

AVALANCHE MITIGATION MEASURES FOR SIGLUFJÖRÐUR – REALIZATION OF THE LARGEST PROJECT WITH SNOW SUPPORTING STRUCTURES IN ICELAND

Stefan Margreth<sup>1\*</sup>, Tómas Jóhannesson<sup>2</sup> and Hrafnkell Már Stefánsson<sup>3</sup>

<sup>1</sup> WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

<sup>2</sup> Icelandic Meteorological Office, Reykjavík, Iceland

<sup>3</sup> Verkís Consulting Engineers, Reykjavík, Iceland

**ABSTRACT:** The avalanche situation of Siglufjörður in northern Iceland is unique because the residential area is located directly at the base of several large avalanche paths. Due to the topographical situation, large deflecting or catching dams cannot be constructed without the removal of buildings except for the southernmost part of the town. Therefore up to 8.4 km of supporting structures in combination with small catching dams were proposed as protection measures for the central and northern part of the town. The main challenges for the application of snow supporting structures are the deep and heavy snowpack, irregular snow depths, rockfall, difficult ground conditions, corrosion problems, formation of large cornices and lack of experienced construction companies.

**KEYWORDS:** Risk management, Avalanche mitigation, Snow supporting structures.

1. INTRODUCTION

After two catastrophic avalanches killed 34 persons in the villages of Súðavík and Flateyri in northwestern Iceland in 1995, a comprehensive national plan was made for assessing avalanche risk and implementing avalanche mitigation measures (Jóhannesson et al., 1996). Siglufjörður is a small fishing town with a population of 1300 inhabitants located in a narrow fjord on the northern coast of Iceland. The town developed around the herring industry that was in much bloom in the 1940s and 1950s, but the herrings are mostly gone now. Catastrophic avalanches killed 18 people in Siglufjörður and neighboring rural areas in 1919. However, none of the fatal accidents of 1919 occurred in the present area of the town. Later in the 20th century, residential buildings were constructed in the runout zone of an avalanche of the 1919 cycle. The avalanche situation in Siglufjörður is unique because the residential area is located directly at the base of several avalanche paths of the Hafnarfjall mountainside. The release zones involve about 40 hectares with potential avalanche volumes of more than 100'000 m<sup>3</sup> for several of the paths. Avalanches are most common during periods with strong NE winds with snowfall. The SLF elaborated a protec-

tion plan for the central and northern avalanche paths of Siglufjörður in 2001 (SLF, 2001).

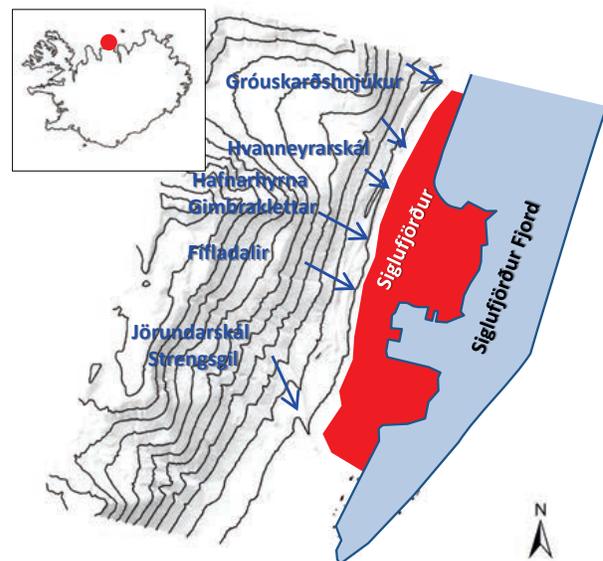


Fig. 1: Location map of Siglufjörður with avalanche paths.

2. AVALANCHE SITUATION

The mountainside above Siglufjörður can be divided into seven avalanche paths. **Jörundarskál** and **Strengsgil** are the main avalanche paths above the southern part of Siglufjörður (Fig. 1). They are located in an ESE facing slope and consist of rather large bowls that merge into narrow gullies.

\* Corresponding author address:  
Stefan Margreth, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH 7260 Davos Dorf, Switzerland;  
tel: +41 81 4170254; fax: +41 81 4170110;  
email: margreth(at)slf.ch.

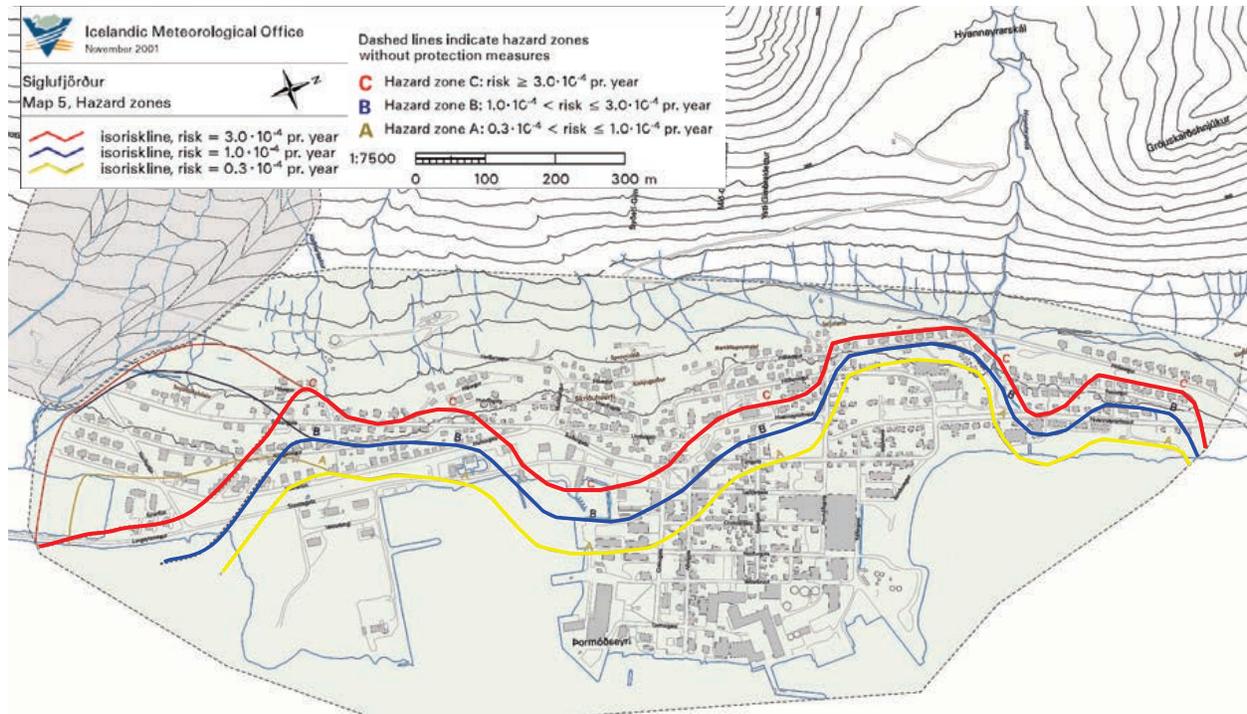


Fig. 2: Hazard map of Siglufjörður with red (C), blue (B) and yellow (C) isorisk lines before the implementation of mitigation measures. In the hazard zone B (situated between the blue and red line) working places can be built, but residential houses should be reinforced. Schools and similar buildings are not permitted. In the C-Zone it is only possible to build structures not permanently occupied.

Large snow drift accumulations occur in the gullies. The avalanche frequency is high and in the past several avalanches reached all the way to the sea before residential houses were constructed in the runout zone. **Fifladalir** is by far the largest avalanche path consisting of different mostly unconfined release areas with average slope angles varying between  $32^\circ$  and  $40^\circ$ . The release area extends from the mountain top of Hafnarfjall at 640 to 170 m a.s.l. with a total width of 700 m. The release area is divided by gullies and a small terrain terrace. Most of the release area consists of scree, interrupted by some unstable rock cliffs. Strong winds from N and NW can produce large snow accumulations in the upper part of the release area. According to the avalanche history no extreme avalanches have been observed from this part of the mountain in the last 100 years. However, several small and medium-sized avalanches have reached almost to or even touched the uppermost houses but the resulting damage was minor. Above the uppermost line of houses there is no runout zone for extreme avalanches. Due to the size and the shape of the starting zones huge amounts of snow can accumulate and large avalanches can release as a consequence. The ex-

trême scenario consists of an avalanche release in the upper release area, triggering or entraining additional snow masses in the lower starting zone. Such an event, which is considered to be very rare, can comprise several  $100'000 \text{ m}^3$  of snow. The tongue of such an extreme event would extend over several rows of houses well into the populated area, which results in a high hazard for a large area in the central part of the town. More than 150 houses are endangered. The release area **Hafnarhyrna** and **Gimbraklettur** is located north of Fifladalir. The starting zone has the shape of a steep triangle with the highest point at 465 m a.s.l. where the ridge becomes less steep and narrower. In the lower part, the width is up to about 250 m. The area is divided by three shallow gullies. In the middle, the surface is composed of loose rock cliffs and the slope angle is about  $40^\circ$ . Because the starting zone has a convex shape, large snow accumulations are only likely in local depressions and shallow gullies. The consequence is that large avalanches are unlikely, however, no runout zone exists above the uppermost houses. **Hvanneyrarskál** is a small release area at a low elevation situated below a large bowl shaped valley. The

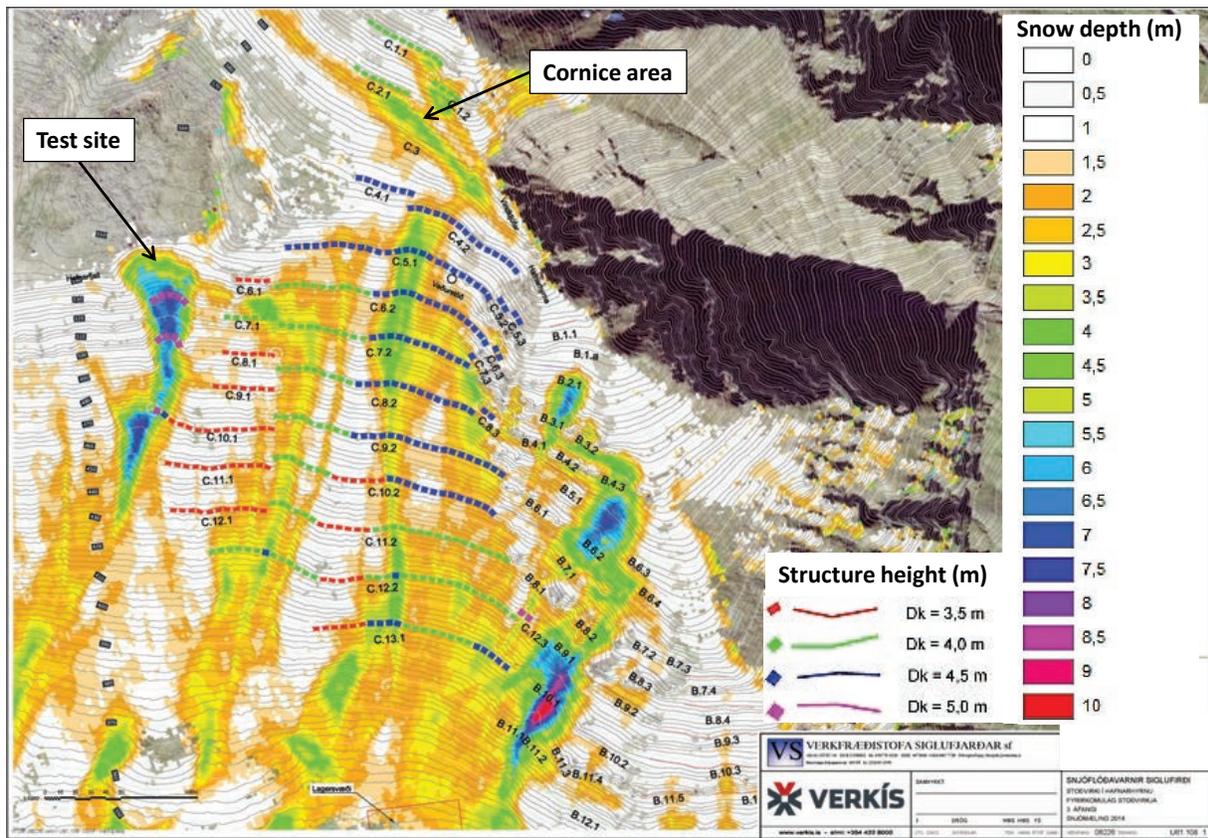


Fig. 3: Snow depth measured with terrestrial lidar (data from the Institute for Geography, University of Innsbruck) on 8 April 2014 of Hafnarfjall with the location and height of the planned supporting structures of phase 3 (red = snow depth 10 m, green = snow depth 5 m).

avalanche hazard is considered to be low, but as the terrain is steeper than  $19^\circ$  at the location of the uppermost houses, the settlement is potentially endangered by even very small avalanches. Gróuskarðshnjúkur is the northernmost avalanche path consisting of a rather small well defined release area situated on a convex ridge and a 300 m wide much steeper release area divided by large cliffs. In 1963, an avalanche reached into the residential area and destroyed one building. Large avalanches can reach the sea.

A substantial part of the town of Siglufjörður is situated in hazard areas with a risk to humans in residential houses higher than  $0.3 \times 10^{-4}$  per year, which is considered to be unacceptable for residential areas according to the Icelandic hazard zoning regulation (Fig. 2). The area in the southern part of the settlement, below Jörundarskál and Strengsgil, has probably one of the highest risks for residential areas in Iceland. The actual risk below Fífladalir is difficult to assess, however, it is clear that the possibility of a large catastrophic avalanche exists. An overall protection plan includ-

ing the construction of defence measures is therefore mandatory to improve the hazard situation and reduce the risk.

### 3. SNOW SITUATION

The snow depth is an important factor which determines the volume of avalanches and the necessary height and design of supporting structures. The height of supporting structures is designed with respect to an estimate of the 100-year snow depth. Snow depths in the release areas above Siglufjörður have been measured with fixed stakes since winter 1996/97. The measurements and winter photographs clearly show that wind causing snow drifts is the main controlling factor for differences in the local snow depth. The measurements indicate that the snow depth does typically not exceed 2 to 3 m on unconfined or concave parts of the hill. The 100-year snow depth may be larger than this by a factor of 1.5 to 2. In gullies and depressions and near the top of Hafnarhyrna, the snow depth can, however, become many times larger than this. There, the snow depth seems to

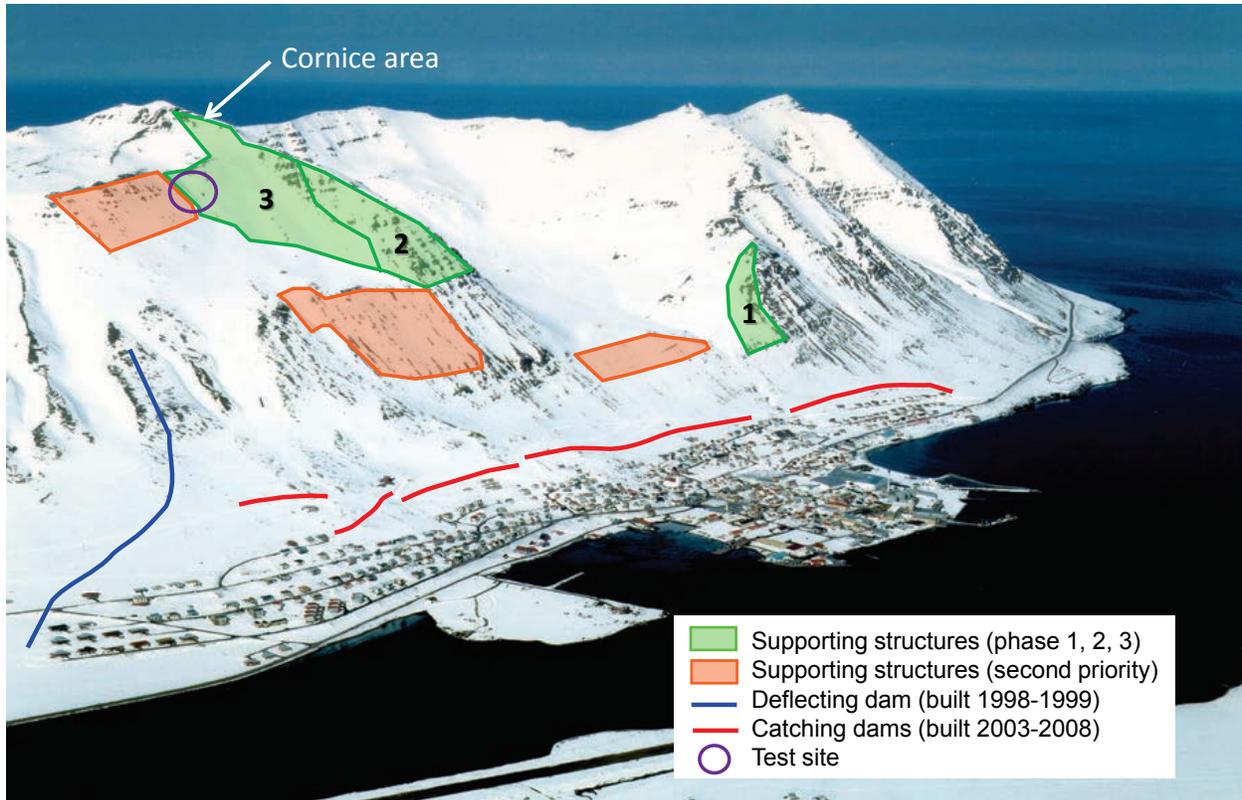


Fig. 4: Overview of Siglufjörður with the realized and planned protection measures (Photo: M. W. Lund).

be mostly controlled by the depth of the depression and other landscape features, rather than by the local amount of precipitation that falls as snow. Observations have shown that vertical snow depths in gullies and depressions have exceeded 10 m. In our 2001 assessment, we estimated the 100-year extreme snow depth to vary between 4 m in unconfined or concave slopes to 13 m in deep gullies. In 2008 and 2014, aerial and terrestrial lidar surveys of the snow-covered mountain-side were used to compile snow depth maps (Fig. 3). The snow depth maps clearly show the preferential accumulation of snow in depressions and on the lee side of gullies. The maps have been very useful for the detailed determination of structure heights. A very conspicuous local feature is the formation of three elongated cornices with heights of 5 to 10 m and lengths of more than 100 m near the top part of the Fífladalir release area. The three long cornices tend to form in most winters at the same locations (Fig. 8). The cornices intersect the preferential location of snow supporting structures and can cause overloading of typical types of structures. High-resolution wind field simulations were carried out to find possible reasons for the cornice formation (Orion, 2005). Most likely, the

cornices are formed by winds governed by the surrounding “large scale” terrain features and not by local obstacles such as rock outcrops or cuts in the mountain ridge.

#### 4. PROTECTION PLAN

Due to the topographical situation north of the avalanche paths Jörundarskál and Strengsgil, where deflecting dams were planned in 1997 (VS and NGI, 1997), large catching dams cannot be constructed. The maximal velocity of an extreme avalanche from Fífladalir is more than 35 m/s which would require a dam height of more than 40 m. Such dams cannot be built without removing of buildings in the residential area. Consequently, we looked for alternative measures. We concluded that the best solution was the combination of supporting structures in the main release areas with 8 to 15 m high catching dams above the residential areas (Fig. 4). A comprehensive field inspection where the topography and geotechnical conditions were examined in detail showed that the construction of snow supporting structures is feasible in large parts of the release area. The main challenges for the application of snow supporting

structures are the deep and heavy snowpack, irregular snow depths, rockfall, difficult ground conditions, corrosion problems, formation of large cornices and a lack of experienced construction companies. A total of 8.4 km of supporting structures were proposed, 4.3 km in first priority and 4.1 km in second priority. The proposed structure heights vary between 3.5 and 5 m; about 30% of the structures have a height of 4.5 and 5 m. In addition, 1.4 km of catching dams were proposed to be built at the base of the avalanche tracks. The total cost was estimated to be 24 Million Euros. An advantage of the proposed project plan is that at first the catching dams can be built within a relatively short time to provide a minimal protection. The dams protect the residential area from debris flows and from rockfall, which can be a threat during the construction of the supporting structures, in addition to providing some protection from small snow avalanches. The construction of the supporting structures will take many years.

## 5. PILOT PROJECT

A pilot project for testing the feasibility of supporting structures in Iceland and for obtaining data to define an optimal setup of such structures under Icelandic conditions was implemented in 1996 in the western part of the Fífladalir release area (Figs. 3 and 4). About 200 m of supporting structures, both stiff steel bridges and flexible snow nets with structure heights varying between 3 and 5 m, were installed in a deep gully and on an open slope. The results of the experiment have been used to formulate guidelines for the design of supporting structures under Icelandic conditions (Jóhannesson and Margreth, 1999). The snow density in Iceland, about  $400$  to  $500 \text{ kg/m}^3$ , is higher than typical in the Alps but on the other hand snow gliding was not observed. The measured snow pressure loads were generally within the corresponding design loads according to the Swiss Guidelines (Margreth, 2007). The structures in the gully have several times been completely overfilled. The maximum tension in upper anchors of snow nets has reached  $350 \text{ kN}$ . The stiff steel bridges seem to be less vulnerable to overloading compared to the snow nets, mostly due to a higher lateral stiffness. Steel bed plates turned out to be better suited for the foundation of supports compared to micropiles. A serious issue was steel corrosion which is especially problematic for wire rope nets. The findings of the pilot project have been very valuable for the development of the different projects involving snow supporting structures in Iceland.

## 6. REALISATION OF THE PROJECT

### 6.1 *Avalanche dams*

Two deflecting dams with lengths of up to 700 m were built below the gullies of Jörundarskál and Strengsgil 1998 and 1999. The dam heights are up to 18 m and the deflecting angle for the larger dam is  $15\text{--}18^\circ$ . The catching dams above the residential area were built between 2003 and 2008. The longest dam has a length of 900 m. The top 5 m of the dams were constructed as a vertical wall to increase the effectiveness during the impact with an avalanche (Figs. 5 and 6).

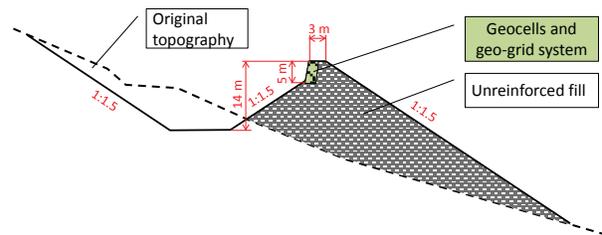


Fig. 5: Cross-section through a catching dam below Fífladalir.



Fig. 6: Catching dam in construction, the steep top section is made of geocells (Photo: Þ. Jóhannesson).

The vertical walls were built with a geocell earth-retention system. The filling of the geocells with processed material was labor-intensive since no heavy machinery could be used. The main advantage of the geocells is that the vertical walls can be vegetated (Indriðason, 2008). The top width of the dams is 3 m and the remaining sides of the dams were built with unreinforced fill with a slope of 1:1.5. Special attention was given to the

visual impact of the avalanche dams. Landscape architects designed the dams with the goal to see the defense measures as an opportunity to create a recreational area for the village (Vilhjálmsson, 2007). That was mainly done by using curved dam crests, implementing local materials and building view points, hiking paths and even a small lake.

## 6.2 *Snow supporting structures*

The first phase of installation, comprising 630 m of snow bridges in the release area Gróuskarðshnjúkur, was successfully completed in 2004. The second phase, the installation of approximately 1600 m snow bridges at Hafnarhyrna and Gimbraklettur, started in 2013 and will be completed in 2015. In the third phase, about 1800 m of steel bridges will be installed at Fífladalir, starting in 2016. The overall project is planned to be completed before 2020. The applied stiff snow bridge system consists of jointed supports and girders forming a three-hinged arch (Fig. 7). This type of static system is rather insensitive to ground deformations. The girder foundations transfer the directionally variable tension and pressure forces into the ground with micropiles and anchors. The anchor lengths vary between 2 m in rock and 6 m in loose soil. Most of the drills reached bedrock. The supports are based on square ground plates. Their sizes range from 300 mm in rock to 800 mm in loose soil. The geotechnical conditions in the Fífladalir release zone will be less favorable than in Gróuskarðshnjúkur. The most problematic areas consist of steep loose debris with many blocks and openings. Therefore test drills and pull-out tests are planned to investigate the conditions for anchoring and to verify the necessary anchor lengths.

The steel parts of the snow bridges above ground are hot-dip galvanized. The corrosion protection of the anchor bars consist of an additional steel thickness of 2 mm on each side in combination with hot-dip galvanization. Reinforced end-of-line structures, consisting of double girders and supports, are used at locations with large snow depths and where the lines end in unconfined slopes.

The planning of the number and location of the structures was made in three steps. A preliminary stake-out was performed in 2001 where the approximate number of structures was estimated, mainly based on the results of the terrain analysis. The necessary quantity, location and height of the structures for preparing the bidding documents was determined by fixing the location and length of the different lines of structures on site (Fig. 3). Fi-

nally, the detailed stake-out, where the exact location of all foundations and drilling point is fixed, was made by the installation contractor in collaboration with the manufacturer of the structures. All steep slopes and rock faces were cleaned of unstable rocks before the construction work started. This work step is very important for the safety of the workers and to ensure adequate service life of the supporting structures. A temporary earth road was built halfway up the mountainside to establish access to the construction site for the workers and to facilitate the transportation of material.



Fig. 7: Steel bridges in the release area Gróuskarðshnjúkur built in 2004. The structure height is 3.5 m and the length of the cross-beams is 4 m (Photo: S. Margreth).

## 6.3 *Wind baffles*

The planning of supporting structures near the top of the Fífladalir release area is challenging because of the three long cornices that are formed in that area. Different options were investigated on how the cornice problem could be handled. Four wind baffles were installed in 2013, for the first time in Iceland, in an attempt to reduce the formation of cornices (Fig. 8). The cross-shaped wind baffles have a height of 3 m and are anchored to the ground with rock bolts. Observations in winter 2014 have shown that the amplitude and location of the cornices are nevertheless similar as in former winters. The wind baffles thus do not seem to have had a large influence on the formation of the cornices in the first winter. The positioning of snow supporting structures at the location of large cornices is not advisable because of the risk of over-snowing and damages. Therefore, we planned to place the lines of supporting structures directly

above and below of the cornices and to construct two stone terraces in between. The goal of the stone terraces is to stabilize the snowpack in between the supporting structures and to prevent a cornice collapse.



Fig. 8: Wind baffles on the top of Hafnarhryrna on 28 March 2014. The beginning of the large cornice is on the right side of the wind baffles. The wind baffles have not led to a substantial change in the snow distribution in winter 2014 (Photo: T. Jóhannesson).

## 7. CONCLUSIONS

The protection plan of Siglufjörður is a good example on how comprehensive avalanche mitigation measures can reduce a high risk situation. The combination of supporting structures and avalanche dams provides an optimised protection for the town. An important point was to plan the mitigation measures proactively and not to react after a disaster. The chosen approach with regard to the planning of snow supporting structures with the initiation of snow depth measurements in the release area and with the installation of test structures could be adopted in other mountain regions also. The participation of landscape architects in the dam design was essential for the acceptance of this large scale project by the community. The application of precise snow depth maps prepared by lidar technology proved to be very helpful for the choice of structure heights. This technique might become standard for the detail planning of snow supporting structures. It is important for such a large scale project to evaluate the effectiveness and state of the structures regularly and to plan the maintenance in time. After the planned completion of the project in 2020, a challenging task will be the assessment of risk in the settlement

below the structures and the formal adaption of the hazard zones.

## ACKNOWLEDGMENT

We dedicate this paper to Þorsteinn Jóhannesson, engineer in Siglufjörður, who passed away in 2013. The planning and realization of the mitigation measures described in this paper would not have been possible without his dedication and support. The authors thank Þorsteinn Jóhannesson for many years of collaboration and stimulating discussions.

## REFERENCES

- Arnalds, Þ., Sauermoser, S., Jóhannesson, T. and Grímsdóttir, H. 2001. Hazard zoning for Siglufjörður. Technical report. Icel. Meteorol. Office, Rep. 01020.
- Indriðason, J. S. 2008. Avalanche protection – some aspects of design and construction. International Symposium on Mitigative Measures against Snow Avalanches. Egilsstaðir, Iceland, March 11–14, 2008, 188–195.
- Jóhannesson, T. 2013. LiDAR mapping of snow depth in avalanche starting zones in Iceland for assessing avalanche hazard and design of supporting structures. Abstract. Davos Atmosphere and Cryosphere Assembly DACA-13, Davos, Switzerland, July 8–12, 2013, 140.
- Jóhannesson, T. and Hopf, J. 2008. Loading of supporting structures under Icelandic conditions. The type of structures and structural requirements in future projects. Results of a field experiment in Siglufjörður. International Symposium on Mitigative Measures against Snow Avalanches. Egilsstaðir, Iceland, March 11–14, 2008, 143–150.
- Jóhannesson, T., and Margreth, S. 1999. Adaptation of the Swiss Guidelines for supporting structures for Icelandic conditions. Icel. Meteorol. Office, Rep. 99013.
- Jóhannesson, T., Lied, K., Margreth, S., and Sandersen, F. 1996. The need for avalanche protection measures in Iceland. Icel. Meteorol. Office, Rep. R96004.
- Margreth, S. 2007. Defense structures in avalanche starting zones. Technical guideline as an aid to enforcement. Environment in Practice no. 0704. Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos. 134 pp.
- Orion, 2005. High resolution wind simulation in Hafnarhryrna starting zone. Project number: SIGL0401 (authors S. Þórðarson and Á. Jónsson).
- SLF. 2001. Siglufjörður, Iceland. Avalanche defences. Protection plan for the residential area. SLF, Rep. G2001.01 (author S. Margreth).
- Vilhjálmsson, R., and Ingþórsson, Ó. 2008. The role of landscape architects in the design team. Why landscape architects are needed in the design team of large scale projects! International Symposium on Mitigative Measures against Snow Avalanches. Egilsstaðir, Iceland, March 11–14, 2008, 196–199.
- VS and NGI. 1997. Siglufjörður. Frumathugun á snjóflóðavörnum (in Icelandic). Siglufjörður, Verkfræðistofa Siglufjarðar and the Norwegian Geotechnical Institute.