SNOW DEPTH MEASUREMENTS IN AVALANCHE STARTING ZONES

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ABSTRACT: In the last few years, Iceland has started an extensive programme to build avalanche defense structures for threatened towns and villages. Part of those defense structures will be retaining structures in the starting zone. The design snow depth is a critical factor in designing such structures because they become much less effective if they get buried. In order to evaluate this design snow depth, we have started a programme of measuring snow depth in avalanche starting zones. The programme consists of several different methods. First, we have put snow stakes in the starting zones, which are read from down below, using theodolites several times throughout the winter. Also in late winter our snow observers go into the starting zones and measure snow depth along a profile, using avalanche probes. We have also experimented using a laser distometer to measure specific profiles in snow free conditions and then also during the winter. The difference will give us the snow depth. We have started experimenting taking aerial photographs of the starting zones in spring and having contour maps made of the snow surface and then using a geographical information system (GIS) to find the difference between the snow surface and the regular surface and thus obtaining the snow depth. In this paper we will give a description of the different methods, compare them and give examples of the results.

KEYWORDS: Avalanche starting zones, snow depth, snow mapping, acoustic depth sensors, laser distometers.

1 INTRODUCTION

Following the avalanche disasters that occurred in Iceland in 1995 the Icelandic Meteorological Office, IMO, compiled a report on the need for avalanche protection in Iceland so as to bring the risk in the various towns and villages that are exposed to threat of snow avalanches down to acceptable levels [*Jóhannesson et al.*, 1996]. It was obvious that retaining structures in the starting zones would be needed at various locations, both as a main defense structure and in combination with other structures. One of the main requirements when designing such retaining structures is a measure of what snow depth can be expected at the individual sites.

In a typical starting zone the snow depth can be very varying, anywhere from less than a meter to several meters. This is caused by the heavy influence of wind and snow drift on the snow loading in the starting zones. Another difficulty that soon became obivious was the heavy snow encountered in Iceland. Density measurements had shown typical densities in the order of 350 to 550 $\frac{kg}{m^3}$. Although some information was available, it was very limited and thus the IMO started a project of measuring the snow depth in the starting zones.

Initially a report was compiled on the various methodologies available to do such measurements [*Árnasson*, 1997]. That investigation was primarily aimed at finding methods that would allow us to monitor the changing snow depth in order to better evaluate the immediate danger. The report suggested various methods to try, and subsequentially various projects started.

2 MANUAL MEASUREMENTS

2.1 Introduction

Every spring when the snowpack has settled, the staff of the avalanche section go into the several starting zones and measure snow depth along various profiles and locations in order to obtain a direct measurement of the snow depth. The snow depth has started to go down at this point but the reduction is known from the snow stake measurements. This is done so as to compliment other measurements.

To be able to evaluate the forces that act on supporting structures, it is not only necessary to know the snow depth. The density of the snow is

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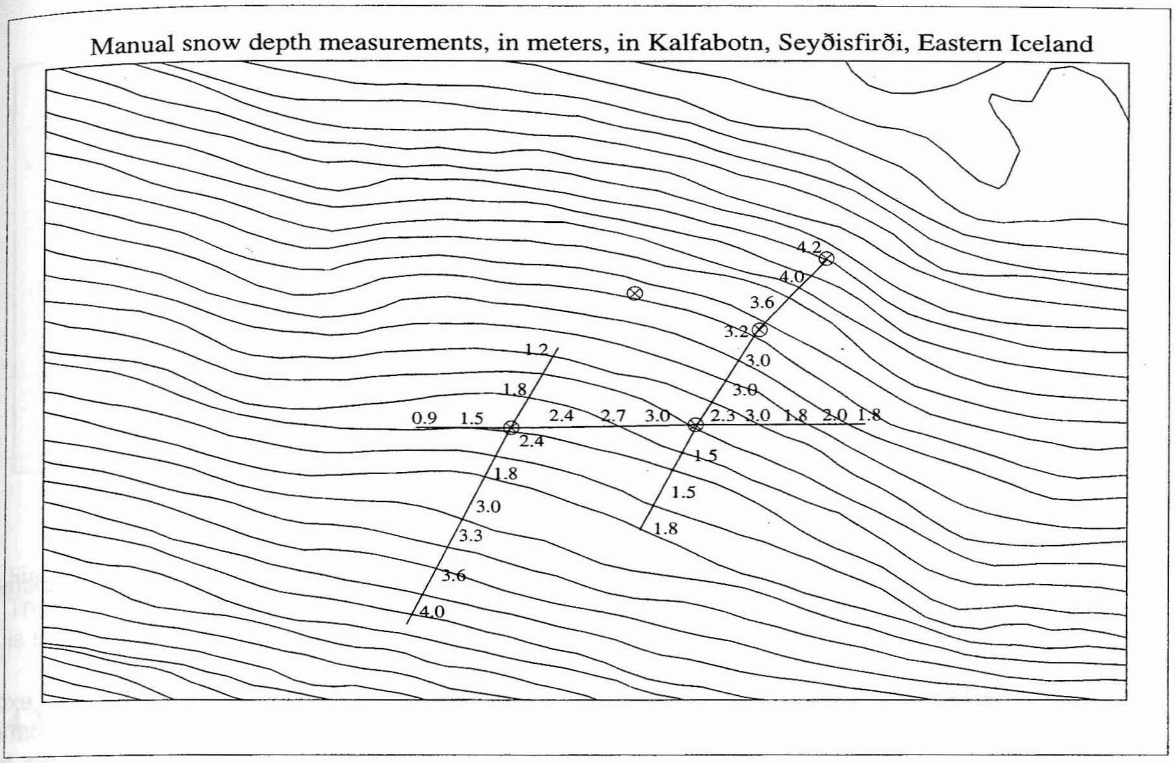

Figure 1: The figure shows the the result of manual measurements done in the starting zone of Kálfabotnar. The crosses mark the locations of snow stakes.

the other major factor in the stress/strain calculations. We have thus made regular density measurements in the starting zones to obtain a more complete picture of the range of densities we can expect and thus be able to dimension the supporting structures better.

2.2 Results

A good example of the variability of snow depth is an area above the town of Seyðisfjörður called Kálfabotn, on the east coast of Iceland. This is a crucial starting zone and is only 70 by 100 meters. Manual measurements show the variability of snow depth See figure 1.

3 SNOW STAKES IN THE STARTING ZONES

3.1 Introduction

The first experiments with fixed snow stakes to evaluate snow depth were done following an avalanche disaster at the village Neskaupstaður on the east coast of Iceland in 1974. Those stakes were located at relatively low elevations so they did not give us an idea of the amount of snow in the starting zones although they gave an idea whether snow was accumulating or not.

In 1996 snow stakes were installed in the starting zones at all the sites where avalanche defenses have been proposed. [*Kiernan et al.*, 1999]

3.2 The Stakes

The stakes are located in places were it is thought that they give a good indication of the average snow depth in neighbouring areas. They are of varying length from 3.6 to 4.5 m and are graduated in intervals of 30 cm. Each stake is fastened with two sets of 3 guy wires anchored 120° apart. The anchors are usually 8 mm bolts, fastend to a rock slab or a large boulder. The higher set of guy wires is fastened to the stake 1.5 to 2 m up the stake and the lower set at ground level. The setup is such that fasteners give before the stake breaks, since they are easier to transport than the stakes.

Initially the graduation was painted on wooden

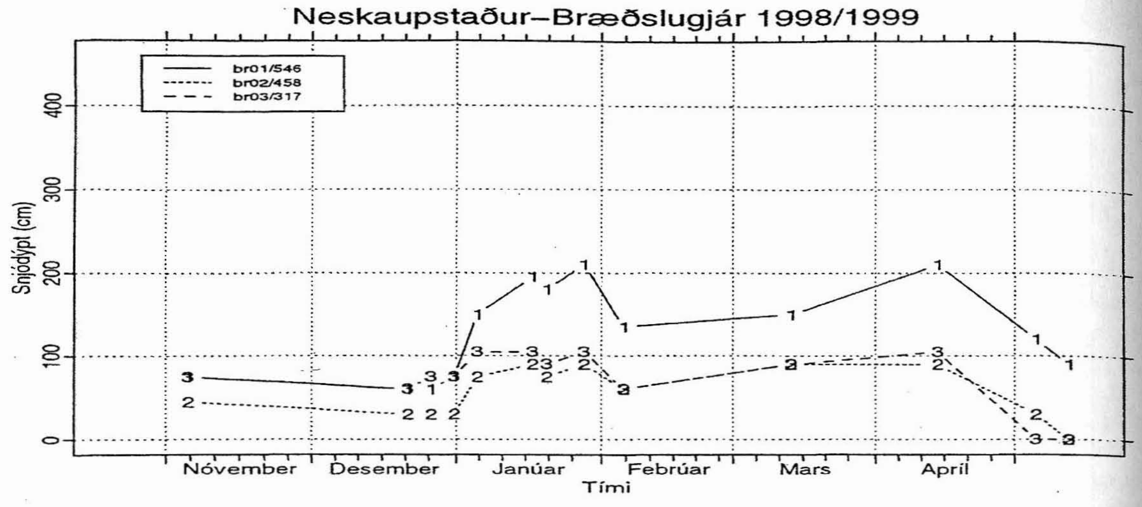

Figure 2: The figure shows the result of stake measurements done above the town of Neskaupstaður, Eastern Iceland, over the winter 1998 and 1999. Snow depth is in centimeters.

stakes, but the paint weathered quickly, so we started using plastic tubing around a wooden core, in 30 cm sections with alternating distinctive colours. This reduces the problem with icing and the markings remain readable for much longer.

Figure 1 shows the location of snow stakes in Kálfabotn and figure 2 shows an example of stake measurements.

3.3 The measurements

The measurements are done using a theodolite from predetermined locations. The "highest" stakes are located near 700 m a.s.l. and the longest line of sight is around 2000 m.

The measurements are made several times through the winter, preferably after each storm. The individual snow observer has set out several fixed stations, where he has sighted in the stakes in good visibility and recorded the azimuth and the inclination using a reference target close by. This allows him to find the stakes in bad visibility.

During measurements, once the stake is sighted in, the number of 30 cm sections that are still visible above the snow are counted, and since the total height of each stake is known, it is easy to calculate what the snow depth is.

3.4 Results

The main problems we have encountered have been how to anchor the stakes, in particular in loose scree on steep slopes and of course excessive snow depth. This has caused us to abandon or relocate some measuring stations. We have lost some stakes to rockfall. In addition, snow creep and heavy winds have caused us problems and as the project matures, we are beginning to experience corrosion problems. Thus it is necessary to overhaul the stakes each fall.

All measurements are maintained in a simple database and thus it is possible to observe how the snow depth develops through the winter. As the observation period extends our estimation of maximum snow depths improves, but already we have discovered that certain potentially very dangerous paths have snow depths such that it will be impossible to install retaining structures in their starting zones.

4 SNOW STAFF

4.1 Introduction

The idea behind the snow staff is that the temperature in the air fluctuates more than temperatures within the snowpack [*Árnasson*, 1997]. The initial staff was built using thermocouples but later models used semiconductors (diodes). Temperature sensors are located every 10 centimeters and the bottom one is used as a reference sensor, seventeen sensors in all. The total length of the staff is 170 cm and thus we are limited as to the snow depth it can measure. We are looking into ways to extend the staff as the snow depth increases.

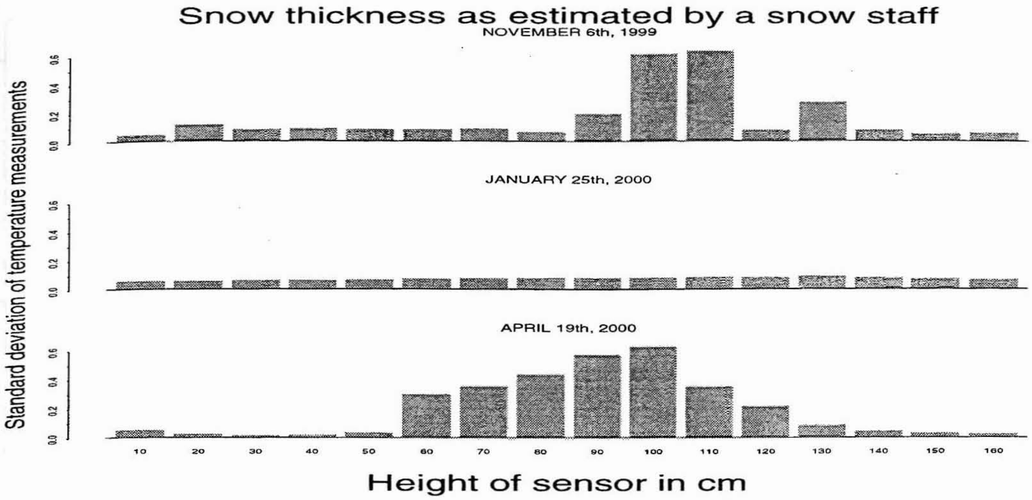

Figure 3: The figure shows the fluctuations in temperature sensors fixed on a staff in 10 cm intervals. The top plot indicates a snow depth of around 90 cm, the middle one suggests that the measuring staff is buried and the bottom figure indicates a snow depth of between 50 and 60 cm.

4.2 Measuring technique

A measurement is made every ten seconds of the difference between the reference sensor at the bottom and the individual sensors going up the staff. Every ten minutes the *standard deviation*, (SD), of the last 60 measurements is calculated for each individual sensor. This value is logged in a CR10 datalogger. When these values are plotted out it can be deduced that the present snow surface is located between the two measurements where there is a large standard deviation and a relatively small one. See figure 3.

4.3 Results

At present there are two staffs in operation. The accompanying graph shows the results from Siglufjörður in northern Iceland at three different times. Where we have a noticable increase in the SD we assume that is where the surface of the snow is located. A more extensive analysis of the data is necessary for us to be able to easily recognize the fluctuations in snow depth.

5 RADAR

5.1 Introduction

An upward looking radar was dug into the slope at Siglufjörður during the summer of 1996. The idea was to evaluate the use of a radar to measure snow depth and map out the layering within the snowpack. This was primarily done in order to monitor the snow depth w.r.t. possible avalanche release and imminent avalanche danger. As it turned out we were unable to get satisfactory results since the snowpack in Iceland is relatively moist and it is not infrequent that we get a heavy rain during the winter months. That causes a formation of an ice lens. This happened several times during our test period. This "blocked" the radar's view and it was not possible to get any reliable results after that ice layer formed.

5.2 Measuring technique

The radar we tested came from the Swiss company Alpug. This is a radar that has been successfully used in the Alps for some time. It operates in the frequency range 4-8 GHz. To save energy it was set to make a measurement every two hours.

5.3 Results

We initially installed the radar in the fall of 1996, and operated it for two winters. To begin with, the radar operated reasonably for a couple of weeks or until it started raining on the 13th of November. Since water is very absorbent in the 4-8 GHz range and the snowpack quickly became satu-

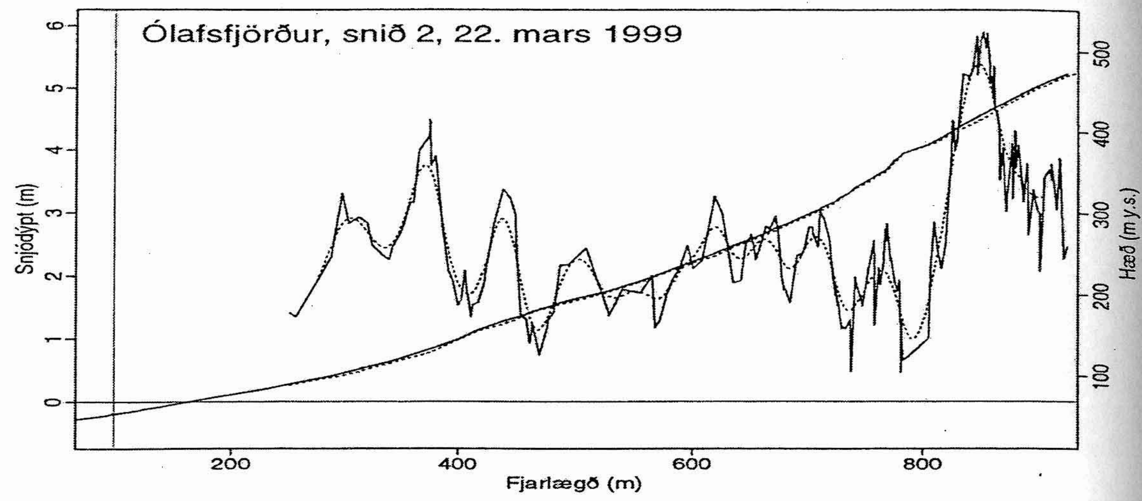

Figure 4: The figure shows the the result of laser distometer measurements done at the village of Ólafsfjörður, Norther Iceland. The straighter dotted line shows the snow free surface and the straighter solid line shows the snow surface. The fluctuating solid line shows the derived snow depth and the fluctuating dotted line shows a running average for the snow depth measurements.

rated, the radar was unable to detect the surface of the snowpack. On the 19th of November, a snowpit was dug beside the radar. The total snow depth was recorded as 100 cm, the top 22 cm were dry snow with the bottom 78 cm very wet snow. Some reflections could be seen within the snow but there was no indication as to where the surface was. Eleven days after the initial rainstorm the snow surface could again be detected.

Subsequent rainstorms and the formation of ice layers within the snowpack eventually blocked the radar completely and from January onwards nothing could be seen.

6 LASER DISTOMETER PROFILES

6.1 Introduction

Since the methods described above give us mostly only point measurements, we searched for a method that would enable us to obtain continuous measurements down an avalanche path. We decided to try a laser distometer, coupled with a mechanical inclinometer, to measure a profile down the paths and comparing the "snow free" profile with a "snow" profile. We thus hoped to be able to obtain an idea of the snow depth down along those profiles. [*Kiernan et al.*, 1999]

6.2 Measuring technique

The instrument we are using is a *Leica Vector 1500* hooked up to a laptop. To ensure that we are measuring the exact same profile every time, the instrument is set up on a tripod at exactly the same positon for every measurement and sighted in onto a distinctive landmark at the top of the path. Hence we measure down a straight path. We are not able to follow the natural flowline down the path. These profiles are then measured a few times during the winter, depending on the snow conditions and the number of storms that have occurred.

The distometer is connected to a laptop computer which collects the results and prepares a profile in ASCII format. This is then transferred to the office computers where the analysis is later performed.

A typical path is less than a 1000 meters long so the accuracy is not overtly affected by refraction in the atmosphere.

6.3 Results

The preliminary results are promising, see figure 4. The Leica instrument has performed well but we have encountered problems with the laptop. The accuracy is somewhat lacking as can be seen by the fact that we sometimes can get negative

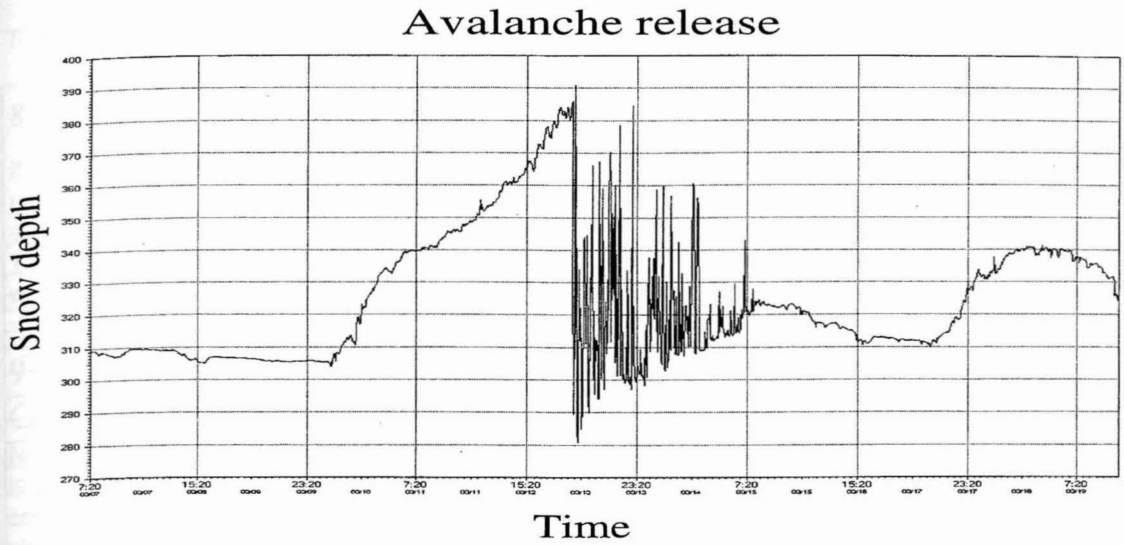

Figure 5: Data from an ultrasonic snow depth sensor located in an avalanche starting zone. The figure shows a release and a fracture height of 90 cm for an avalanche that ocurred in Seljalandsdalur near Isafjordur, NW Iceland.

snow depth. But we are able to get a reasonable idea as to the distribution of snow down along the profile.

We have been somewhat restricted by the fact that we can only measure down a straight path and of course by the fact that weather conditions have to be favourable.

7 ULTRASONIC SNOW DEPTH SENSORS

7.1 Introduction

We have operated acoustic snow depth sensors for six years now in an avalanche starting zone.

We have encountered several problems with the sensors, in particular due to the harsh environment we are trying to install them in. The membranes seem to corrode and rupture on a regular basis and the sensors have a tendency to fill with moisture and thus stop working.

This situation did not improve until we started hand picking the sensors, inspecting the membrane under a microscope and selecting sensors that do not have visible flaws in their membrane. This has given us good results and for the past two years the sensors have operated throughout the winter. The sensors are replaced every summer.

7.2 Measuring technique

The sensors we have been using up till now are SR50's, made by Campbell Scientific Canada Ltd. The measuring is based on an echo system based on the travelling time of an acoustic pulse. The measurements are temperature compensated in the data logger and the travelling time gives a measure of the distance travelled. Thus we obtain the distance from the sensor to the surface of the snow. since the distance from the sensor to the ground is known, we can calculate the snow depth.

A mast was erected in the starting zone, and the sensor was pointed at right angles down onto the slope. Data is collected via a phone line.

7.3 Results

For the last two winters the sensors have operated well and given us a satisfactory result. We have been able to monitor the change in snow depth although during snow storms the readings can be suspect. After the storm it is easy to edit out noise and any unwanted spikes and the resulting graph shows the changing snow depth through the winter.

A very interesting result was obtained when an avalanche ocurred in Seljalandsdalur, near Ísafjörður in NW Iceland. See figure 5. One can see very clearly the sudden drop in snow thick-

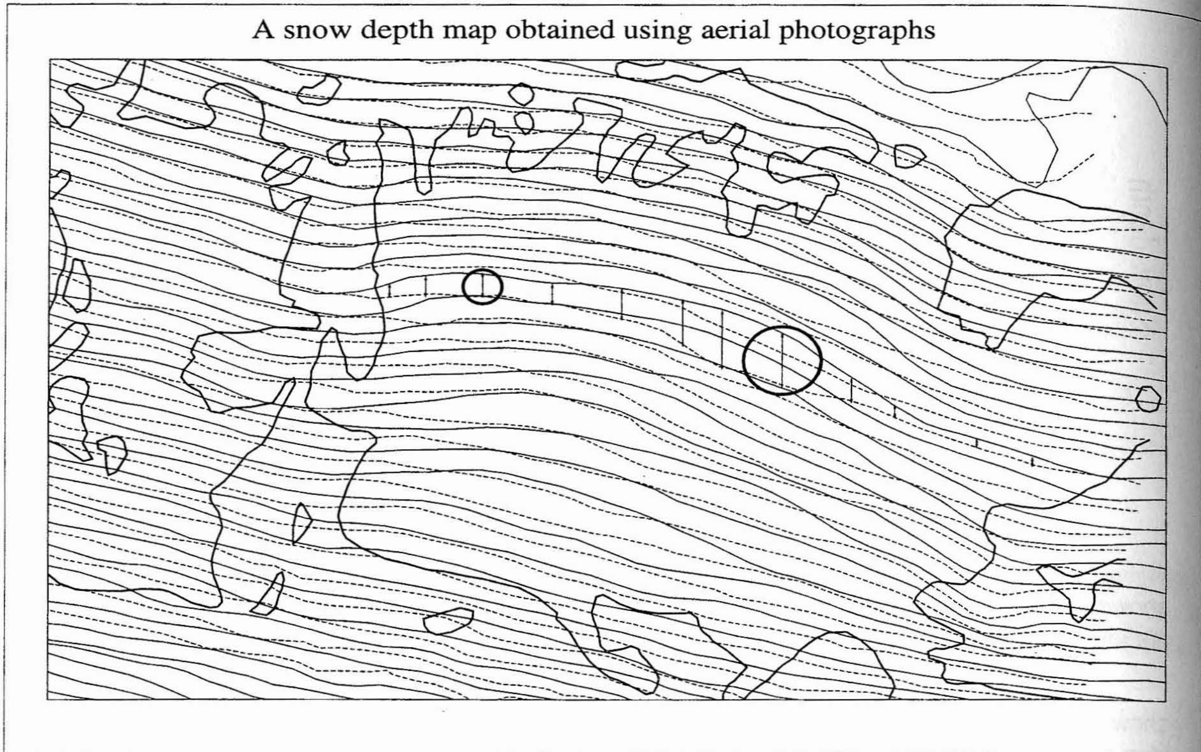

Figure 6: The figure shows the actual contour lines in the starting zone at Kálfabotnar (thin solid line), the snow contour lines (dashed line). The arrows indicate how far "down" the contours have been displaced. The thick line shows the extent of the snow patches. The large circle shows that the snow contours are now aligned with ground contours close to 5 to 10 m lower, indicating an average vertical snow height of about 7 m in the area close to the larger circled arrow. Similary, the smaller circle indicates an average snow height of 3 to 4 m.

ness at the time the avalanche released. The avalanche turned the sensor so that it was no longer pointing at right angles onto the slope. When the snow observers climbed up into the starting zone and reset the sensor it again showed the correct snow depth. Manual measurements confirmed the value given by the sensor, the thickness of the slab was 90 centimeters.

8 AERIAL PHOTOGRAPHY

8.1 Introduction

Detailed topographic maps of avalanche towns and villages have been made for the Icelandic Meteorological Office. The maps extended well into the mountains above the villages and included the catchment areas for the starting zones. Thus the idea came up to take aerial photographs of the starting zones in the spring when it can be assumed that the thickness of the snow cover is near its winter maximum. The accompanying figure 6 shows the Kálfabotn starting zone above the village of Seyðisfjörður on the east coast of Iceland. When the aerial picture was taken the snow cover had already decreased by approximately 2 meters from the winter maximum as indicated by stake meaurements. We have thus areas surrounding the starting zone where the bare ground is visible, giving us a good reference.

8.2 Measuring technique

For the photgrapy itself a simple $2\frac{1}{4} \times 2\frac{1}{4}$ Hasselblad camera was used. Vertical pictures were taken. The local snow observers climbed up into the starting zones and put markers on prominent rock outcrops prior to the flight that were used as reference. A cartographic company then made a topographic map based on the photographs. The resulting maps were then compared to the original maps and the difference was assumed to be the thickness of the snow pack.

8.3 Results

It is obvious from the initial results that the camera used is not sufficient. A better camera is necessary, one that is calibrated as an aerial camera. The results were varying, in some places they were satisfactory and in others were not.

9 COMPARISION BETWEEN THE VARIOUS METHODOLOGIES

No single method has given us a completely satisfactory result. It is more the case that they complement each other. The aerial photography is very expensive but it gives a good picture of the overall snow depth. The accuracy of the method is not completely satisfactory and is dependant upon the conditions under which the pictures are taken and the accuaracy of the initial contour map.

The ultrasonic sensor, the stakes and the snow staff only give point measurements whereas the laser distometer and the manual measurements give us a profile down a specific path.

To obtain an overall picture of the snow depth in the starting zones we need all the above measurements. The retaining structures in the starting zones cover an extensive area which is difficult to cover using point measurements. Also, the snow depth in the starting zones of some of the more dangerous paths is such that it is next to impossible to install any kind of measuring devices. Thus we have to rely on the manual measurements and the laser measurements as well as the aerial photographs, to provide us with the data for areas of heavy snow accumulation.

The primary results of the snow depth measuremennts in the starting zone of avalanches is that the snow depth is very high in places. In particular, it has become clear that some of the most dangerous paths have snow depth so great that it will be impossible to install retaining structures at those locations. Had retaining structures been installed in those areas before these results were available, it is clear that extensive damage would have occurred to the structures.

Since it is relatively easy to take readings of the snow stakes it is possible to obtain frequent measurements of the snow depth. This helps us in the monitoring of the avalanche danger by providing information of how the snow is accumulating.

We are in the process of organizing the various data comparing the various results and use the various methodologies to complement each other. We hope that when construction starts on avalanche retaining structures in the various villages, we will have obtained enough data to be able to provide the designers with reliable information on the snow depth in the starting zones for them to properly dimension and correctly design the structures, so that they provide the protection needed to reduce the risk to the inhabitants of those towns and villages.

ACKNOWLEDGEMENTS: We would like to thank our colleagues at the avalanche section and the snow observers that perform the work described here. We would also like to thank Helgi Kristinsson of Hnit Consulting Engineers Ltd., who performed the difficult task of drawing the snow surface contour lines from the aerial photographs.

References

Jóhannesson, T., K. Lied, S. Margreth, and F. Sandersen, An overview of the need for avalanche protection measures in Iceland, Technical Report VÍ-R96004–ÚR02, Icelandic Meteorological Office, 1996.

Kiernan, S., J. G. Egilsson, and T. Jóhannesson, Snjódýptarmælingar á stikum, við leiðigarða og á snjódýptarsniðum fjallshíðum veturinn 1998/1999, Technical Report VÍ-G99021–ÚR11, Icelandic Meteorological Office, 1999.

Árnasson, K., Mælingar á snjósöfnun í upptakasvæðum snjóflóða - staða í febrúar 1997, Technical Report VÍ-G97006–ÚR04, Icelandic Meteorological Office, 1997.