minimal loading/ weakening	Difficult to trigger/ stubborn	A	B	C
	Very difficult to trigger/	A	A	B

Avalanche Hazard Level		Avalanche size			
		Sz 1 Small	Sz 2 Medium	Sz 3 Large	Sz 4/5 Very/ Extr. large
Probability of triggering	E	3	4	4	5
	D	2	3	3	4
	C	1	2	3	4
	B	1	2	2	3
	A	1	1	2	2

Table 9.5: Avalanche Danger Assessment Matrix ADAM

The matrix for probability gives a letter code from A to E, which in turn is inserted in the left-hand column of the *matrix for avalanche risk* below. By assuming a certain size of potential avalanche, a degree of risk is determined for an avalanche.

Description of terms used in ADAM

Avalanche trigger

Avalanche trigger describes the sensitivity of the snowpack to avalanche release; in other words, how easy it is for a person to trigger an avalanche or whether naturally triggered avalanches would be expected. Avalanche triggers are divided into four classes which are defined as follows:

1) **Very difficult to trigger / No natural avalanches*** – There is little or no avalanche problem. The snowpack has no well-developed weak layers, it is difficult to initiate a fracture and the ability of the snowpack to propagate fractures is poor. Naturally triggered avalanches are rare or mostly of avalanche size 1.

   Typical observations: unbonded dry snow; hard and compact snow; absence of class I observations (recent avalanche activity, rumbling, shooting cracks); stability tests give little or delayed results without fracture propagation: ECTX/ECTN >20 / "step-shaped" fractures during tests.

2) **Difficult to trigger / Few natural avalanches*** – There is an avalanche problem, but it is not very pronounced. The snowpack has some weak layers, but these layers either have a poor ability to propagate fractures or are situated deep and/or are well-protected beneath hard (stable) layers. *Some naturally triggered avalanches may occur. These are often loose snow avalanches and/or wet avalanches and are rarely larger than avalanche size 2.

   Typical observations: few class I observations (individual recent avalanches; rumbling may occur; no shooting cracks), ECTN; "step-shaped" fractures during tests.

3) **Easy to trigger / Some natural avalanches*** – There is an avalanche problem in the uppermost metre of the snowpack. One or more weak layers are well-developed. These can easily be released by a person or a heavy snowfall, for example, but they do not always

have a good ability to propagate fractures (e.g. the avalanches rarely become large). *Many naturally triggered avalanches can occur, but they are rarely larger than avalanche size 3.

<u>Typical observations:</u> some class I observations (recent avalanches; rumbling in the snow; short shooting cracks); ECTP > 10; smooth fractures in some tests.

4) **Very easy to trigger / Many natural avalanches*** – There is an avalanche problem in the uppermost metre of the snowpack. One or more weak layers are well-developed. These can easily be released by a person or a heavy snowfall, for example and they have a good ability to propagate fractures. *Numerous naturally triggered avalanches can occur, including avalanches up to size 4/5.

<u>Typical observations:</u> unequivocal class I observations (recent avalanches; rumbling in the snow; long shooting cracks); ECTP <10; light and smooth fractures in some tests.
* dependent on the weather conditions and the distribution

Distribution of the avalanche problem
Distribution describes the number of slopes within an area of 100–200 km^2 which are expected to have an avalanche problem with a given “avalanche trigger”. There will for example be “some” slopes on which avalanches are “easy to trigger”, while on all other slopes, avalanches will be “difficult to very difficult to trigger”. It will sometimes be possible to identify one or more cardinal directions which are more exposed than others. This will then provide additional information which will make it easier to avoid the avalanche problem. In practice, the evaluation will depend on how easy it is to detect the avalanche problem and in which terrain formations, if any, it is most prominent.

“Distribution” is divided into three levels, depending on typical signs that an avalanche problem exists:

1) **Few**:
   a. The avalanche problem only exists in very exposed/specific terrain formations.
   b. No danger signs are observed (with the possible exception of a few small avalanches).

2) **Some**:
   a. The description for neither “few” nor “many” slopes fits.
   b. The avalanche problem is often linked to certain typical terrain formations.
   c. <u>Some</u> danger signs are observed.

3) **Many**:
   a. The avalanche problem exists across most terrain formations (possibly within a certain elevation interval).
   b. Many danger signs are observed.
   c. Remote triggering is possible.

The following questions should be asked when evaluating distribution:

- How easy is it to detect an avalanche problem?
- Where in the terrain is the avalanche problem located?
  - Does it only occur in special terrain formations?
  - How widespread is this type of terrain formation in the area/region?
- Have many danger signs been observed (recent avalanches, rumbling, shooting cracks)?
- Is remote triggering possible?

Terrain formations describe geographic phenomena across a wider mountainside: gullies, ridges, edges, knolls, bluffs, hollows, cliffs, leeward sides, open slopes, shady sides and mountain sides exposed to the sun.

Avalanche size

The matrix for avalanche size describes the run-out lengths and damage potential of the various sizes of avalanche. The scale for avalanche size is logarithmic, i.e. if a size 2 avalanche is expected, a few avalanches of size 3 and possibly even more of size 1 may also occur, but size 4 avalanches should not occur.

For details of avalanche sizes, see Table 9.4.

Using the avalanche risk scale to determine the degree of risk

The Avalanche hazard scale can also be broken down to use the snowpack analyses in order to determine the hazard level. The avalanche risk scale is presented in section 9.1. The avalanche hazard scale is considered again below, but this time, the scale has been broken down into *additional load, distribution* and risk of *naturally triggered avalanches*.

Hazard level	Snowpack stability	Additional load	Distribution	Naturally triggered avalanches
1 Low	The snowpack is generally well-bonded and stable.	Avalanche triggering is generally only possible with high additional loads.	On a few extreme slopes	Only small or medium-sized naturally triggered avalanches are possible.
2 Moderate	The snowpack is moderately well-bonded on some steep slopes; bonds are otherwise strong.	Triggering is possible, particularly with high additional loads.	On some steep sloes	Very large naturally triggered avalanches are not expected.
3 Considerable	The snowpack is moderately to weakly bonded on many steep slopes.	Triggering is possible, also with minor additional loads.	On many steep slopes.	Under certain circumstances, some large, occasionally very large, naturally triggered avalanches are expected.
4 High	The snowpack is weakly bonded on most steep slopes.	Triggering is probable, even with small additional loads.	On many/most steep slopes.	Under certain circumstances, many large and some very large naturally triggered avalanches are expected.
5 Very high	The snowpack is generally weakly bonded and very unstable.	Small additional load / natural triggering.	Also in moderately steep terrain	Many very large, and in some cases extremely large, naturally triggered avalanches are expected.

Table 9.6: The avalanche hazard scale broken down into *additional load*, *distribution* and *naturally triggered avalanches*

Dividing the likelihood of avalanches into the three factors, additional load, distribution and probability of naturally triggered avalanches, makes it easier to use the avalanche risk scale to support decisions relating to hazard level. It also helps to indicate what factors to look for when making observations in the field.

The tests on the snowpack will help to determine what additional load the layering will tolerate (see section 9.4.3.3 Additional load for more details). Distribution is evaluated through observations of the snowpack and an understanding of the processes that lead to the formation of the various types of snow crystals (see section 9.4.3.4 Distribution for more details).

Frequency of slab avalanches at different hazard levels

If slab avalanches are observed or there are confirmed indications of the likelihood of slab avalanches, the matrix published by SLF (the Swiss Federal Institute for Snow and Avalanche Research in Davos, Switzerland) of frequencies of slab avalanches against the various hazard levels may be used. 'Artificially triggered avalanches' also includes avalanches triggered by skiers. This matrix distinguishes between artificially triggered, remotely triggered and naturally triggered avalanches. Naturally triggered avalanches require an increase in load (in the form of precipitation) or weakening of the bonds (heat, rain). In order for remote triggering to be possible, the snowpack must be loaded, and a weak layer must collapse as a result of the additional load. The weak layer, in this case, will consist of large crystals from constructive transformation (facets, depth hoar or surface hoar).

Hazard level	Artificially triggered avalanches	Remotely triggered	Naturally triggered avalanches
1 Low	Rare	Very rare (normally small)	Rare
2 Moderate	Isolated	Rare	Rare
3 Considerable	Typical	Isolated to typical	Isolated to typical
4 High	Frequent	Typical	Typical (large avalanches to some extent)
5 Very high	Frequent	Frequent	Frequent (often very large avalanches)

Table 9.7: Frequency of avalanches broken down between the various hazard levels

The frequency of the various avalanches is divided into a 4-step scale broken down according to the following evaluations: rare, isolated, typical and frequent (source: SLF, Switzerland).

Large, naturally triggered avalanches often start high up and extend all the way down to the valley bottom.

Summary of the decision-making basis

If several buddy pairs make observations and collect information, it may be useful to summarise and compare the information obtained from each pair, rather than simply comparing the conclusions. Such a summary can easily be prepared using the table below. This is the same procedure as that used by avalanche groups during major exercises. It also provides a good overview of developments in the snowpack over time and therefore acts like an "archive" of previous evaluations of the snowpack. The overview must be prepared for each of the avalanche problems concerned.

Avalanche problem 1			
	Pair 1	Pair 2	Example
Avalanche trigger			Difficult
Distribution			Isolated slopes
Likelihood of release*			A
Size			Size 1
Degree of risk			1
Exposure			NW-N-NE
Elevation			0–1000 m a.s.l.
Probability**			Unlikely

Table 9.8: Summary of the decision-making basis

***Probability of release:** Letter code between A and E from the ADAM matrix for likelihood.

****Probability:** Text to be inserted in the avalanche forecast which describes the probability of an avalanche being released. Description of probability according to the criteria below:

1) Very probable
2) Probable (EAWS – More than 50% probability of an avalanche being released)
3) Possible (EAWS – Less than 50% probability of an avalanche being released)
4) Unlikely

9.5 Issuing of avalanche forecast

Avalanche forecasts during exercises

During all exercises where there is a possibility of avalanches occurring, qualified personnel who prepare daily avalanche forecasts must be subordinated to the exercise leader (UD-2-1 section 5.13.2.8, (2018-07-10)). For details concerning the establishment of an avalanche group, see Chapter 11 Establishing an avalanche group). The personnel must have completed an avalanche forecasting course run by the Norwegian School of Winter Warfare (UD 2-1 section 5.13.2.7 (2018-07-10)). During exercises involving more than one battalion or equivalent, an avalanche group must be established which issues daily avalanche forecasts which are valid for 24 hours (UD2-1 5.13.2.8 (2018-07-10)). In the event of unforeseen changes in the weather situation, it must be possible to increase the avalanche hazard level at short notice. Such an evaluation will often be carried out in the morning during the period covered by the current avalanche forecast following a re-assessment of the weather forecast and the weather situation. It is important that the avalanche forecast reaches all participating units, right down to individual teams and patrols.

Military avalanche forecasts

A military avalanche forecast should state at least a hazard level and the period during which the forecast applies. To improve the information that reaches the units involved in an exercise, avalanche forecasts should also include:

a) Avalanche problems
b) Most exposed terrain, in terms of both elevation and exposure
c) Distribution (few, some or many steep slopes)
d) Probability of avalanche release

The following information may also be useful:

e) Avalanche type

f) Avalanche size (1–5)

g) Cause of release (natural, small or large additional load)

Probability of triggering an avalanche follows the descriptions given below:

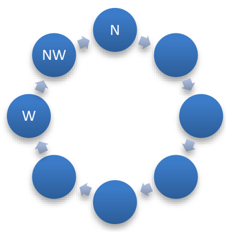
- Very probable
- Probable (* EAWS – More than 50% probability of an avalanche being released)
- Possible (* EAWS – Less than 50% probability of an avalanche being released)
- Unlikely

The following tables show examples of avalanche forecasts:

Avalanche forecast valid from: **10 DTG 052000Z – DTG 062000Z MAR 2018**	
Degree of risk	Danger level 2 – Moderate 

Table 9.9: Military avalanche forecast with minimum content

The hazard level can also be described numerically instead of using illustrations.

Additional information for units with approval to traverse avalanche terrain:	
Avalanche problem 1	Wind-drifted snow
Cardinal direction	 (W to N)
Elevation	700–1000 m a.s.l.
Distribution	Few slopes
Avalanche trigger	Easy to trigger
Probability of release	Probable
Avalanche type	Slab avalanche

Avalanche size	1 Harmless

Table 9.10: Avalanche problem 1
Example of additional information for divisions with approval to traverse avalanche terrain

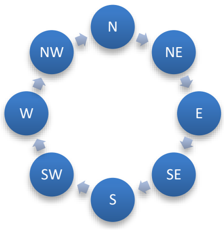
Additional information for units with approval to traverse avalanche terrain:	
Avalanche problem 2	Persistent weak layers
Cardinal direction	 (All cardinal directions)
Elevation	400–700 m a.s.l.
Distribution	Few slopes
Avalanche trigger	Difficult to trigger
Probability of release	Unlikely
Avalanche type	Slab avalanche
Avalanche size	1 Harmless

Table 9.11: Avalanche problem 2
Example of additional information for divisions with approval to traverse avalanche terrain.

Error sources in forecasts

One of the challenges to be faced when preparing avalanche forecasts is to make observations and evaluations, and to take decisions in an objective manner. Our observations and decisions are often subconsciously influenced in a way that forms a prejudiced picture of the situation, or a picture we wish to form. If a unit is to relocate in challenging mountain terrain, many preparations must be made in advance, and expectations will be formed. These expectations will influence our observations and decisions. There will also be a desire to succeed with the planned action in which time, energy and emotions have been invested. Peer pressure can develop within a group which can influence our decisions.

The avalanche forecaster or avalanche group must distance themselves from subjective expectations and opinions, so that they have the best possible basis for issuing as objective a forecast as possible. Otherwise, our snow and avalanche expertise will be of little benefit. Avalanche forecasters should therefore have a specific task which is separate from the unit's operational plans, goals and wishes. In order for the work involved in preparing avalanche forecasts to be traceable and transparent, it should include a quality control system. This could for example be a log of the work, to create a basis for a decision, and valid avalanche forecasts from day to day. All observations which are avalanche-related must be entered in this log. This could include snow profiles, slippages, rumbling in the snow, the amount of loose snow, the weather, accumulated precipitation, etc. Avalanche forecasting must not be based on a single snow profile and a single set of tests, and the hazard level must be determined on the basis of several profiles from different elevations and exposures, observations of signals in nature and updated weather forecasts.

Figure 9.10: The human factor and our evaluation
It is important to ensure that the subjective aspects of an avalanche forecast are minimised or avoided altogether, and that the forecaster considers known facts.

Other possible error sources in avalanche forecasts include variations in the characteristics of the snowpack and the validity and interpretation of the tests. By building up experience of the avalanche forecasting process, one becomes more aware of variations in the characteristics of the snowpack, and better at interpreting the various observations and tests on the snowpack. Experience of avalanche forecasting and testing of the snowpack can help to reduce the significance of test results as an error source. Test results can influence the impression of the stability of the snowpack, either because they over or underestimate the probability of avalanches or because the tests were carried out in the wrong locations and therefore do not reflect the actual conditions.

11 Avalanche Map M711 SK

11.1 General

The M711 map series, at a scale of 1 : 50,000 and equidistance 20 m, covers the entire country with its 727 map sheets. Avalanche maps (M711 SK) are based on M711 maps, but show release and run-out areas for avalanches based on NGI's topographic model. The terrain has also been inspected and evaluated by specialist personnel in order to identify zones which are not immediately apparent from the contours. The maps were prepared for the Norwegian Armed Forces in connection with the planning and execution of exercises. A total of just under 100 map sheets have been prepared showing avalanche release and run-out zones. These maps cover the areas in which most of the Norwegian Armed Forces' exercises take place.

The safety margins on the avalanche maps take account of the 100-year avalanche, and the run-out zone is dimensioned accordingly, i.e. it is considered likely that an avalanche can reach the end of the run-out zone with a return period of 100 years. In order for avalanches to reach their maximum range in the run-out zone, they must be large, i.e. the terrain must be extensive, there must be a lot of snow and conditions must be unstable with good fracture propagation characteristics. Avalanches which are released on short slopes cannot grow into large avalanches in terms of volume, but they can still extend across flat terrain. Maps which take account of risk linked to infrastructure are significantly stricter, and the safety margins take into account the maximum reach of avalanches during a 1000-year cycle. A section of an avalanche map is shown in Figure 10.1 (1432 III GRATANGSBOTN).
Digitally prepared slope angle maps, where the terrain has not been visually inspected, have been made available on the following websites: www.skrednett.no and skredkart.ngi.no. Slope angle

maps without run-out zones are also available via www.senorge.no, www.xgeo.no and in Varsom and NGI's application.

Statistically, the lowest slope angle for the release of slab avalanches is considered to be around 30°, although slab avalanches are also released on slopes with angles of as little as 25°. When the equidistance is 20 m, 30° corresponds to a distance between contours of 0.7 mm. If the distance between the contours is less than or equal to this, the slope will be sufficiently steep for a slab avalanche to be released. In this way, possible release areas can be delimited on the map. It is important to be aware that steep slopes which are less than 30–40 m high often cannot be detected using the contours on a map. The steepness between contours shows the average slope of the terrain. For short slopes up to 40 m high, we only have the difference in height between two contours to use as a basis. Maps in this scale are not sufficiently accurate to determine the steepness of short slopes. The Norwegian Armed Forces' avalanche maps have therefore been checked to identify such hidden steep slopes.

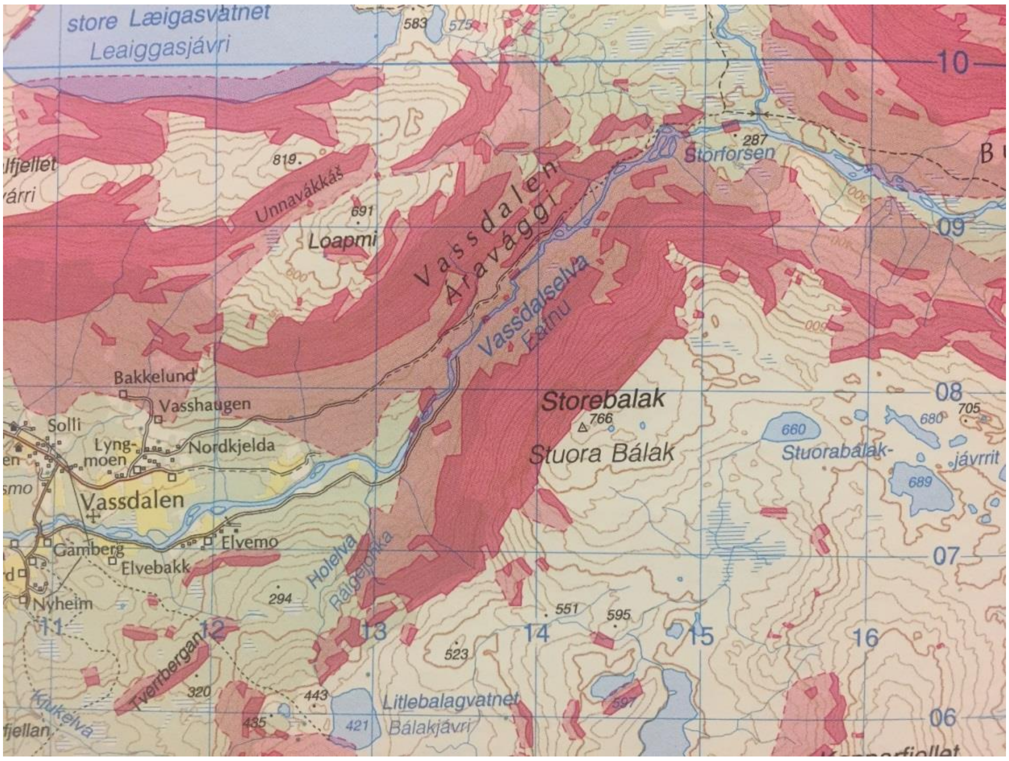


Figure 10.1: Avalanche map *1432 III GRATANGSBOTN*

The dark pink colour indicates the release area (zone I), while the pale pink colour indicates the run-out area (zone II).

The dark pink colour indicates zone I, which is terrain steeper than 30°, also known as the 'release area'. The pale pink colour indicates zone II, which is the run-out area. The valley bottom in Vassdalen is an example of an axis that will be closed off in the event of avalanche hazard level 4 – High avalanche risk. The road axis north of the river Vassdalselva will be closed in the event of avalanche hazard level 2 or 3. In overlapping run-out areas, it is difficult to define where the maximum run-out length or half-way out into the run-out area lies, viewed in relation to military movement rules.

11.2 Zonal subdivision of avalanche maps

The maps have been divided into the following zones (see Figure 10.1):

– Zone I: Avalanche release area. Dark pink colour code.

– Zone II: Avalanche run-out area (based on 100-year avalanche*) Pale pink colour code.

* A 100-year avalanche is an avalanche which is only expected to occur once in a hundred years.

Zone I

Zone I is based on the map contours and is marked where the distance between 20 m contours in 0.7 mm or less, i.e. 30° or steeper, and where there is no dense forest. Zone I is indicated by a dark pink colour. The terrain in zone I is sufficiently steep for an avalanche to be released. Some steep areas have been omitted because the forest is so dense that the risk of avalanches is considered to be low (following visual inspection).

The colour code for zone I is RGB (230, 66, 143) with a solid contour line in colour code RGB (201, 38, 115).

Zone II

Zone II is terrain situated below the release areas which can be reached by avalanches, known as the 'run-out area'. Zone II is indicated by a pale pink colour. The extent of Zone II is determined using a method which estimates how far an avalanche might extend, based on experience of a large number of avalanche paths (NGI's topographic model). As zone II is based on a nominal annual probability of 1/100, this means both that a relatively large avalanche will be required in order for it to reach the outer limits of the run-out zone, and that such avalanches are not expected to occur more than once every hundred years.

The colour code for zone II is RGB (255, 186, 222) with a dashed contour line in colour code RGB (201, 38, 115).

11.3 Limitations of avalanche maps

The maps show release areas which can be identified on the basis of contours. Much of the terrain has also been inspected visually in order to identify short steep slopes which cannot be identified from the contours. Avalanches may nevertheless occur from short slopes which are not marked on the map. The height difference in stream valleys is often less than 40 m, and such valleys are not always shown on avalanche maps. Stream valleys represent terrain traps. The maps do not provide any information on how frequently avalanches occur or where in the terrain the snow accumulates. In some areas, avalanches may be released every year, while elsewhere, many years may pass between each avalanche.

11.4 Using avalanche maps

Avalanche maps are well-suited for use in the planning of exercises and routes. When planning operations in the terrain, consideration must be given to the limitations of the maps and the way in which they were produced. Because of the prevailing wind directions, the snow on certain mountainsides may have been removed by the wind. It may therefore be safe to traverse such mountainsides even if the route passes within zone I or II on the avalanche map. Note that even if the mountainside appears to be devoid of snow, there may be snow in gullies and stream valleys on the slopes. If the snowpack is thin, it may represent an increased risk. Sections of the route may also not be visible from below. In the event of uncertainty or if it is not possible to obtain a satisfactory overview, the slope should not be traversed.

11.5 Military movement rules

The Norwegian Armed Forces follow movement rules linked to the avalanche hazard level. The avalanche risk scale is printed on the reverse of avalanche maps along with movement rules. The movement rules can be found in the last column of the avalanche hazard scale and are known as 'additional military regulations' (see section 9.1).

11.6 Electronic planning maps showing release and run-out areas

Planning maps covering areas of Norway for which no avalanche maps have been prepared

Since autumn 2016, FMGT has distributed digital maps showing release areas (zone I) and run-out areas (zone II). These maps are produced by the Norwegian Geotechnical Institute (NGI) and refined in a partnership between FMGT and the Norwegian School of Winter Warfare. These maps can be used during the planning and execution of exercises in areas which the M711 SK map series does

not cover. The accuracy of zone 1 is very satisfactory, whilst that of zone 2 is variable and in some cases can extend slightly too far out into the terrain.
The Norwegian Armed Forces' avalanche maps must be used if they cover the exercise area. Contact the Norwegian School of Winter Warfare if you have any questions concerning the avalanche-related evaluations behind the basis for the map. Contact FMGT if you have any technical questions regarding the maps.

Production method and source data

The map is a further development of NVE/NGU's susceptibility maps for avalanches. The run-out area (zone II) is identical, while the release area (zone I) has been extended through the addition of areas where the slope is between 28° and 90°. No consideration has been given to dense forest either, with the result that release areas will also be found where the terrain is covered by dense forest. The data set used in the computation is the Norwegian Mapping Authority's elevation data set which has a resolution of 10 m and dates from 2013. The computation was performed using the tool Slope in ArcGIS 10.3.1.

Display on the map

To ensure that *planning maps showing avalanche zones,* prepared by FMGT and FVS, are not confused with the Norwegian Armed Forces' avalanche maps, different colours have been used to indicate release areas (zone I) and run-out areas (zone II).

Release area (zone I)

Run-out area (zone II)

RGB values of the colours:

- Release area – 255, 100, 0
- Run-out area – 255, 200, 0

Figure 10.2: *Colour codes for digital avalanche maps, planning maps showing avalanche zones, published by FMGT and FVS.*

12 Establishing avalanche groups

12.1 General

The exercise leader or person leading an activity is responsible for ensuring that an avalanche hazard evaluation is carried out for training and exercises in avalanche terrain. The professional responsibility must be delegated to a person who possesses expertise within avalanche hazard evaluation (UD 2-1, section 5.13.2.2 (2018-07-10). Terrain evaluation starts when planning of the exercise has reached the stage where the exercise area has been determined. The terrain must first be evaluated based on avalanche maps. The snowpack must be evaluated before the activity takes place, so that the avalanche forecast is valid before personnel enter the terrain. The exercise leader will use the avalanche forecast as a basis for the subsequent evaluation of personnel safety. Based on the avalanche forecast, the exercise leader must decide whether any specific measures are necessary in order to reduce risks and consequences.

12.2 Organisation of avalanche groups

In the case of exercises involving more than one battalion, a specific avalanche group must be established (UD-2-1 section 5.13.2.8 (2018-07-10)). Personnel from the avalanche group should be involved in the planning of the exercise and take part in reconnaissance of the terrain. Staffing of the avalanche group will depend on the geographic extent of the exercise area and the number of participating units. The size of the avalanche group will be determined for each exercise. If there are major climatic or geographic differences, it may be appropriate to divide the avalanche forecast into several zones. Avalanche groups should have at least two patrols, including the leader of the group. The leader of the avalanche group should report directly to the exercise leader, and the avalanche group should be administratively linked to the exercise leadership and be exempt from any other duties.

If the exercise area is extensive, it may be appropriate to decentralise the buddy pairs in the avalanche group in order to reduce travel times and prioritise time to make observations of the snowpack.

12.3 Duties and responsibilities of avalanche groups

Typical duties and responsibilities of avalanche groups are listed below:

- Acquisition of information on the snowpack and the avalanche hazard level.
- Processing of information.
- Preparation of daily avalanche forecast. The first avalanche forecast must be issued before the units commence their operations in the terrain and should be available to the units during the final part of the planning phase.
- Give avalanche instruction to the units upon request.
- Provide assistance in the event of avalanche accidents in order to assess risks in the avalanche area and in the terrain which leads into and out of the area.
- Participate in the exercise leader's planning of the exercise as and when necessary.
- The avalanche group leader should attend a daily briefing for commanders and observers/controllers.
- Assist the units involved in the exercise through the provision of further information which can help to improve the planning and execution of their operations.
- If the exercise area is extensive and there are clear differences in the snowpack, the avalanche forecast can be divided into appropriate zones.
- The exercise area should be reconnoitred by helicopter both immediately prior to the exercise and during the exercise in order to obtain an overview of the distribution of snow in the terrain and any avalanche activity. The helicopter requisition must be sufficiently flexible to enable it to be repeated when the weather conditions render it appropriate.

12.4 Avalanche group equipment and materiel

The avalanche group should possess the following equipment:

- Vehicles with trailers (the vehicles must have four-wheel drive)
- Two winter off-road vehicles (LTK-V) per patrol
- Means of communication, satellite telephones
- Avalanche probes
- Shovels
- Transceivers
- Thermometer
- Slope angle gauge
- Raster plates
- Tents/Jerven bags
- Cooking apparatus
- Solid skis, ski boots and poles
- GPS, preferably with digital avalanche maps
- Electronic search equipment (RECCO, etc.)
- Log books for snow profiles
- PC with internet access
- Overview map of the exercise area, including M711 SK (avalanche map)

12.5 Reconnaissance

The avalanche group should ideally reconnoitre the exercise area by helicopter. Reconnaissance should be carried out at the start-up of the avalanche forecasting process. Reconnaissance should also be carried out by helicopter during the exercise, depending on developments in the weather and the stability of the snowpack.

13 Appendices

Appendix 1: International Classification of Seasonal Snow on the Ground (2009)

Appendix 2: Form for snow profile (example)

Appendix 3: Form for recording observations (with explanation)

Appendix 4: Explanation for observations form

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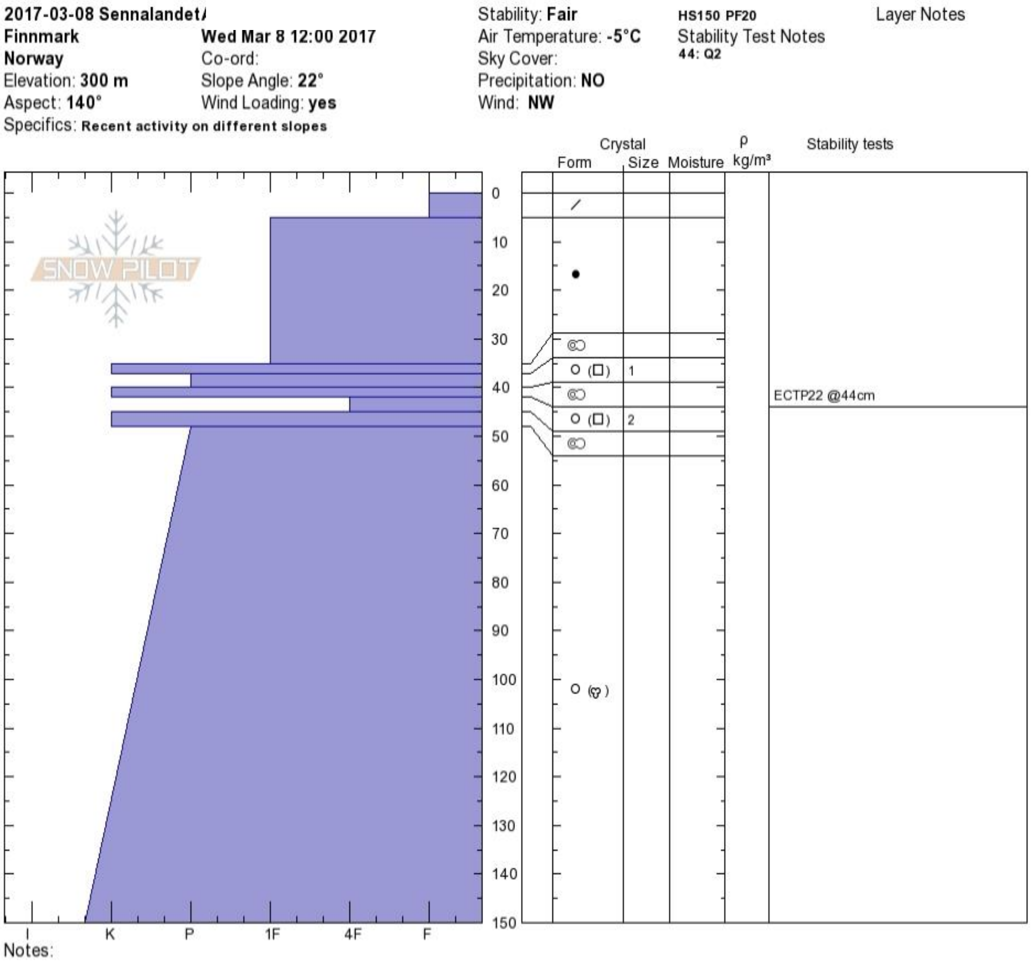
15 Effective date

This document enters into force on 2020-08-01. UD 6-81-8 E Instruction in Winter Service – Snow Awareness of 2011-02-01 shall lapse as of the same date.

Appendix 1: International Classification of Seasonal Snow on the Ground (2009)

Appendix 2: Form for snow profile (example)



Appendix 3: Form for recording observations.

Date/ Time: | **Place/ Coord.:**

A: m.a.s.l | **Treeline:** O U @ | **Slope:** ° | **Aspect:** °

Temp: °C | **Clouds:** /8 | **Precipitation:** Sn Sl R N | **Wind:** C L M S X Dir: °

Drift: Nil L M I | **Footsink:** cm | **Surf. Hum.:** D M W V S | **Stability:** G M P

Danger signs: Fresh av. Whoomping Shooting Cr Heavy snowfall Surf. hoar Rapid t °C incr. High water content

Avalanche act: None Not possible to record Last 24hrs Older than 24hrs

Loose snow av. Slab av. Slush av. Nat. rel. av. Skier trig. Snowmob. trig.

Comments:

↓ D (cm)	F	4F	1F	P	K	I	↓ t (°C)/ Humidity/Tests/Notes

A= Altitude in meters.**Treeline**: Elevation of treeline in meters. **Aspect**= direction of the pit. **Temp**= in Celsius. **Clouds**= cloudcover out of 8/8. **Precipitation**= Snow, slush, Rain, None. **Drift**= Snowdrift, Light, Moderate, Intense. **Footsink**= Footsink in cm. **Surf.Hum.**= Snow surface humidity: Dry, Moist, Wet, Very wet, Soaked. **Stability**= Good, Intermediate, Poor. **Danger signs**= Fresh avalanches, Whoomping sounds, Heavy Snowfall, Surface Hoar, Rapid temperature increase, High Water content. **Avalanche activity**= None, Not possible to record, Avalanches last 24hrs, Avalanches older than 24hrs. Loose snow avalanches, Slab avalanches, Naturally released avalanches, Skier triggered avalanches, Snowmobile triggered avalanches.

Appendix 4: Explanation for observations form

Symbol/Abbreviation	English	Norwegian
A	Elevation in metres	Høyde over havet i meter
T.L.	Tree line	Tregrense
Slope	Slope angle	Helningsvinkel/bratthet
Aspect	Pit opens towards (direction)	Snøprofilens himmelretning
Temp.	Air temp. in Celsius 2m above ground	Lufttemperatur 2 m over Bakken
Clouds	Out of 8/8	Skydekke ut ifra 8/8
Prec.	Precipitation	Nedbør
Wind	Calm, Light, Moderate, Strong, Extreme.	Flau, lett, moderat, sterk, ekstreme.
Wind Dir.	Wind direction (blowing from)	Vindretning (blåser fra)
Drift	Wind-drifted snow; Light, Moderate, Intense	Snøfokk; lett, moderat, intense
Sink	Foot sink in cm	Fotinnsynkning
Surf.Hum.	Snow surface humidity; Dry, Moist, Wet, Very wet, Soaked	Snøverflatens fuktighet; tørr, fuktig, våt, svært våt, gjennomvåt
Stability	Good, Intermediate, Poor	Stabilitet; god, middels, dårlig
Danger signs	Fresh avalanches, Rumbling, Heavy snowfall, Surface hoar, Rapid temperature rise, High water content.	Ferske skred, drønn, stort snøfall, overflaterim, hurtig temperaturstigning, høyt vanninnhold
Avalanche activity	None, Not possible to record, Avalanches last 24hrs, Avalanches older than 24hrs., Loose snow avalanches, Slab avalanches, Naturally triggered avalanches, Skier triggered avalanches, Snowmachine triggered avalanches.	Skredaktivitet; ingen, ikke mulig å observere, skred siste 24 t, skred eldre enn 24 t, løssnøskred, flakskred, naturlig utløste skred, skiløperutløste skred, skuterutløste skred.