Veðurstofa Íslands
Report

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Pilot Project in Siglufjörður

Interpretation of observations from the winter 1996/97 and comparison with similar observations from other countries

VÍ-G98033-ÚR26
Reykjavík
September 1998

CONTENTS

SUMMARY

Suitable design parameters for supporting structures under Icelandic conditions are being investigated in an experimental installation of steel bridges and snow nets constructed in Siglufjörður in Northern Iceland in the autumn of 1996. Snow height in the test area, snow density, gliding of the snow pack and the loading of the structures were monitored during the following winter. The snow depth in a part of the test area became very high during the winter and the structures were partly buried and heavily loaded. The equivalent average snow density for loading computations was measured to be close to 400 kg/m^3 during the middle of the winter when the snow depth was at a maximum. It increased to close to 500 kg/m^3 after the snow pack had become isothermal in the spring. The gliding of the snow pack along the slope was low, only a few cm during the winter. The maximum loading of the structures, as monitored in one of the uphill anchors of the snow nets, occurred around the time of maximum snow depth. The onset of melting led to a sharp decrease in the loading of the snow nets. There were no indications of an increase in the loading due to deformation or gliding introduced by melting.

The results from Siglufjörður are consistent with measurements of snow properties and loading of supporting structures obtained by NGI at the Grasdalen research station in southern Norway from 1976 to 1998. These measurements come from a wet maritime climate similar to the Icelandic climate and span a much longer period than the measurements from Siglufjörður.

With regard to the design of supporting structures, the main results of the first winter are that corrosion protection of snow nets needs to be improved for Icelandic conditions, Austrian-type ground plates need to be anchored to the slope in order for the structures to withstand wind pressure caused by uphill winds, and the feasibility of micropile anchoring of snow nets in loose materials needs to be evaluated. An appropriate mid winter snow density for the design of supporting structures for Icelandic conditions is estimated to be 400-450 kg/m^3 and the effect of gliding on snow loading appears to be small. There are no indications of a variation in density or snow loading with height above sea level or with the aspect of the slope under Icelandic conditions. Strength requirements for supporting structures in Iceland should therefore be independent of the height above sea level and the aspect of the slope. Apart from this, traditional formulations for snow loading of supporting structures, which are used in Alpine countries, appear to be adequate for Icelandic conditions when proper account has been taken of the higher snow density in Iceland.

The results of the experiment after the first winter must be considered preliminary. Additional instruments for measuring the loading of the structures were installed in the autumn of 1997 and more detailed results will be available after data from the second winter of the experiment have been analysed.

1. INTRODUCTION

The Icelandic Meteorological Office (IMO) has implemented a pilot project for testing the feasibility of supporting structures for avalanche protection in Iceland and for obtaining data which will be used to define an optimal setup of such structures under Icelandic conditions. About 200 m of supporting structures, both stiff steel constructions and snow nets, have been installed for experimental purposes in Hafnarfjall above the village Siglufjörður in northern Iceland. The project is financed by the Icelandic Avalanche Fund.

Due to the wet maritime climate, the properties of the snow cover in Iceland differ from typical properties of snow in Alpine countries, where most supporting structures have been designed. The average yearly temperature in lowland areas in Iceland varies from 3-4 °C in northern parts of the country to 4-5 °C in the western, southern and eastern parts, with higher values in the range 5-6 °C at a few locations (Einarsson, 1976). Average temperatures in January are typically in the range -2 to 0 °C and in July in the range 9-12 °C. Starting zones of avalanches that threaten inhabited areas in Iceland are most often in the altitude range 300-700 m a.s.l. The rate of decrease of the temperature with altitude may be assumed to be about 0.6 °C per 100 m. Snow in starting zones will in a normal winter repeatedly be exposed to temperatures around 0 °C and often also to rain, and as a consequence the densification of the snow pack proceeds rapidly throughout the winter. A significant proportion of the snow pack has also in many cases been redistributed by wind in the windy Icelandic climate and has therefore acquired a relatively high initial density.

Gliding of the snow pack along the slope is believed to be low in Iceland because of a relatively strong contact between the slope and the snow formed in the moist climate and due to a relatively high ground roughness and lack of vegetation in the starting zones.

Loading of supporting structures in Iceland may be expected to be different compared with Alpine countries due to the conditions described above; the high snow density leads to higher loading than in Alpine countries under otherwise similar conditions, but the low gliding has a counteracting effect. Traditional snow nets of a French design, which were installed in Auðbjargarstaðabrekka and Ólafsvík in Iceland in 1984 and 1985, have suffered structural damages due to heavy snow loads (see Sigurðsson, Jóhannesson and Sigurjónsson, 1998). This experience indicates that the result of the abovementioned counteracting effects is a higher load under Icelandic conditions compared with Alpine conditions.

Guidelines for supporting structures in Alpine countries specify different snow loading on the structures depending on height above sea level and aspect of the slope through a so-called *height factor* and a higher value of the *gliding factor* in ENE-S-WNW exposed slopes compared with WNW-N-ENE exposed slopes (*cf.* EISLF, 1990). Wet snow metamorphosis and windpacking in the wet and windy Icelandic climate may be expected to lead to more uniform densification of the snow pack in Iceland compared with the continental climate of Alpine countries. Starting zones of avalanches that threaten inhabited areas in Iceland are, furthermore, in the narrow altitude range 300-700 m a.s.l. and there are no indications of a variation in density, gliding or snow loading with height above sea level or aspect of the slope in Iceland. Strength requirements for supporting structures in Iceland should be such that irrelevant variations with height above sea level and aspect of the slope are not imposed. Apart from this, traditional formulations for snow loading of supporting structures, which are used in Alpine countries, appear to be adequate for Icelandic conditions when proper account has been taken of the higher snow density and the lower gliding in Iceland as will be further described below.

In addition to the different conditions with regard to snow density and gliding described above, extreme snow depths in many starting zones in Iceland may be expected to pose serious problems for supporting structures under Icelandic conditions. As a consequence of frequent snow drift in the windy Icelandic climate, snow depth in starting zones in Iceland is often quite nonuniform. The snow preferentially accumulates in depressions and gullies, where vertical snow heights in excess of 6 m are common, even in average winters, whereas the snow depth on ridges and concave parts of the starting zones remains low throughout the winter. One may expect that supporting structures are impractical due to extreme snow depths in many important starting zones above inhabited areas in Iceland due to this reason. This problem is not unique to Iceland, as similar problems are sometimes encountered in high altitude avalanche starting zones in Alpine countries.

Another problem in connection with the snow depth in starting zones in Iceland, is that it is in general difficult to estimate an appropriate design snow depth for supporting structures due to lack of long term snow depth measurements. Snow depth measurements in starting zones of avalanches in Iceland have only recently been started (Sigfússon and Jóhannesson, 1997; Kiernan and others, 1998), and it will take some time before estimates of long term maximum snow depths in the relevant starting zones become available.

Corrosion conditions in Iceland are more severe than in Alpine countries and supporting structures for Icelandic conditions must be designed with due regard to these conditions. Observations of supporting structures in Auðbjargarstaðabrekka, Ólafsvík and Siglufjörður in Iceland and a compilation of relevant information about corrosion protection of steel structures in Iceland is described in the report by Sigurðsson, Jóhannesson and Sigurjónsson (1998).

In spite of these problems, it is clear that supporting structures are a viable avalanche protection for several avalanche prone areas in Icelandic villages, especially where conditions are unfavourable for other protection methods and where extreme snow depths in depressions and gullies are not expected to be a problem.

The following report describes observations of snow height, snow density, gliding and the loading of the supporting structures in the pilot project in Siglufjörður during the winter 1996/97. Some observations from the following winter 1997/98 are also mentioned, but they are described in more detail in a separate report. The observations are, furthermore, compared with similar observations from Alpine countries and Norway.

2. SUPPORTING STRUCTURES IN SIGLUFJÖRÐUR

The supporting structures in Siglufjörður are located at 490-530 m a.s.l. in the mountain Hafnarfjall west of the village Siglufjörður. They are stronger than the nets which were previously installed in Iceland in Auðbjargarstaðabrekka and Ólafsvík because they are designed for higher values of the snow density which are believed to be appropriate for Icelandic conditions. The structures are arranged in four rows which are labelled I, II, III and IV from above (Fig. 1, photograph 2 in the Appendix). The types of structures of each row are given in Table 1.

Table 1: Types of supporting structures in Siglufjörður.

Row	Type	Producer	Length (m)	Number of posts	Height (D_k, m)
I and IV	bridges	J. Martin	110	38=24+14	3-5
II	nets	Geobrugg	50	14	3-4
III	nets	EI	41.5	15	3-4

The posts in each row are numbered starting with 1 from north to south and each post can therefore be identified with its row number and the sequential number within the row, *e.g.* II-8 for the eighth post from the north in the Geobrugg nets in row II.

A part of the snow bridges from J. Martin was damaged in a storm shortly after the installation of the structures in the fall of 1996. This was repaired by drilling anchors through the groundplates of all the posts that are mounted on groundplates. Mistakes were made in the installation of 5 posts in the Geobrugg net line, which are founded on micropiles in loose material, and these posts failed

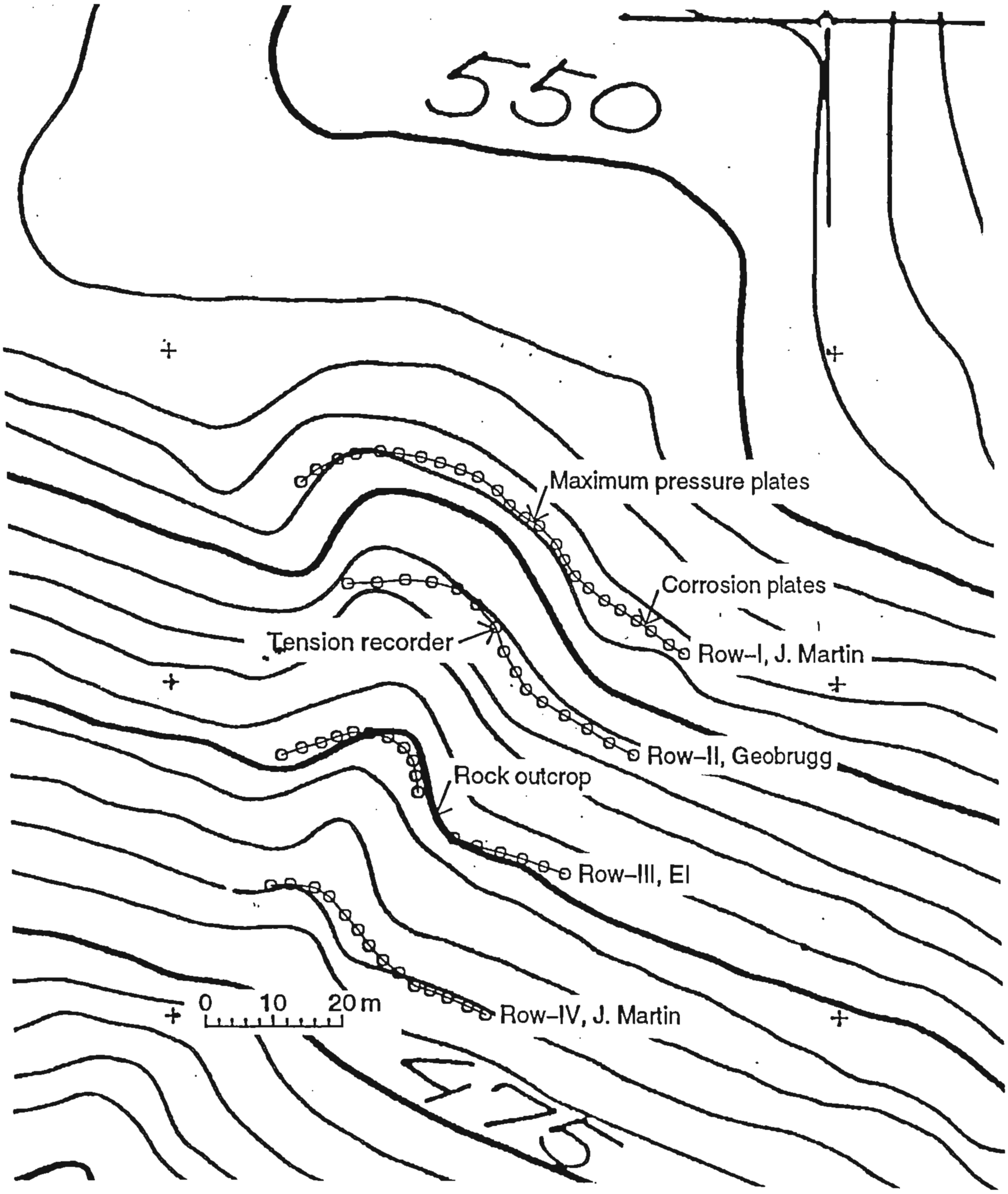

Figure 1. Location map of the supporting structures in Siglufjörður in scale 1:1000 showing the location of the upper anchors in each row together with the placement of measuring instruments in the rows. The contours, which are taken from a map in scale 1:5000, are not accurate in every detail but they give a picture of the general landscape in the test area.

during the first winter. This was repaired in the fall of 1997 by replacing the micropiles of these posts with groundplates. No damages of the structures occurred during the following winter 1997/98.

A part of the supporting structures in Siglufjörður is intentionally located in a gully where there is a large accumulation of drifting snow in most years. The structures in the gully were buried in the winter 1996/97, but this did not lead to failures of the structures, with the exception of the abovementioned damages to the micropiles in the Geobrugg net line.

3. SNOW HEIGHT

The extreme vertical snow height is the most important design parameter for supporting structures. As discussed in the introduction, there are special problems associated with the determination of design snow depths for supporting structures in Iceland. The pilot project in Siglufjörður will not address these problems in general, but the observations in the test area will show what problems are encountered in that particular area. The purpose of snow depth observations in the pilot project is primarily to gather data for the interpretation of the loading measurements described later in the report.

3.1 Observations from Siglufjörður

Snow depth perpendicular to the slope was measured at each post in the test area on several days during the winter. The results are shown in figures 2a-d below. The numbers at the top of each figure are the sequential post numbers starting with 1 at the northern end of each row. Snow depth values at several stakes, which were buried by the snow or where measurements are missing for other reasons, were inferred from the measurements at other stakes. This was done by assuming that the melting of the snow cover proceeds at approximately the same rate at each location after the maximum snow depth of the winter has been reached. Such inferred values are indicated with symbols (stars) in the figures. It is seen that snow depth in the gully reaches values in excess of 4-5 m perpendicular to the slope and remains high until late in the spring. These values correspond to 5-6 m vertical snow height. The snow depth to the north of the gully was never higher than approximately 2 m and started to go down early in the spring. At its maximum, the snow depth was about 1 m above the structures in most of the gully and between 1 and 2 m above the structures in a part of the Geobrugg nets.

3.2 Snow depths measured in starting zones in Iceland

Although very high, the snow depths observed in the gully in the test area in Siglufjörður in 1996/97 are not uncommon for starting zones in Iceland judging from the scarce snow depth data available. A snow thickness profile versus altitude from Skollahvilft in Flateyri, northwestern Iceland, from May 1997 shown in Figure 3 (left panel) indicates that the maximum vertical snow height of that winter reached 6 m in the top 50 m of this very wide starting zone. The winter 1996/97 may be assumed to have been an "average winter" with regard to snow depths and significantly higher snow depths may therefore be expected in the starting zone in extreme winters. Higher snow depths have indeed been observed. The maximum vertical snow height in the fracture line of the catastrophic avalanche from Skollahvilft on 26 October 1995 was approximately 7.5 m (5.34 m along the sloping fracture; Pétursson, report in the archives of the IMO; Haraldsdóttir, 1998) as shown in Figure 3 (right panel, solid curve). The vertical depth of the fracture itself was more than 5 m (3.7 m along the sloping fracture). Even this snow depth should not be considered a maximum for the Skollahvilft starting zone, since the snow was in this case deposited by a single extreme weather event at the beginning of winter. If an avalanche had not been released, continuing snow fall during the winter would have increased the snow depth still further. Figure 3 (right panel, dashed curve) also shows a density profile taken at the fracture line of the catastrophic avalanche in Tunguskógur in Ísafjörður, northwestern Iceland, on 5 April 1995. The maximum vertical snow height was approximately 5.4 m (3.81 m along the sloping fracture; Pétursson, report in the archives of the IMO).

The height of the fracture lines in Flateyri and Ísafjörður were measured at the point of maximum snow height and the average snow height along the whole fracture line was in both cases significantly smaller. Neither measurement was, however, from a gully or a local depression and these maximum snow depths are therefore representative for an area of a considerable extension in both cases. In connection with supporting structures, these maximum snow depth values are highly relevant, since a part of an installation of supporting structures in the corresponding starting zones would be exposed to these or higher snow depths in an extreme winter. In both cases, it is doubtful that it would be

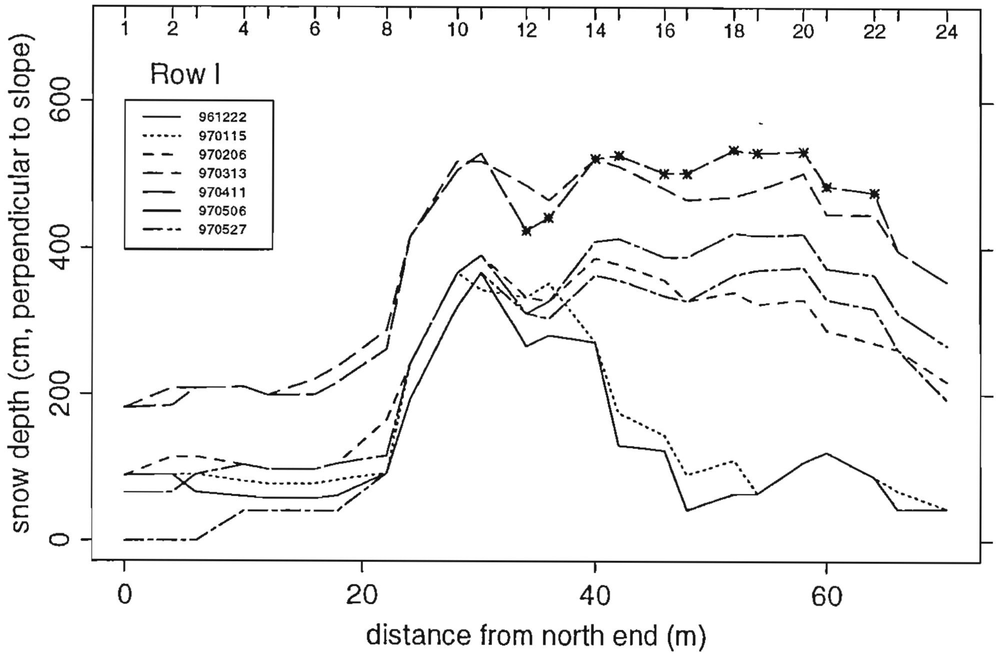

Figure 2a. Snow depth along row I.

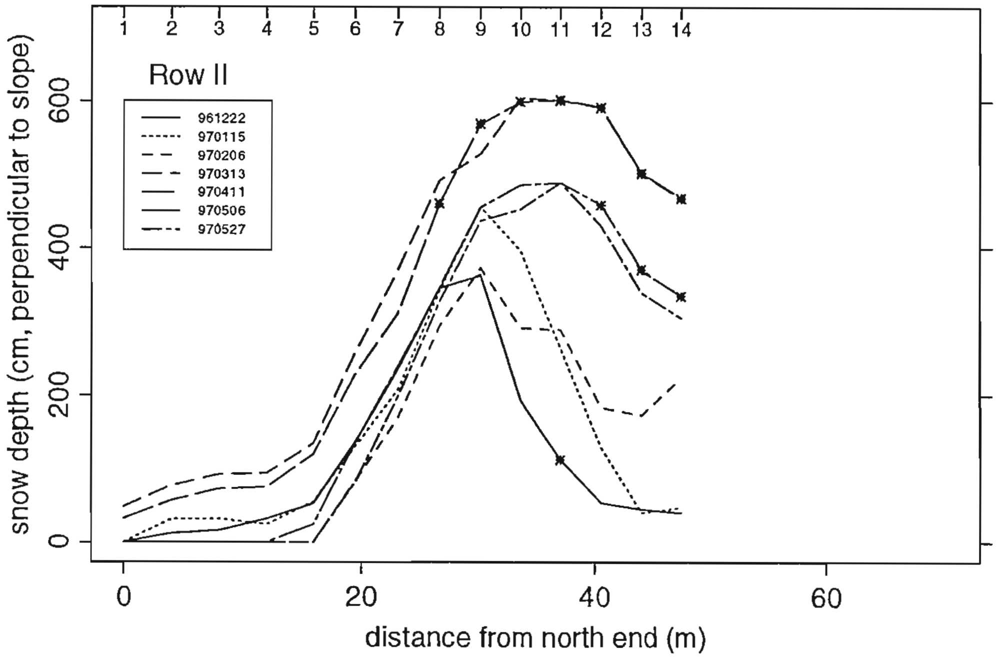

Figure 2b. Snow depth along row II.

technically feasible to construct supporting structure which would be able to withstand the snow load corresponding to long term maximum snow depths estimated from these observations.

4. SNOW DENSITY

Loading of supporting structures is linearly related to snow density in the starting zone, which is belived to be higher in Iceland than in Alpine countries as discussed in the introduction. One of the goals of the pilot project is to quantify this expectation.

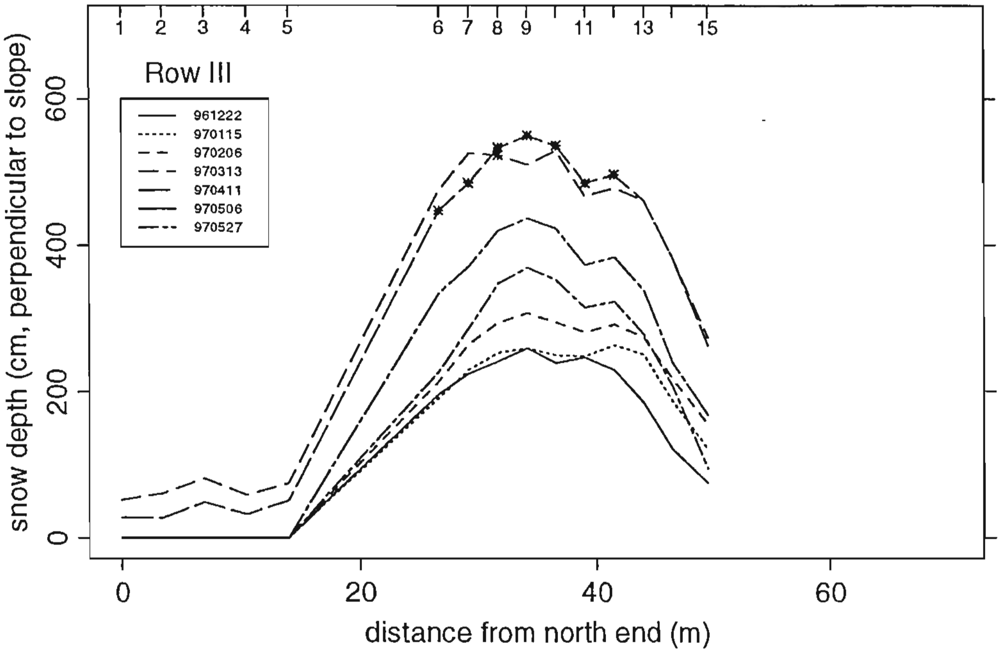

Figure 2c. Snow depth along row III.

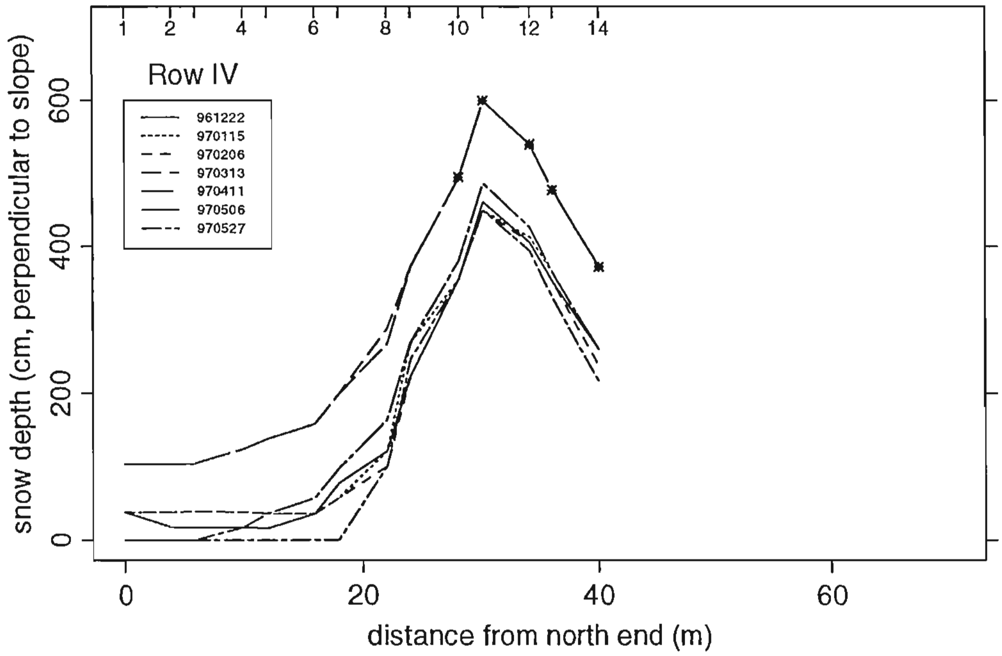

Figure 2d. Snow depth along row IV.

4.1 Observations from Siglufjörður

Snow profiles were measured on several days in pits between rows I and II in the test area in Siglufjörður (Fig. 4). Except for the topmost meter following a snow fall, the equivalent average density for loading computations (see eq. (1b) below) was typically about 400 kg/m^3 during the winter (*cf.* Fig. 4, early pits). It increased to close to 500 kg/m^3 after the snow pack had become isothermal in the spring (*cf.* Fig. 4, the last pits), but this higher value was not reached until the snow depth had started to decrease.

The loading of supporting structures is usually computed on the basis of a snow pack with a

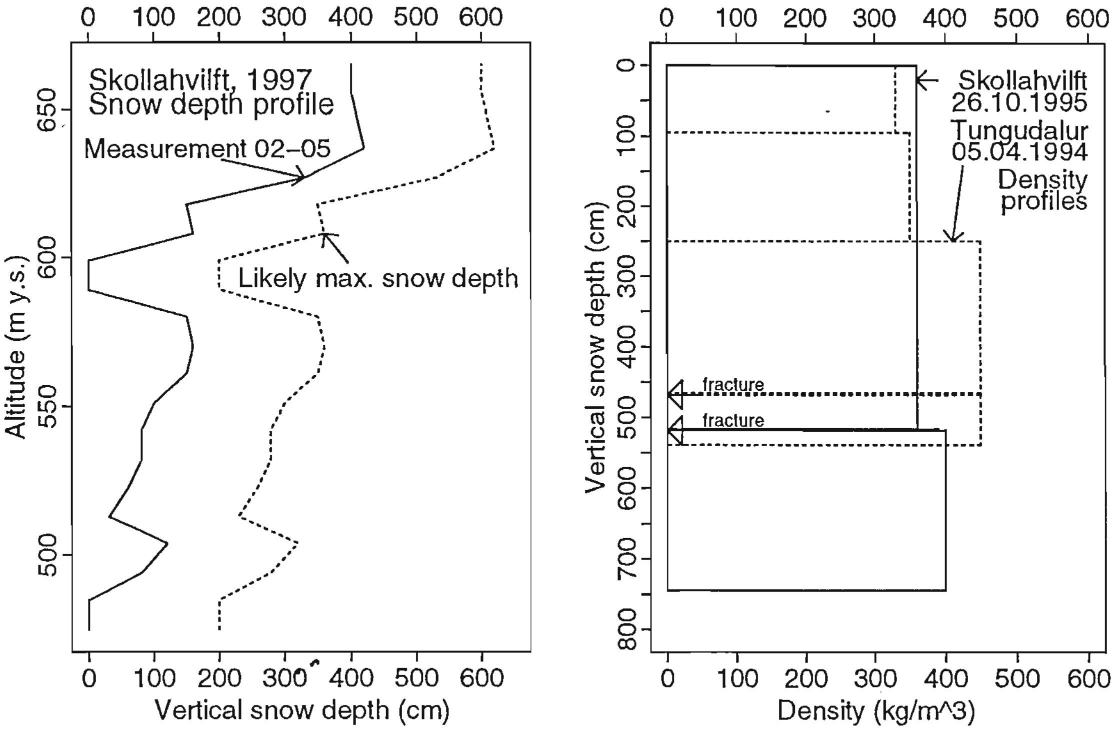

Figure 3. Snow thickness profile from Skollahvilft in Flateyri measured on 2. May 1997 together with an estimate of the maximum vertical snow height of the winter 1996/97 (left) and snow density profiles from the fracture lines at 600-700 m a.s.l. of the catasrophic avalanches that hit the village of Flateyri on 26. October 1995 (right, solid curve). and Tunguskógur in Ísafjörður on 5. April 1994 (right, dashed curve). The fracture depths of the Flateyri and Tunguskógur avalanches are indicated with arrows.

constant density ρ (*cf.* EISLF, 1990). The snow density is, however, usually lowest in the top layers of the snow and increases with depth (*cf.* Fig. 4). The depth averaged density $\bar{\rho}$ given by

$$\bar{\rho}_e = \frac{1}{D}\int_0^D \rho\, d\xi, \tag{1a}$$

leads to an overestimate in the computed loading because the uppermost low density layers in the snow are relatively more important for the snow loading than the more dense bottom layers. This may be taken into account in an approximate way by computing the equivalent average density for depth integrated loading computations $\tilde{\rho}$ according to the equation

$$\tilde{\rho}_e = \frac{1}{\frac{1}{2}D^2}\int_0^D\int_\xi^D \rho\, d\eta\, d\xi. \tag{1b}$$

The equivalent average density $\tilde{\rho}$ is different from the depth averaged density $\bar{\rho}$. The different parts of the snow cover contribute differently to the loading of constructions that extend through the thickness of the snow such that the uppermost layers contribute relatively more to the loading than the lower layers as mentioned above. This is because stresses arising from the weight of the uppermost layers contribute to the loading at all depths in the snow whereas the bottom layers only contribute to the loading of the constructions near the bottom of the snow (see eq. (1b)). Conceptually, $\tilde{\rho}$

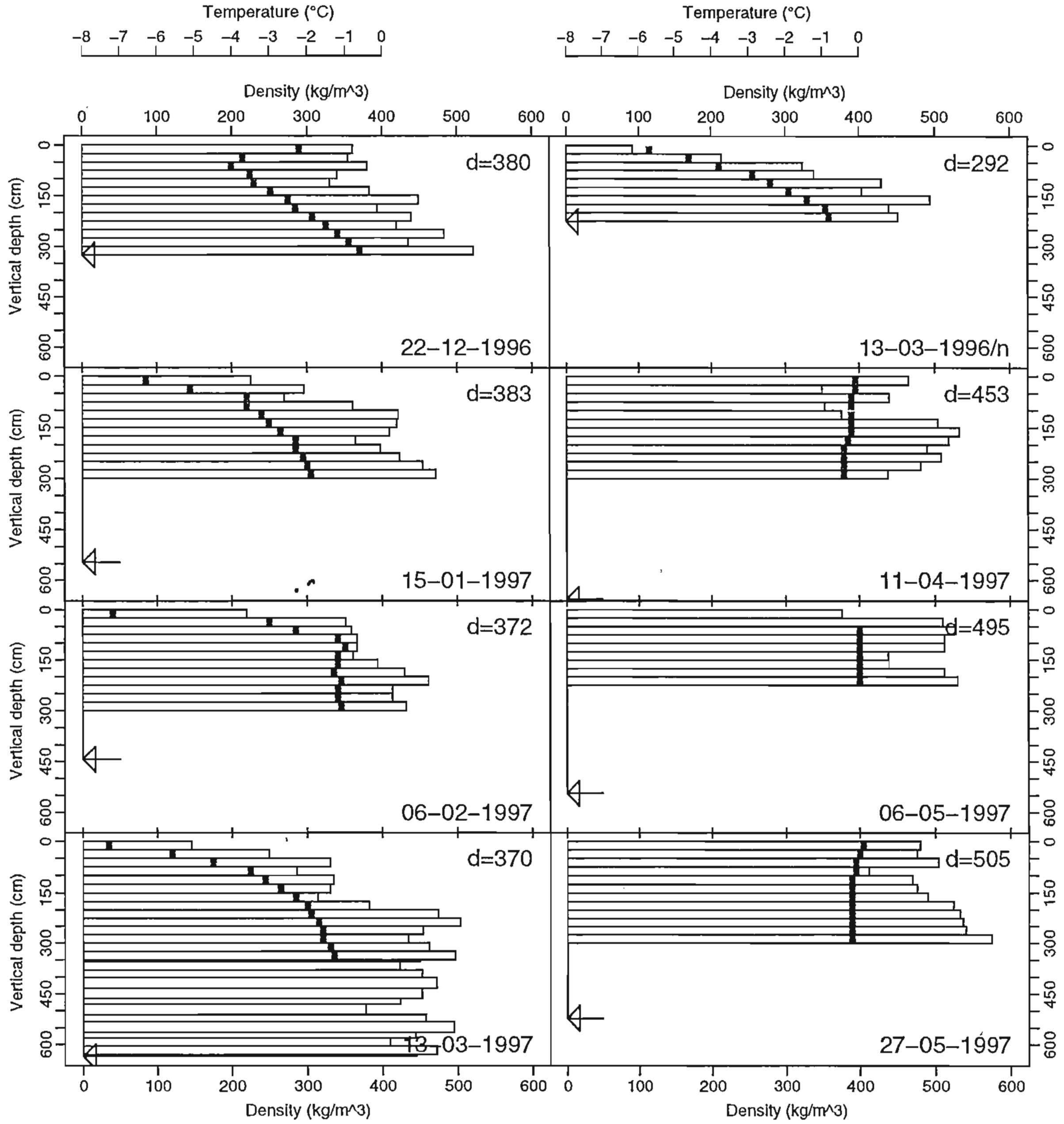

Figure 4. Density profiles from pits located between rows I and II. Temperature measurements are denoted with symbols. The profiles were in all but one case measured down to a depth of approximately 3 m. The vertical snow height is indicated with an arrow to the left in the figures. All the profiles, except 13-03-1997/n, were taken near the northern margin of the gully between rows I and II. Profile 13-03-1997/n was taken for comparison in an area with thinner snow cover to the north of the gully. The number in the upper right hand corner of the figures gives the equivalent average density of the whole snow layer (*cf.* eq. (1b)). For pits that do not reach the bottom of the snow, the density below the bottom of the pit is assumed to be equal to the average density of the lowest 0.5 m of snow in the pit.

represents the density of a snow pack of uniform density which gives the same integrated snow load on constructions as a snow pack with a given depth varying density and the same thickness.

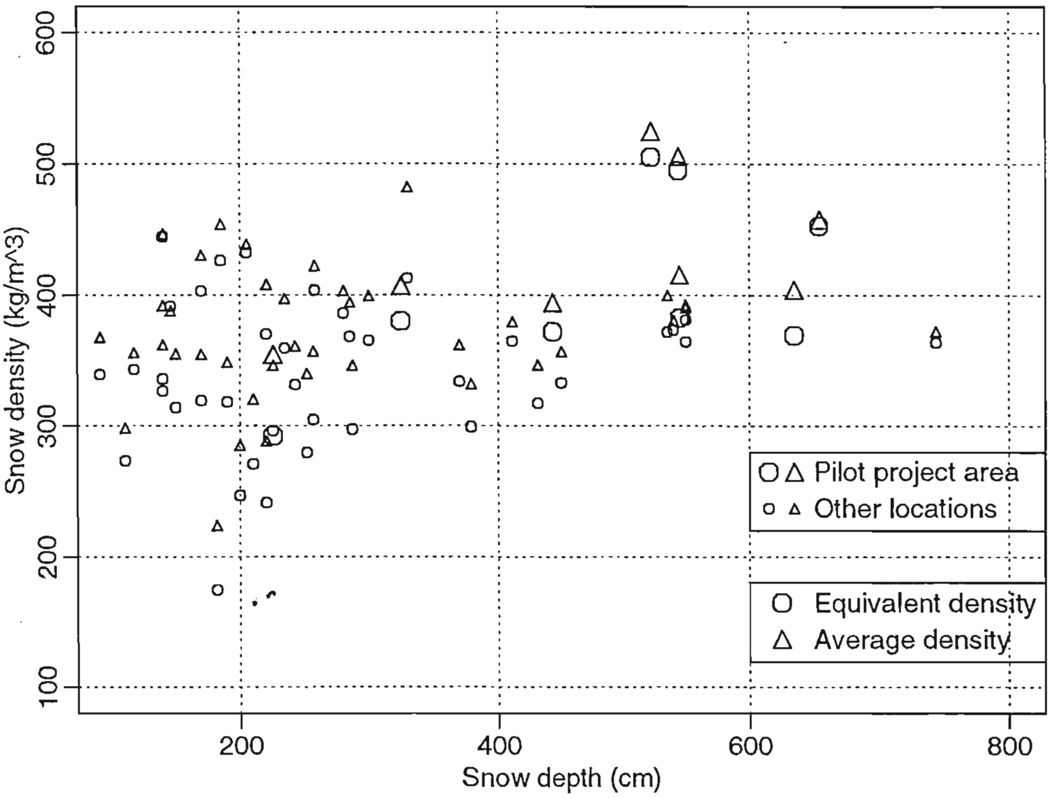

Figure 5. Snow density measurements from slopes above avalanche prone villages in Iceland 1990-1998 plotted against vertical snow height. The measurements from the pilot project area in Siglufjörður are shown with large symbols and measurements from other areas are shown with small symbols. The figure shows both the average density $\bar{\rho}$ computed from eq. (1a) and the equivalent density $\tilde{\rho}$ computed from eq. (1b).

4.2 Snow density measured in highland areas and starting zones in Iceland

Measurements in snow pits on glaciers in Iceland (Sigurðsson, pers. comm.) and at the Hveravellir weather station in the Icelandic highland (data from the archives of the IMO) indicate that typical values for the winter density are around 400-450 kg/m^3 and that the density reaches values in excess of 500 kg/m^3 during the spring months. These measurements are consistent with the observations from Siglufjörður described above.

In the last few years, some observations of snow densities in the neighbourhood of avalanche starting zones have been made by the local avalanche observers of the IMO. Figure 3 (right panel) shows snow density profiles measured in the fracture lines in Flateyri and Ísafjörður which were discussed in the previous section about snow depths. They show that the density of the newly wind deposited snow in the starting zones had a density close to 400 kg/m^3. Figure 5 shows all available such snow density measurements from Ísafjörður, Flateyri, Súðavík, Bolungarvík, Seyðisfjörður and Neskaupstaður, including the measurements shown in Figures 3 and 4.

The density measurements from Siglufjörður shown in Figures 4 and 5 and the density profiles from Flateyri and Ísafjörður shown in Figure 3, indicate that an equivalent average density of 400-450 kg/m^3 is appropriate for extreme snow depths during the middle of the winter in avalanche starting zones in Iceland. Densities in excess of 500 kg/m^3 are reached after the onset of melting in the spring when snow depths have started to decrease.

The snow depth and density profiles from Flateyri and Ísafjörður in Figure 3 clearly demonstrate the importance of wind transport for determining the conditions encountered in avalanche starting zones in Iceland. It is critical for the success of any supporting structure project in Iceland that starting zones with the most extreme snow accumulation due to wind transport are avoided. Otherwise, structures may be installed in areas where they will almost certainly be destroyed by snow loads, as has happened in the snow net installations in Ólafsvík and Auðbjargarstaðabrekka. These extreme conditions will, however, not be encountered in all starting zones.

4.3 Observations at NGI's research station in Grasdalen

Snow density and loading of supporting structures have been monitored by NGI at the Grasdalen research station in southern Norway from 1976 to 1998. These measurements come from a wet maritime climate similar to the Icelandic climate and span a much longer period than the measurements from Siglufjörður. Of primary interest with regard to the design of supporting structures is the density when the snow pressure on the constructions reaches its maximum. For the rigid retaining structure in Grasdalen this has been observed to happen at the end of the winter season when the snow pack reaches an 0 °C isothermal condition, normally at the end of April or in the beginning of May. For the snow nets this is also true, but the heavy snow later on in May and June can give stresses in the cables which are similar or even higher. The maximum point load in the retaining structures can also reach its highest level after the isotermal condition appear in May or even June. To compare the density measurements from Grasdalen with measurements from Iceland and Central Europe, we focus on densities measured during periods of maximum pressure on the constructions from early April to June in the period from 1976 to 1998 which are tabulated in Table 2 below.

Table 2: Snow depth (perpendicular to the slope, D), density and average snow creep pressure measured at NGI's research station in Grasdalen.

Year	Date	Snow depth perp. to slope D (cm)	Density ($\bar{\rho}$) (kg/m^3)	Aver. Press. (kPa)
1976	14-apr	490	426	16
	18-mai	370	520	13
1979	27-apr	250	395	8
1981	04-mai	410	430	13
1982	19-mai	230	388	6
1983	01-apr	350	397	9
	03-mai	310	513	8
1984	13-apr	390	433	10
	14-mai	330	508	11
1985	02-mai	230	390	3
	16-mai	180	478	3
1987	19-apr	310	400	8
	14-mai	250	448	6
1989	11-apr	490	488	15
	09-mai	440	486	13
	19-mai	440	474	13
1990	10-apr	480	456	15
	19-apr	460	465	15

Year	Date	Snow depth perp. to slope D (cm)	Density ($\bar{\rho}$) (kg/m^3)	Aver. Press. (kPa)
	08-mai	380	520	10
1991	20-apr	260	467	
1994	22-apr	290	397	
	05-mai	250	500	
	14-mai	220	513	
1995	29-apr	380	441	
	20-mai	330	500	
	26-mai	300	537	
1997	20-apr	475	463	
	27-apr	475	475	
	10-mai	470	468	
	17-mai	410	510	
	03-jun	350	516	
1998	05-apr	300	470	

One or more density observations are taken from each year in this period, with more than one observation from years with a deep snow pack when the snow pressure remained at a high level for a longer period of time (for example in 1976, 1989, 1990 and 1997).

Figure 6 shows the average density tabulated in Table 2 as a function of snow depth measured perpendicular to the slope. The high average densities for snow depths below 4 m are mainly from the last part of winter in May and June when the snow pack is wet after the appearance of isothermal conditions. The low average density in the same snow depth region is the maximum in winters with a relatively shallow snow pack.

A typical winter distribution of density with heigth above the ground from Grasdalen is shown in Figure 7 which may be compared with figures 3 and 4 from Flateyri, Ísafjörður and Siglufjörður. Normally, the snow density is relatively low at the top of the snow pack, and sometimes also near the bottom. In late winter the density distribution is more even than earlier in the winter.

If the density measured in Grasdalen is compared with the measurements from Siglufjörður in Iceland, it is found that the density distributions and values are similar. Average late winter and spring densities from Siglufjörður are in the approximate range 460 to 525 kg/m^3 in a snow pack with vertical depth varying from 6.5 to 5 m between 11 April and 27 May 1997, and the corresponding equivalent densities are in the range 450 to 500 kg/m^3 (*cf.* Fig. 4). In Grasdalen, average densities are in the range 463 to 516 kg/m^3 in the same period between 20 April and 3 June 1997 in a snow pack with vertical depth from 5.2 to 3.9 m (slope perpendicular depth from 4.75 to 3.5 m, *cf.* Table 2). The equivalent densities corresponding to the Norwegian measurements may be expected to be sligtly lower then the average densities (*cf.* Fig. 7). The measurements from Iceland and Norway are thus very similar. The highest densities discussed above are obtained after the snow depth has started to decrease. The densities corresponding to the highest integrated loading of the constructions are therefore somewhat lower than the highest observed densities which are found near the end of the spring.

4.4 Comparison with guidelines from the Alps

The Swiss Guidelines specify a reference dimensioning value of 270 kg/m^3 for snow density at the time of maximum snow depth in late winter (EISLF, 1990). This value is assumed to be appropriate at 1500 m a.s.l. for WNW-N-ENE exposed slopes and variations in density with altitude are taken into account through a *height factor* which increases by 2% per 100 m change in altitude from 1500 m a.s.l., *i.e.* between 1 and 1.3 in the altitude range 1500 to 3000 m a.s.l. This formulation

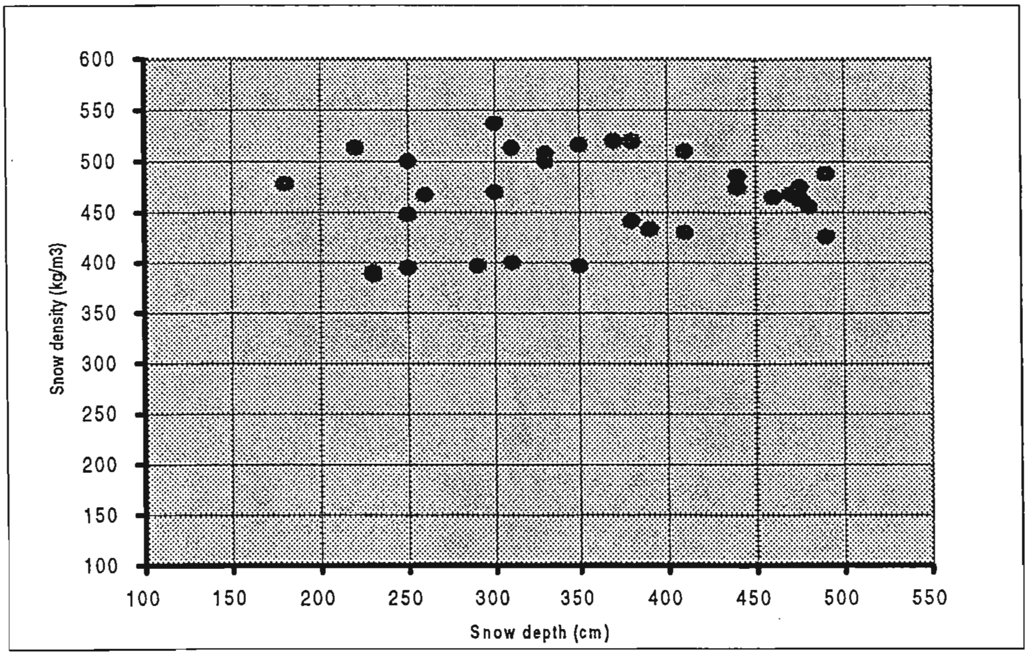

Figure 6. Snow density measurements from Grasdalen, southern Norway. The figure shows the depth averaged density (*cf.* eq. (1a)) against snow depth measured perpendicular to the slope.

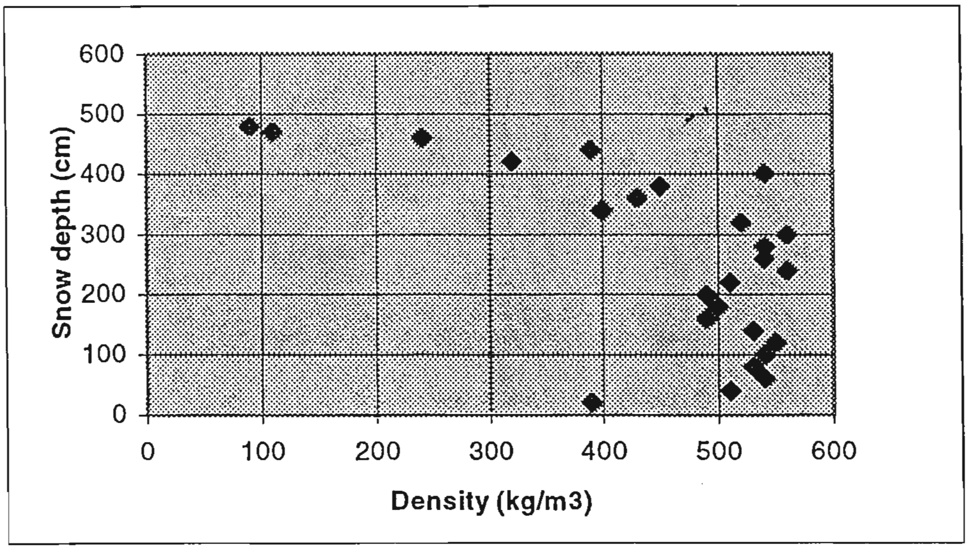

Figure 7. Snow density profile from Grasdalen, southern Norway, measured on 5 April 1990. Note that vertical snow *height* from the bottom of the pit is plotted along the y-axis (rather than the snow *depth* from the surface as in Fig. 4). The average snow density of the profile (eq. (1a)) is 466 kg/m^3 and the equivalent density (eq. (1b)) is 433 kg/m^3.

corresponds to a density of 351 kg/m^3 at the maximum elevation of 3000 m a.s.l. The Icelandic and Norwegian density measurements indicate a substantially higher density than even this highest density used in the Alps according to the Guidelines.

The Swiss Guidelines also specify a higher density which is used for reduced snow heights after melting starts in the spring (the so-called second case of loading). This higher density is 400 kg/m^3 at 1500 m a.s.l. for WNW-N-ENE exposed slopes which corresponds to 520 kg/m^3 at 3000 m a.s.l.

Thus the specific snow pressure during spring is assumed to be increased by a factor of 1.3 compared to mid winter conditions in some loading computations and is applied over snow depths reduced by a factor of 0.77. These Alpine spring densities are in most cases lower than the spring effective densities found in Siglufjörður and Grasdalen which are close to 500 kg/m^3 (*cf.* Figs. 4, 5 and 6).

Variation of dimensioning density with altitude through a height factor as in the Swiss Guidelines seem largely irrelevant in Iceland because of the narrow altitude range of the starting zones and since there are no indications of a variation in density with altitude. On the basis of the density data from Siglufjörður and Grasdalen, a dimensioning density in the range 400-450 kg/m^3, independent of altitude, seems to be appropriate for mid winter conditions when snow depths are at a maximum. Similarly, a dimensioning density close to 500 kg/m^3 seems to be appropriate for spring conditions when the snow depth has started to decrease. In order to complete the definition of the second loading case, a relative reduction in snow depth from the winter maximum needs to be specified. One possibility would be to use the same relative reduction in snow depth as the relative increase in snow density from the winter value to the spring value as is done in the Swiss Guidelines. This choice has the simple interpretation that the higher spring density is reached because snow melted during the initial stages of melting in the spring is assumed to refreeze or accumulate as liquid water in deeper layers in the snow before runoff from the snow pack starts. An explicit recommendation of dimensioning densities based on the pilot project will not be made until measurements from the second winter of the experiment have been analysed.

5. GLIDING

Gliding of the snow pack along the slope is one of the most important parameters determining the required strength of supporting structures. According to Swiss Guidelines (EISLF, 1990), loading of supporting structures is linearly related to a gliding parameter N, which varies from 1.2 to 3.2 under Alpine conditions. An appropriate estimate of gliding under Icelandic conditions is therefore critical for proper dimensioning of supporting structures in Iceland.

The gliding of the snow cover depends mainly on two conditions: the characteristics of the surface of the terrain and climatic conditions during the formation of the snow cover. The characteristics of the terrain are a permanent factor, the climatic conditions during the formation of the snow cover vary from year to year. A thick snow cover formed early in the autumn with a temperature around 0 °C on top of an unfrozen subsoil tends to produce gliding through the entire winter under Alpine conditions. Such "glide winters" are seldom and might have a return period between 20 and 30 years. The most extreme such winter in the Alps was in 1974/75 and caused extensive damages of ski lifts, forrests and in some cases supporting structures.

Although no direct observations of gliding have been made in Iceland before the pilot project in Siglufjörður, the gliding is believed to be low because there are little signs of gliding in starting zones in Iceland, such as marks in the ground due to loose stones being dragged along with the snow pack. The reason for the low gliding is likely to be related to the moist climate and soil conditions which facilitate strong binding of the snow pack to the ground.

5.1 Observations from Siglufjörður

The gliding of the snow pack along the slope was measured at two locations within the test area with 20x30 cm glide shoes which were free to slide with the snow pack along the slope. The two measurements yielded only 2 and 10 cm movement during the winter. A part of the measured gliding may have taken place when the snow pack had become thin in the spring, especially for the shoe showing 10 cm movement which was almost melted out when the observation was made. Although it is not possible to draw general conclusions from only two measurements, the observations are consistent with the expectation that gliding of the snow pack is comparatively low under the moist Icelandic meteorological conditions.

Observations during the winter 1997/98 from three glide shoes in the test area and on the open slope to the north of the test area show gliding of less than one cm and are therefore consistent with the measurements from 1996/97.

5.2 Indirect observations from snow stakes

Snow depth in starting zones has been monitored for a few years in several avalanche prone villages in Iceland starting with stakes installed in Neskaupstaður in 1994. The wooden stakes, which are 3-4.5 m high, are placed in shallow holes in the ground and supported by three thin steel wires fastened to the middle of the stake and bolted to the ground about 1 m from the stake. The stakes are in the altitude range 100 to 700 m a.s.l. and the slope of the hill where the stakes are located is typically in the range 30-40°. The number of stakes has increased from 26 in the winter 1994/95 to 97 in the winter 1997/98. Vertical snow height in excess of 3 m have often been observed in this period. Although many stakes fall at the end of the winter because the uphill wires break, the stakes have survived the winter in most of the cases. Apart from stakes lost in avalanches, only about 5 stakes have been broken since the beginning of the measurements, one near the middle, one about 0.3 m above the ground and the rest about 1 m above the ground.

It seems likely that a stake with the bottom end fixed in a depression in the ground and locked in a snow pack several metres in tickness, will break near the bottom end if the snowpack glides more than a few cm or tenths of cm. All stakes that have survived the winter without breaking or falling may therefore be considered indirect observations of comparatively low gliding during the corresponding winter at that location. The stakes that have fallen and the few stakes that have broken may be explained by creeping of the snow pack and it is actually rather surprising how many stakes survive the winter. There are therefore no indications of gliding from the stake observations since 1994 and the snow observers that maintain the stake network have not seen other indications of gliding in their work connected to the maintenance of the stakes.

The above indirect evidence from the stakes is of course not equivalent to direct gliding measurements with glide shoes, but they lend support to the low gliding measurements from Siglufjörður in 1996/97 and 1997/98. Observations from Alpine countries indicate that gliding typically occurs in "glide winters" with much lower gliding in other years. The indirect evidence from the stakes indicates that such "glide winters" have not occurred in Iceland since at least 1994. Although this is still a short period it is better than having gliding observations from only two years!

5.3 Observations at NGI's research station in Grasdalen

Gliding has been measured in Grasdalen both with glide shoes on the ground and physical snow creep and glide measurements at points at different distances from the constructions. No measurements in the period until the snow pack becomes isothermal in the spring show any significant movement, *i.e.* the total movement is below 2 cm. At the end of the winter there have been no measurements above 10 cm. Compared with the creep, the measurements in Grasdalen indicate the gliding of the whole snow pack at the ground surface is negligible. The ground in the research area is a rock slope tilting 25°, and it is not known how the situation would be on a smooth grass covered slope. The possibility of gliding should therefore be examined in other projects where data from Grasdalen is used for dimensioning purposes.

The low glide observations from Grasdalen are consistent with the observations from Siglufjörður, which span only two years. They indicate that gliding forces are comparatively unimportant compared with creep forces in the moist maritime climate of these two locations, at least for rock slopes.

6. SNOW CREEP

From the low glide measured in Siglufjörður and Grasdalen, one may conclude that forces due to the creep of the snow pack will be most important for determining dimensioning loads for supporting structures under the conditions at these locations. Direct measurements of snow creep do, however, not directly provide useful data for dimensioning purposes. Snow creep was, nevertheless, monitored in the test area during the first winter in order to compare it with similar measurements from other areas.

6.1 Observations from Siglufjörður

Snow creep was observed in six holes at two loctions withing the test area in the winter 1996/97 by pouring sand and coal dust into narrow vertical holes made by snow stakes in mid winter and measuring the displacement of the sand or coal dust later in early spring. Total displacement near the surface of the snow during the period 13 March to 30 April due to internal creep was in the range 10-20 cm in a 4-6 m thick snow pack.

6.2 Observations at NGI's research station in Grasdalen

Snow creep has been measured Grasdalen in several winters. In 1989 snow creep was observed in a period of one month from mid April to mid May. The observations were made in a snow profile, and also around a pole construction in a pattern of one measurement pr. m^2. The distribution of snow creep with height in a 5 m deep snow pack in a neutral zone 10 m above the supporting structures shows a near linear distribution up to 0.5 m below the surface. The average creep velocity was between 1 and 2 mm pr. day near the middle of the snow pack and the total surface movement was in average about 10 mm pr. day during the period.

In 1997 and 1998 snow creep was measured in shallower snow packs. The measurement in 1998 shows a velocity of 0.1 mm pr. day at the surface of a 3 m deep snow pack located 5 m upslope from the snow net construction in Grasdalen. The snow creep was linearily distributed with depth.

The snow creep measurements Siglufjörður and Grasdalen are consistent with each other and indicate that snow metamorphosis in the similar climates at the two locations is comparable. This indicates that useful dimensioning information for Icelandic conditions may be obtained from the long term measurements at Grasdalen.

7. TENSION AND PRESSURE MEASUREMENTS

Direct measurements of forces on the constructions are the most important measurements for determining dimensioning criteria for supporting structures. Such measurements have been made in Siglufjörður and over a much longer time period in Grasdalen.

7.1 Observations from Siglufjörður

Snow loading of the constructions in Siglufjörður was monitored by a continuous recording instrument (type Seamon load produced by Hugrún Ltd. in Reykjavík) in the upper anchor between posts 8 and 9 in the Geobrugg nets in row II, and by manual measurements of the tension in the downhill wires in the Geobrugg and EI net lines in rows II and III, and by three 70x70 cm maximum pressure plates which were fixed to the J. Martin steel structures in row I (see Fig. 1).

Figure 8 shows the tension recorded by the instrument in row II (see photograph 2 in the Appendix). It is seen that the tension increases steadily as long as the snow depth increases and reaches a maximum of almost 20 tons in early April. The onset of melting leads to a sharp decrease in the tension. There are no indications of an increase in the loading due to deformation or gliding introduced by melting.

Recalibration of the recording instrument after the winter indicates that the calibration of the tension sensor changed by several tons during the winter, possibly due to a load induced hysteresis in

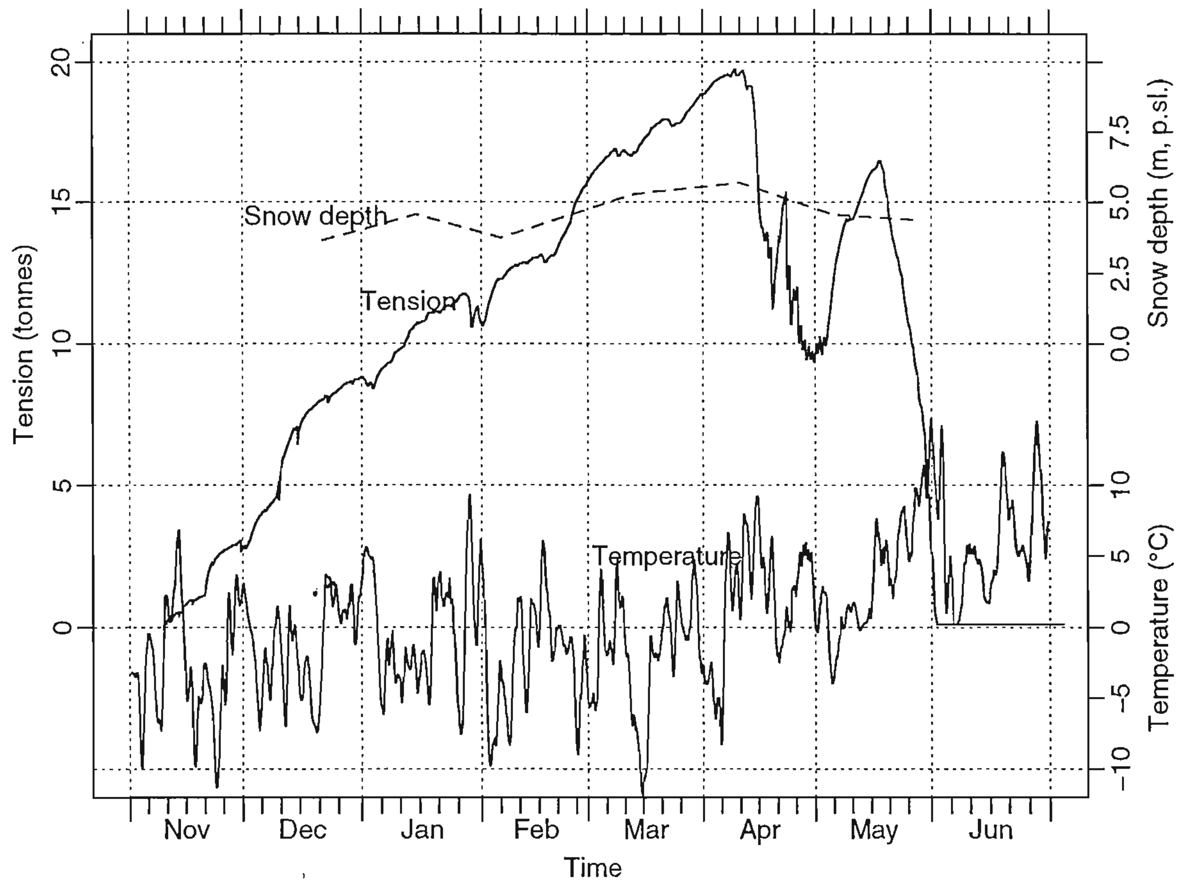

Figure 8. Tension in an uphill anchor in the Geobrugg nets in Siglufjörður. Also shown are the snow depth perpendicular to the slope in the nets at the location of the tension recording instrument and temperature recorded at a meteorological station at sea level in Siglufjörður.

the steel beem of the instrument. This problem will be further analysed on the basis of the data from the winter of 1997/98, but one must consider the tension measurements after the maximum was reached in early April to be unreliable. The data before this time are belived to be accurate.

The manual measurements of tension in the downhill wires were carried out by a Piab RTM 20-C rope tension meter which was calibrated for the types of wires which are used in the snow nets in Siglufjörður (see photograph 3 in the Appendix). The results are given in the following table.

Table 3: Tension in downhill wires of the snow nets (kN). Missing measurements because the corresponding post was under the snow cover are indicated with "NA".

Post	13 Mar	06 May	27 May
Geobrugg			
II-5	12.9	0	0
II-6	25.5	0	0
II-7	35.6	36.0	30.6

Post	13 Mar	06 May	27 May
II-8	43.1	67.0	57.8
II-9	2.5	12.2	18.1
II-10	58.8	55.9	65.5
II-11	NA	0.9	2.6
II-12	NA	NA	4.0
II-13	NA	NA	1.8
II-14	NA	NA	0.0
EI			
III-6	32.8	26.2	20.3
III-7	47.8	52.8	37.9
III-8	NA	7.0	5.7
III-9	7.2	30.0	25.6
III-10	2.3	10.1	18.6
III-11	8.6	20.9	21.2
III-12	14.0	33.5	31.7
III-13	23.2	31.2	22.0
III-14	41.1	42.5	28.2
III-15	16.6	4.6	0.0

The three maximum pressure plates were mounted between posts 11 and 12 of the steel bridges from J. Martin in row I where $D_k \approx 4$ m. The were mounted at distances 230, 140 and 90 cm from the bed (measured perpendicular). Each plate was fitted with 5 conical pins which made conical depressions in cylindrical aluminum surfaces with a diameter of 30 mm when the plate was subjected to pressure (see photograph 4 in the Appendix). The diameter of the conical depressions in the aluminum, d, in mm is a function of the applied load, f, in kg according the equation $d = 0.178 \cdot f^{0.5127}$, which was derived with a laboratory calibration. It was verified by calibration with loads of different duration that the diameter of the conical depression in the aluminum surface *only* depends on the maximum load and *not* on the duration of the load or on the load history. The results of the measurements are given in the following table.

Table 4: Maximum loads measured in Row I.

Plate	Distance from slope (cm)	Load (kN)
I	230	47.4
II	140	37.5
III	90	29.1

The maximum snow thickness of the winter was approximately 5 m perpendicular to the slope at the location of the plates (*cf.* Fig. 2a). Each plate has an area of approximately 0.5 m^2. It may be expected to support snow pressure corresponding to a larger area due to bridgeing, perhaps extending a distance on the order of the dimensions of the plate in all directions. If it is assumed that each plate supports snow pressure corresponding to 2-3 times its area (the relative area of the steel surface of the beams in the stiff steel constructions is about 55%), the measured total load on each plate (in kN) given in Table 4 multiplied by a factor in the range 0.75-1 will be approximately equal to the snow pressure on the plate (in kPa). This is admittedly a crude way to interpret the observations and should be improved in the interpretation of future data from the maximum pressure plates. Plates I and II are

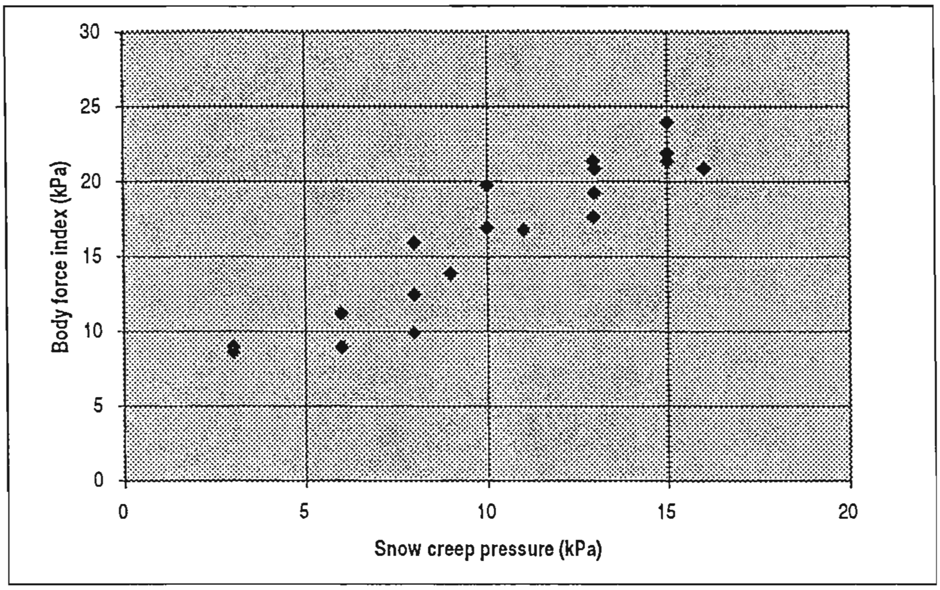

Figure 9. Body force index and snow creep pressure from Grasdalen, southern Norway (see text for explanation).

located at a depth below the snow surface where the snow pressure reaches a relative maximum (*cf.* Fig. 2 in McClung and others (1984)). The depth averaged snow load will therefore be lower than the measurements in Table 4 indicate. The qualitative vertical variation of snow pressure with depth given in Figure 2 in McClung and others (1984) indicates that, over the whole construction, the depth average corresponding to the load on the plates given in Table 4 is approximately equal to 30 kN. This corresponds to depth averaged snow pressure in the range 20-30 kPa (using above estimate of the effect of bridging).

These measurements indicate that the loading of the structures can be interpreted by the same formulas as used for the design of supporting structures in Alpine countries if allowance is made for the higher density of snow in Iceland (see below). There seems to be little loading due to gliding of the snow cover along the slope, which in part compensates for the higher loading due to the high snow density.

7.2 Observations at NGI's research station in Grasdalen

Strain in the beams and supports of a stiff supporting structure in Grasdalen has been measured during the period from 1976 to 1990. Snow pressure has also been measured with $\phi = 100$ mm sensors mounted in the center of 0.8x0.8 m plates. In addition, stress in the wires and poles of a net construction has been measured in the period 1991 to 1998. As the anchors of the net have failed during some of the winters due to heavy loading there are few results from the measurements in the snow nets.

The average snow pressure on the 3.3 m high construction has been calculated from the measured strain in the supporting structures (Table 2 above and Larsen, *et al.*, 1982) and was found to vary strongly with snow depth. The highest depth averaged pressures were found to be about 16 kPa for snow depths measured perpendicular to the ground of almost 5 m. Figure 9 shows the pressure variation with the so-called *body force index* (McClung, 1993) which is defined as a product of density times snow depth (measured perpendicular to the slope) times acceleration due to gravity.

There are few reliable records from the pressure plates due to the fact that the results found from the first winters seem to be different and incorrect compared with later estimates of the pressure on the whole structure. At the end of April 1976 a pressure of 12 kPa was measured 0.8 m above the ground surface in a 5 m thick snow pack when the snow became isothermal and the average pressure was 16 kPa on the structure. In 1981 a pressure of 17 kPa was measured with the same sensor in 4.1 m snow cover under average snow pressure of 13 kPa as the snow pack became isothermal (Larsen, 1982).

The tension measured in the cables of the snow net in Grasdalen show the same development as seen in the measurements from Siglufjörður with the highest values near the end of April or in May. Different from the supporting steel structure, the tension in the net has been found to continue to increase or maintain the peak values also after the snow pack becomes isothermal. Tables 5a,b below show the peak values observed in the wires in the period 1991 to 1997. The 12 m long net is of heigth $D_k = 3$ m and consists of four posts labelled M1, M2, M3 and M4 with a spacing of 4 m. The wire tension is measured both at the bottom (B) and at the top (T).

Table 5a: Tension in the wires of the snow nets at NGI's research station in Grasdalen in the winters 1991-1997, sensors at posts M1 and M2.

Year	Date	Str.wir. M1-T (kN)	Str.wir. M1-B (kN)	Str.wir. M2-T (kN)	Str.wir. M2-B (kN)
1991	20-apr	64	51	10	39
1994	22-apr	85	2	93	0
	05-mai	133	2	57	0
	14-mai	0	0	88	0
1997	27-apr	212	42	0	4
	17-mai	252	47	0	19

Table 5b: Stress in the wires of the snow nets at NGI's research station in Grasdalen in the winters 1991-1997, sensors at posts M3 and M4.

Year	Date	Str.wir. M3-T (kN)	Str.wir. M3-B (kN)	Str.wir. M4-T (kN)	Str.wir. M4-B (kN)
1991	20-apr	24	72	29	19
1994	22-apr	31	16	51	15
	05-mai	0	18	0	11
	14-mai	0	8	84	6
1997	27-apr	0	65	0	4
	17-mai	0	109	0	18

The zeros in the tables indicate problematic measurements due to the problems with the net construction which were mentioned above. The tablulated loads must be used with some reservation due to these problems.

The recorded maximum tension is quite variable from post to post and also from the top to the bottom on the same wire. This indicates a complicated loading distribution on the construction which among other things is due to a load distribution along the wires of the net. The highest tension measurements are above 200 kN (20 tons) and are reached when slope perpendicular snow depth in the area is ranging from 4.75 and 4.1 m (*cf.* Table 2). This is slightly higher than the maximum value of approximately 200 kN from Siglufjörður which was reached for a vertical snow height of about 5-6 m.

8. SNOW PRESSURE ON CONSTRUCTIONS

According to the Swiss Guidelines (EISLF, 1990; see also Salm, 1977) the total snow pressure along the slope on a solid construction oriented perpendicular to the slope is given by

$$S'_N = (\rho/1000)g\frac{H_k^2}{2}KN, \quad [\text{kN/m'}] \tag{2}$$

where ρ is snow density with a reference value of 270 kg/m^3 for Alpine countries, g=10 m/s^2 is the acceleration of gravity, $K = f(\rho, \psi) \approx 0.7 - 0.9$ is a creep factor, N is a gliding factor in the range 1.2 to 3.2, H_k is extreme vertical snow height, ψ is the slope of the hill, and [m'] in the units denotes distance along the row of the supporting structures. The value of the creep factor for a slope of ψ =36° and density of ρ =400 kg/m^3 is $K = 0.79$ and an appropriate value of the gliding factor for very little gliding is $N = 1.2$ (EISLF, 1990). This gives $S'_N = 72.4 - 104.2$ kN/m' for D_k=5-6 m (H_k=6.1-7.4 m).

McClung and Larsen (McClung and others, 1984; McClung and Larsen, 1989; McClung, 1993) have developed another formulation for snow pressure on constructions

$$\frac{S'_N}{\rho g D_k^2} = \left[\left(\frac{2}{1-\nu}\right)\left(\frac{L}{D_k} + \frac{D}{D_k}\right) \right]^{\frac{1}{2}} \sin\psi + \tfrac{1}{2}\left(\frac{\nu}{1-\nu}\right)\cos\psi, \quad [\text{N/m'}] \tag{3}$$

where $\nu \approx 0.4$ is the Poisson's ratio of the snow cover (McClung and others, 1984), D is a parameter related to gliding and $L/D_k \approx 0.26$ is a coefficient, which is a function of the slope of the hill ψ=36° and the Poisson's ration ν=0.4 in the special case of no slip along the structure subject to the pressure. In the absence of gliding (D/H=0), this equation gives $S'_N = 80.0 - 115.3$ kN/m' for D_k=5-6 m, a very similar result as found above from the snow pressure formulation of the Swiss Guidelines expressed by eq. (2).

The good agreement between eqs. (2) and (3) is largely fortuitous since it is better than would be expected from the accuracy of some of the underlying coefficients such as N, ν or L/D_k. Lower values of ν in the range 0.25-0.4 in eq. (3) yield lower values of S'_N in the approximate range 56-80 kN/m' for D_k=5 m. Increasing the slope to ψ=45° (the design slope for most supporting structures), leads to a greater increase in the snow load according to eq. (2) than for eq. (3), *i.e.* 99.6 and 89.9 kN/m' respectively.

The loading of $S'_N \approx 72 - 80$ kN/m' for D_k=5 m and $S'_N \approx 104 - 115$ kN/m' for D_k=6 m predicted by eqs. (2) and (3) may be compared with the maximum pressure measurements from row I and the tension recorded in the Gebrugg nets described in the previous section. Since the steel constructions with $D_k \approx 4$ m were overfilled with snow by about 1 m at the time of maximum snow depth and maximum loading, the total pressure given by S'_N must be distributed over the actual slope perpendicular length of the structures which may for this purpose be estimated as 4 m. The gives a predicted depth averaged snow pressure of about 19 kPa for D_k=5 m in row I, which is somewhat lower than the observed value of 20-30 kPa derived from the maximum pressure plates in the previous section. As discussed above, there are interpretation problems arising from bridging near the plates associated with this observed value and the comparison can therefore not be considered accurate.

The maximum tension recorded in the Geobrugg nets cannot be directly compared with the predicted snow pressure because loading of nets is affected by the weight of snow directly supported by the nets, which leads to an increased loading, and by regelation of the snow past the wires of the nets, which leads to a decreased loading. The decrease in loading due to the regelation effect is by a factor of 0.8 according to the Swiss Guidelines. If weight of snow directly supported by the nets is neglected together with the effect of the geometry of the nets, the total snow load supported by the upper anchor with the tension recording instrument is approximately equal to $S'_N * L \approx 110 * 3.5 * 0.8$

≈ 310 kN ≈ 31 tons for D_k=6 m in the Geobrugg nets in row II, where $L = 3.5$ m is the post spacing of the nets. This is in somewhat higher than the measured maximum load of approximately 20 tons. This comparison will be readdressed with more detailed analysis of force balance in the nets when data from the second winter of the experiment are available.

The tension data from Grasdalen indicate that loading of snow nets is fairly complex with irregular variations in the load between different parts of the constructions. These variations between the different parts of the constructions are clearly much greater than the differences between the two theoretical formulations for snow pressure expressed by eqs. (2) and (3) above.

It is difficult to draw general conclusions from tension measurements in only one uphill anchor from Siglufjörður. The two net lines in Siglufjörður, with a total of 29 posts and 32 uphill anchors and a total length of 91.5 m, have survived two winters with very high snow depths along more than half of the length of the lines. The nets have withstood the snow load without damages except for the failure of the micropiles in loose material in the Geobrugg nets. This observation of the total structure over two winters experiencing highly variable loads and snow depths beyond the design loads, is perhaps a more valuable "data point" than a tension data series from a single location. The observation that the main supporting elements of the constructions have withstood the applied loads indicates that the overall strength of these structures is not insufficient for Icelandic conditions. These conclusions do also apply to the stiff steel constructions in rows I and IV which have also withstood the applied snow loads without damages.

9. PRELIMINARY CONCLUSIONS

The following preliminary conclusions for the design of supporting structures in Iceland may be drawn from the observations in the test area in Siglufjörður which are described in this report.

1. For extreme values of the snow height, $\bar{\rho}$ =400-450 kg/m^3 seems to be an appropriate equivalent average snow density for the design of supporting structures in Iceland. This corresponds to the first case of loading according to the Swiss Guidelines. An appropriate density for the second case of loading is 500 kg/m^3 or more.
2. The effect of gliding on snow loading appears to by low.
3. Maximum loading of the structures occurs around the time of maximum snow depth. Densification, deformation or gliding induced by spring melting is not significant for the dimensioning of supporting structures.

Although these results are preliminary since they are derived from measurements from only one winter, the available additional observations from Norway and previous related observations from Iceland give additional support to these conclusions. Additional analysis of data gathered during the second winter of the experiment is required in order to formulate explicit guidelines for supporting structures under Icelandic conditions based on existing guidelines from Alpine countries.

The overall agreement between observed loads and theoretical predictions based on the Swiss Guidelines, when the high density of snow in Iceland is taken into account, indicates that modified Swiss Guidelines with higher reference dimensioning density will provide adequate requirements for supporting structures for Icelandic conditions. This implies that most requirements regarding the internal structure and relative strength of elements in the constructions, such as stronger end elements, relative forces in uphill and downhill anchors, *etc.*, will be unmodified. Apart from the higher density, the modifications would for example include an elimination of the height factor and an explicit determination of a low glide factor.

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APPENDIX A: PHOTOGRAPHS FROM THE TEST AREA

Photograph 1. The supporting structures in Hafnarfjall in Siglufjörður, northern Iceland.

Photograph 2. The tension recording instrument in the Geobrugg nets in row II.

Photograph 3. The Piab RTM 20-C rope tension meter.

Photograph 4. The maximum pressure plates in the J. Martin structures in row I.