

MONITORING SNOWPACK TEMPERATURE GRADIENT USING AUTOMATIC SNOW DEPTH SENSOR

Örn Ingólfsson*

POLS Engineering, IS-400 Ísafjörður, ICELAND

Harpa Grímsdóttir, Magni Hreinn Jónsson

Icelandic Meteorological Office, Avalanche Research Center, IS-400 Ísafjörður, ICELAND

ABSTRACT: An instrument for measuring snow depth and snow temperature has been developed by POLS engineering in Iceland. The snow sensor (SM4) consists of a series of digital thermistors mounted with a fixed interval on a pole that extends through the snowpack. An algorithm has been developed to calculate the snow depth based on the temperature data. The temperature profile is obtained as additional information.

Avalanches in Iceland are most commonly triggered directly by heavy snowfall and high wind speeds. However, stability tests and data from avalanche crowns indicate that facets are one of the most common crystal types in persistent weak layers in Iceland. Comparing historical data from the SM4 sensors to avalanche occurrences indicates that avalanche cycles that are not explained solely by severe weather may in many cases be explained by high temperature gradients for a long time, which may be assumed to lead to the formation of a weak layer of facets.

Methods have been developed to detect and visualize layers with temperature gradients that exceed a critical value, assumed to be the critical gradient to produce facets. The duration of the temperature gradient above the critical value is also shown.

Showing the location and time periods of critical temperature gradient in a visual way should help avalanche forecasters to detect warning signs related to possible facet formation. This will improve the avalanche forecast for both human and naturally triggered avalanches and decrease the risk of a failure to forecast avalanches that are not a direct consequence of severe weather.

KEYWORDS: snow sensor, avalanche monitoring, snowpack temperature, faceted crystals, weak layers

1. INTRODUCTION

In Iceland snow avalanches are often the direct result of heavy precipitation and/or high wind speeds. Therefore, the greatest focus in avalanche monitoring has been on these weather factors. However, unusual avalanche cycles and human triggered avalanches have in many cases been related to persistent, faceted weak layers. Facets tend to form when the temperature gradient is high somewhere in the snowpack causing high growth rates of crystals.

The Icelandic Meteorological Office (IMO) has the role of monitoring avalanche hazard in Icelandic settlements and for that purpose automatic snow sensors have been installed in or near to avalanche starting areas.

The main aim has been the continuous monitoring of snow depth in avalanche starting areas, but one type of snow sensor, the SM4 sensor, shows the temperature profile in the snowpack as well. Methods of using that to help detect possible formation of weak layers in the snowpack are being developed.

2. FACETED CRYSTALS AS A WEAK LAYER IN ICELAND

Faceted crystals, that are weak and can cause serious avalanche conditions, tend to form at high growth rates when the temperature gradient

**Corresponding author address:*
Örn Ingólfsson, POLS engineering
Urðarvegur 72, IS-400 Ísafjörður,
Iceland, phone: +354 892 3923,
e-mail: orn72@simnet.is

is high. The critical temperature gradient to produce faceted forms in alpine snow is about $10^{\circ}\text{C}/\text{m}$ and below this value rounded forms tend to appear (McClung and Schaerer, 1993). Facets sometimes form above or below crusts and this is commonly observed in Iceland. The air temperature often goes above 0°C during winter causing crusts to form when the surface freezes again. Also, rain on snow events are common in all months. .

In recent years, quite a few examples of avalanches or avalanche cycles caused by faceted layers have occurred in the vicinity of IMO's Avalanche Research Center in the town Ísafjörður as well as in other areas in Iceland, causing avalanche forecasters to increase their focus on detecting this type of weak layers at an early stage. When looking at snowpit data from avalanche crowns in Iceland two common failure layers are 1) thin layers of faceted crystals, sometimes in combination with crusts, and 2) a less dense snow layer buried under a dense windslab.

3. THE SM4 SNOWSENSOR AND THE VISUALIZATION OF THE DATA

The snow sensor (SM4) consists of a series of digital thermistors mounted with a fixed interval on a pole that extends through the snowpack.



Figure 1. SM4 snow sensor mounted to a pole installed in Suðavíkurhlíð mountain.

Measurements from the thermistors are logged with a few minutes interval to an internal memory and are transferred regularly to a central computer through a wireless GSM telephone connection. The output is a temperature profile that extends through the snowpack and up into the air (Figure 2). The data from the existing sensors are displayed on the website: www.snowsense.is in realtime. More information about the sensor is in Ingólfsson and Grímsdóttir (2008).

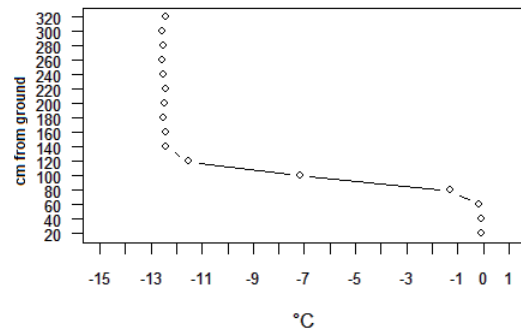


Figure 2: Temperature profile from SM4. The snow surface is in 130 cm. The bottom 80 cm of the snowpack is snow that has melted and frozen again. New snow is on top of that and the temperature gradient is high.

It is relatively easy to install SM4 in steep areas up in the mountains since it doesn't need a high mast or big foundation (Figure 1).

SM4 measures snow depth indirectly by identifying thermistors buried in the snow based on the damping of temperature fluctuations that is caused by the snowpack compared with temperature fluctuations in the air. An algorithm has been developed to calculate the snow depth automatically based on the temperature data. The results are displayed in graphs (Figure 3).

In order to use the data for monitoring possible formation of faceted layers a red dot is marked on the graph each time the temperature profile between two thermistors exceeds the critical value of $10^{\circ}\text{C}/\text{m}$. When this situation exists over some time period a red line appears on the graph showing the location within the snowpack (Figure 3). If the temperature gradient between the uppermost buried sensor and the lowest one in the air is greater than the critical value, a red line appears that does not go above the surface

of the snow on the graph. This is most likely a different situation from having the gradient within the snowpack.

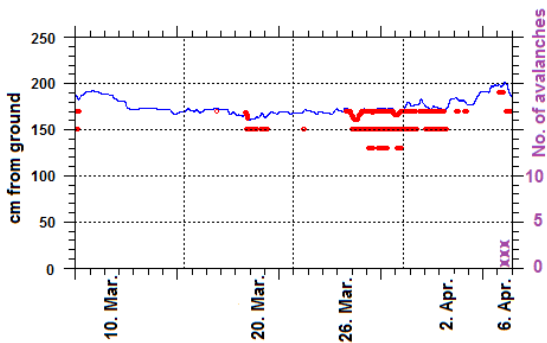


Figure 3: Visualization of conditions favourable for facet formation. The blue line shows the snow depth and the red lines appear when the temperature gradient between two thermistors is greater than 10°C/m. The data are from the year 2010.

The purpose is to create a tool for avalanche forecasters helping them to detect possible faceting in the snowpack. If red lines are persistent on the graphs it may be a good idea to get snow pits to see what is going on.

4. CASE STUDIES: AVALANCHES CAUSED BY FACETED WEAK LAYERS

Case 1: On the 9th of February 2007 faceted weak layers were detected in a snowpit in a test site in the mountains close to Ísafjörður. The faceted weak layers were in between 4 crusts that had formed at the surface when the temperature rose slightly above 0°C for short periods of time at the end of January. The weak layers were found high in the snowpack and not likely to cause any problems at that stage (Figure 4).

The first half of February was characterized by unusually cold weather with clear skies and then a little snowfall every now and then later in the month. Faceted forms continued to form around the crusts, and a stiff slab developed on top of that in some places. The first, recorded avalanche that was confirmed to fail on these layers was triggered by a snowmobiler on 25th of February.

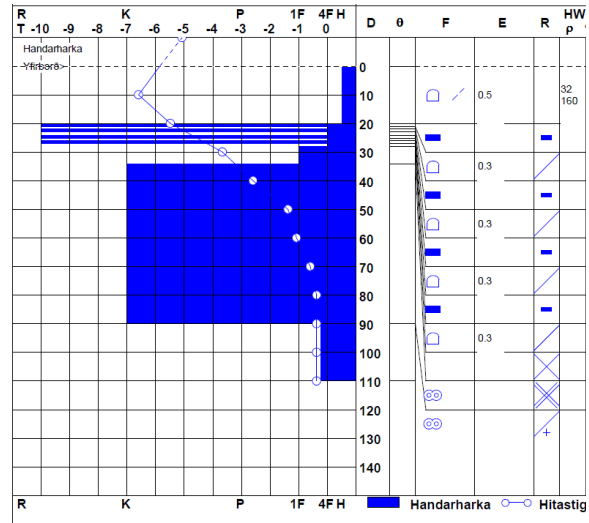


Figure 4: Snowpit from Kistufell from 9th of February 2007. Thin crusts with weaker layers in between are buried under 20 cm of new low density snow.

Over the next few weeks large avalanches fell in the area, most likely on this weak layer. For a few avalanches, this was verified with a snow pit in the crown. Only very little precipitation or weather changes triggered large, natural avalanches and some of them were close to settlements. Homes were evacuated a few times during this period, even when the weather was relatively good. Figure 5 shows that the temperature gradient was over the critical value most of February. Many avalanches fell in March since the weak layer was persistent in the snowpack, even though the temperature gradient was reduced in March.

Many factors may affect whether or not avalanches fall in connection to such conditions:

- The time span of the period with critical temperature gradient.
- The amount and characteristics of the snow on the top of the possible weak layer.
- Possible triggers, either human or natural.
- Destructing factors.

In praxis, avalanche forecasters would be alerted when red lines are forming within the snowpack on the graphs and persist for a few days. They may ask snow observers for snow pits with a special focus on this layer where it would be checked whether facets are forming, whether crusts are within the snow and continue to keep a good eye on these layers. This will make it easier for avalanche forecasters to get more targeted data and reduce the risk of human errors such as being taken by a surprise by avalanches in connection to faceted layers.

7. NEXT STEPS

The approach described here will be tried out by IMO's forecasters during the next winters and methods modified.

Continuous and automatic measurements of temperature profiles in the snowpack in avalanche starting areas may, however, be of use for avalanche forecasting in other ways than described in this paper. Methods for calculating accumulated temperature gradient related to facet formation will be tested. The data might also indicate how faceted layers are destroyed. At first sight it seems like once formed, faceted layers can persist for a long period in the snowpack even though the temperature gradient is below 10°C/m. However, when the air temperature goes above 0°C the layers may be destroyed rather quickly. This will be looked further into. The data may also give indications on other types of instabilities in the snowpack, such as instabilities due to rapid warming and even surface or depth hoar formation.

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