

LESSONS FROM SEVERAL AVALANCHES IMPACTING AVALANCHE PROTECTIVE STRUCTURES IN ICELAND IN JANUARY 2020 AND MARCH 2023

Tómas Jóhannesson^{1,*}, Harpa Grímsdóttir¹, Kristín Martha Hákonardóttir², Sveinn Brynjólfsson¹, Óliver Hilmarsson¹, Alexander H. Jarosch³

¹*Icelandic Meteorological Office, Reykjavik, Iceland*

²*Verkís Consulting Engineers, Reykjavik, Iceland*

³*ThetaFrame Solutions, Kufstein, Austria*

ABSTRACT: Seven snow avalanches from two recent avalanche cycles in Iceland, that interacted with snow supporting structures, braking mounds, deflecting dams and catching dams, provide empirical data about the effectiveness of avalanche protective structures. Observations of the avalanches also provide important indications about rest risk in protected settlements. One of the cycles occurred at Flateyri, NW-Iceland, in January 2020. The settlement at Flateyri is protected with two 14–20-m-high deflecting dams with an upstream slope of 40°, and a 10-m-high catching dam, built from un-reinforced loose materials. Field observations at Flateyri indicate that the dense core of the avalanches was preceded by a rapidly-moving fluidized front, which overflowed the dams, damaged cars and buildings, and buried a person in snow in her bedroom. The dense core of both avalanches was deflected away from the settlement. The dams channelled the dense core into thick, powerful streams along the dams, and this part of one of the avalanches caused great destruction in the harbour of the village. The other cycle was in Neskaupstaður, E-Iceland, in March 2023 where several snow avalanches interacted with snow supporting structures, braking mounds and catching dams. Field observations and backcalculations indicate that the supporting structures reduced the release volume of several avalanches in this cycle and that the structures, together with braking mounds and dams in the run-out zone, prevented several avalanches from reaching the settlement. Our interpretation of observations from the two avalanche cycles indicates that steep dams and mounds may have more effect than structures with gentler-sloping upstream sides on rapid fluidized fronts, preceding some dry-snow avalanches. Channalized streams along deflecting dams need to be taken into account in the revision of hazard zones in areas below deflecting dams where the hazard may be increased at some locations. Rest risk below some avalanche dams in Iceland might be considerable and evacuation plans are needed for the uppermost houses to deal with this risk. Finally, due to the inherent uncertainty associated with avalanche forecasts and decisions on evacuations, permanent mitigation measures are essential for high-risk areas in settlements in Iceland.

Keywords: Avalanche protection measures, avalanche dams, dam overflow, rest risk, fluidized flow.

1. INTRODUCTION

Snow avalanches have caused many catastrophic accidents and severe economical loss in Iceland since the country was first settled in the 9th century (Jóhannesson and Arnalds, 2001). Snow avalanches are the type of natural hazard in Iceland that has claimed the largest number of human lives, if indirect deaths due to famine caused by natural disasters, such as volcanic eruptions and sea ice, and lives lost in storms at sea and on land are excluded. Many towns and villages are threatened by snow avalanches and landslides, particularly in NW-, N- and E-Iceland. Shortly after urbanisation started in Iceland in the second half of the 19th century, the first large avalanche catastrophes occurred in towns and villages. Two separate accidents that occurred in the villages of Súðavík and

Flateyri in NW-Iceland in 1995 and claimed 34 lives, led to fundamental changes in avalanche hazard management in the country. New methods of hazard mapping were developed and monitoring of impending danger was improved. Municipalities with high-risk areas (red zones on hazard maps) are required to take permanent action to lower the risk, either by relocating settlements, or by the construction of defence structures. A National Snow- and Landslide Fund was established to finance permanent protection measures, as well as hazard zoning and monitoring equipment. Since 1995, defence structures have been built in many areas, and more than fifty snow avalanches have interacted with the structures. This paper describes two recent snow-avalanche cycles where avalanche defence structures were put to test, one at Flateyri in the Westfjords in NW-Iceland in January 2020, and the other in Neskaupstaður in the Eastfjords in E-Iceland in March 2023. Both cycles included dry, fast-moving snow avalanches with rapid fluidized fronts. They provide important lessons about the effectiveness of different types of protection measures as well as

*Corresponding author address:

Tómas Jóhannesson, Icelandic Meteorological Office
IS-105 Reykjavík, Iceland;
tel: ++354 522 6000; email: tjvedur.is

indications about the level of rest risk in the protected settlements after the construction of the defence structures.

2. AVALANCHE SITUATION IN ICELAND

Snow avalanches and landslides have claimed 172 and 40 lives in Iceland, respectively, since 1900. About 50% of the fatalities occurred within settlements, mainly in residential buildings and work places hit by snow avalanches, and about 50% of the accidents involved people travelling on roads or in rural areas or engaged in recreational activities such as skiing or hiking. Most of the fatalities have occurred in a few catastrophic accidents when snow avalanches have impacted dense settlements: in Hnífsdalur in the Westfjords in 1910 where 20 people were killed, in Neskaupstaður in the Eastfjords in 1974 where 12 people were killed, and in Súðavík and Flateyri in the Westfjords in 1995 when 14 and 20 people, respectively, were killed. The hazard situation that led to these accidents developed in connection with the comparatively recent urbanization of the societies in mountainous, coastal regions in NW-, N- and E-Iceland where several villages were established in the late 19th and early 20th century, and expanded considerably in 1960–1980, in areas that later turned out to be located within the run-out zone of avalanches. Avalanche hazard assessment carried out after 1995 (Arnalds et al., 2004) indicate that avalanche risk in the most hazardous areas within dense settlements, where hundreds of people currently live, exceeds $3 \cdot 10^{-4}$ per year (the nominal, annual probability of being killed by an avalanche, this risk level corresponds to the category C hazard zone according to the Icelandic hazard zoning regulation).

3. GOVERNMENT PROGRAMME FOR CONSTRUCTING PROTECTION MEASURES

The catastrophic accidents at Súðavík and Flateyri in 1995 prompted a reorganization of avalanche hazard zoning and preparedness regarding avalanche and landslide danger in Iceland. The Icelandic Meteorological Office was given the responsibility for hazard zoning as well as avalanche forecasting and evacuation of settlements in times of impending danger, in collaboration with local civil defense authorities. Municipalities are required to construct permanent protection measures or relocate the most dangerous residential areas of dense settlements (C-zones), but the hazard in lower-risk zones (B- and A-zones) can be mitigated with temporary measures such as evacuations. A National Snow- and Landslide Fund was established to finance avalanche and landslide protection measures (90% of construction cost and 60% of maintenance cost) and preparations were started to build protection measures for the most seriously threatened settlements

(Jóhannesson et al., 1996). Protection measures have since then been constructed for tens of avalanche paths in twelve towns and villages at a total cost of ~250 million €, in addition to a few projects in rural areas and the relocation of the residential buildings of the village of Súðavík after the avalanche accident in 1995. In total, 24 deflecting dams, 27 catching dams, and five wedges for splitting avalanches have been constructed in run-out areas and >12 km of supporting structures have been installed in avalanche starting areas. The dams are designed according to European guidelines for avalanche protective dams (Jóhannesson et al., 2009; Rudolf-Miklau et al., 2015), and supporting structures are required to fulfill the Swiss Guidelines for such structures (Margreth, 2007), with some adaptation to local Icelandic conditions (Jóhannesson and Margreth, 1999). The programme to construct protection measures for towns and villages endangered by snow- and landslides in Iceland is still ongoing and it is estimated that somewhat more than half of the required structures have been completed.

4. AVALANCHES IMPACTING PROTECTION MEASURES

More than 50 avalanches have hit the recently constructed deflecting and catching dams since the programme to build protection measures for Icelandic towns and villages began in 1995 (Jóhannesson et al., 2019). Dams that have been constructed below the highest frequency snow avalanche paths at Flateyri and Siglufjörður have been hit up to more than ten times since 1998. Many of these avalanches would have reached very close to or beyond the uppermost houses in the respective settlements so this experience bears witness to the extreme level of danger that these settlements were facing before the construction of the protection measures, with inferred return periods of avalanches reaching the most endangered settlements on the order of ten years (!). Some avalanches have also been released from starting areas where supporting structures have been installed, and field observations indicate that the structures have substantially reduced the release areas and thereby the released avalanche volume in several cases. The avalanches have hit both deflecting and catching dams, as well as braking mounds. The dams have been overrun by fluidized fronts on some occasions, as further described below, and the dense core has been observed to reach up to 13 m vertical run-up on a deflecting dam in one case (Jóhannesson, 2001). Avalanches have overrun 17–20-m high catching dams in two cases. People have not come to harm in these avalanches but there have been some close calls, indicating a significant level of rest risk in the uppermost settlements below the protection measures.

5. FLATEYRI, JANUARY 2020

Two avalanches were released from the gullies Innra-Bæjargil and Skollahvilft above the village of Flateyri on 14 January 2020 after 4–5 days of NE-winds with snowfall and heavy snowdrift from the large catchment area on the flat mountain top north of the village (Hilmarrsson et al., 2020). Both avalanches overflowed the 14–20 m high deflecting dams that were built above the village in 1997–1998 as well as a catching dam located between the deflecting dams close by the uppermost houses, Fig. 1).

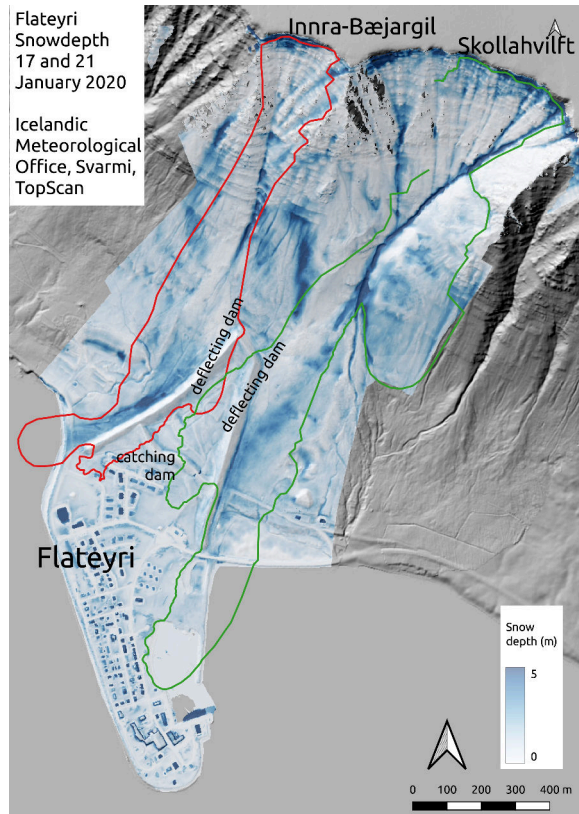


Figure 1: Outlines and snow depth on the ground for snow avalanches from Innra-Bæjargil and Skollahvilft gullies at Flateyri on 14 January 2020.

Field observations indicated a distinct difference in the avalanche deposits above and below the deflecting dams. The snow in the deposits on the upstream side was more coarse-grained and dirtier than the snow on the downstream side, which appeared cleaner and with smaller grains and was less dense than the snow on the upstream side (the average density of the deposits on the upstream side was 495 kg/m^3 whereas the average density on the downstream side was 415 kg/m^3 , see Fig. 2). The snow on the downstream side contained some twigs and branches broken from trees and shrubs over-run by the avalanches whereas the snow on the upstream side contained a substantial amount of debris that created a distinct colouring with an indication of streaklines in the flow of the dense core along

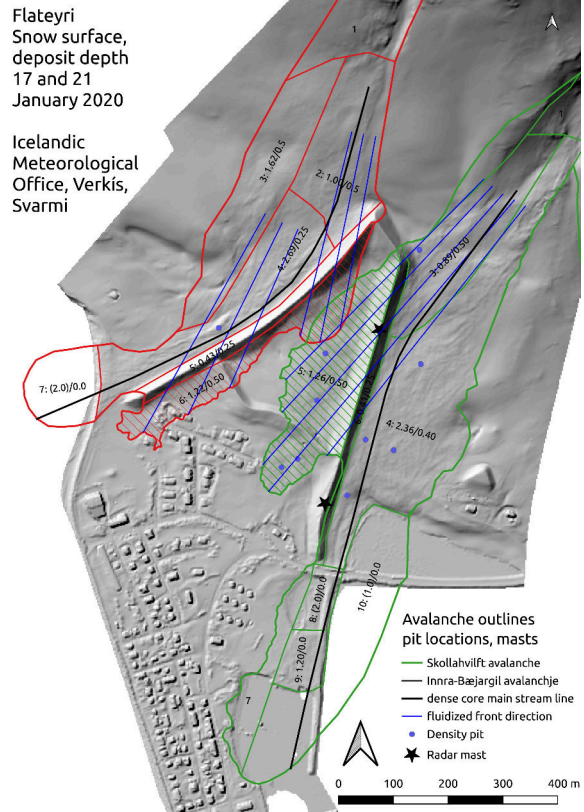


Figure 2: Run-out areas of snow avalanches from Innra-Bæjargil and Skollahvilft gullies at Flateyri on 14 January 2020. Locations of density measurements, FMCW radar masts, and estimated deposit depths and depth of underlying undisturbed snow are indicated with symbols and numbers. Overflow areas below dams are indicated with oblique red and blue line patterns. Inferred flow directions of fast-moving fluidized fronts of the snow avalanches are indicated with thin blue lines. Inferred streaklines of the deflected dense core of the avalanches are shown with thick black lines.

the upstream side of the dams, which was entirely absent in the avalanche deposit on the downstream side, see Fig. 3.



Figure 3: The run-out areas of the snow avalanches from Innra-Bæjargil (right) and Skollahvilft (left) gullies at Flateyri on 14 January 2020. Photo: Haukur Sigurðsson, 19 January 2020.

The surface of the avalanche deposits was mapped by UAV lidar on 17 and 18 January and the deposit volume was estimated by comparison with a lidar

map of the snow-free terrain after a correction for the depth of the undisturbed snow below the avalanches (see Fig. 2). Table 1 lists the estimated volume and mass of the avalanche deposits as well as the streamwise distance of the overflow for each dam. For comparison, the catastrophic avalanche in October 1995 is estimated to have been $430 \cdot 10^3 \text{ m}^3$, and with a return period of $\sim 110\text{--}150$ years. A design avalanche with a return period of ~ 1000 years for protection measures for the settlement must be assumed to be larger than the 1995 avalanche. The substantial overflow observed for the smaller avalanches in January 2020 is interesting in light of this comparison.

Table 1: Volume, mass and overrun distance of the fluidized fronts for snow avalanches from Innra-Bæjargil and Skollahvilft gullies at Flateyri on 14 January 2020, as well as the catastrophic snow avalanche in 1995. The overrun distance is measured along interpreted streamlines (see Fig. 2).

	Volume (10^3 m^3)	Mass (10^3 tonnes)	Overrun (m)
Innra-Bæjargil	240	115	120–150
Skollahvilft	315	150	>300
Skollahvilft 1995	430	180	–

The field observations described above are interpreted such that the dams were overflowed by fluidized fronts (sometimes called the intermittency regime) (Sovilla et al., 2018; Issler et al., 2020) that preceded the dense core of the avalanches by hundreds of metres whereas the dense core was in both cases entirely deflected away from the settlement and into the ocean, see flow directions indicated on the map in Fig. 2. The part of the avalanches that overflowed the deflecting dams broke windows and doors and some other structures such as fences and caused some other damages to buildings and structures that were hit by the avalanches. An interpretation of field observations within the avalanche deposits below the dams in terms of impact pressure, flow velocity and flow depth of the fluidized fronts is given in Hákonardóttir et al. (2022) and in a separate paper in the ISSW 2024 proceedings (Hákonardóttir et al., 2024).

An FMCW radar with two antennae from the Swiss company AlpuG was operating on the Skollahvilft dam when the avalanches occurred, see map on Fig. 2. The spectra measured by the radar are shown in Fig. 4. The upper radar (red curves) only recorded a few measurements before the fluidized front hit the dam and broke the upper radar mast. The distinct fluctuations in the upper radar reflective power with velocity as the avalanche approaches the radar, as evidenced by the increasing maximum power from frame to frame, may perhaps be interpreted as resulting from mesoscale coherent structures within the fluidized front (Sovilla et al.,

2018). This measurement indicates flow velocity of the fluidized front preceding the dense core in the range 45–60 m/s. The lower radar (green curves) appears to measure the slower dense core travelling towards the dam at 35–45 m/s, arriving perhaps 6–10 s. later within the ca. 500 m detecting range of the lower radar than the fluidized front at the upper radar, which indicates that the fluidized front preceded the dense core by several hundred metres. Subsequently, the dense core flowed more-or-less as plug flow with gradually decreasing velocity along the dam for >15 s.

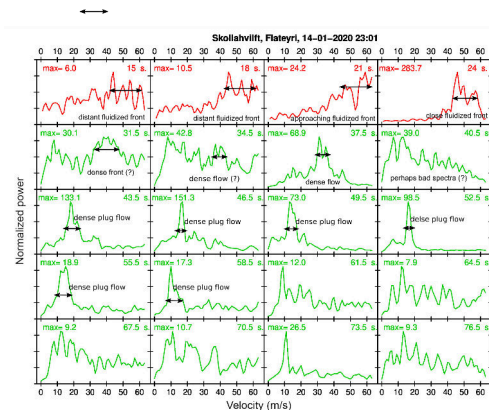


Figure 4: FMCW radar spectra from the snow avalanche from Skollahvilft at Flateyri on 14 January 2020. Red curves are measurements from the upper antenna, green curves are measurements from the lower antenna. Arrows and labels indicate an interpretation of the radar time series in terms of the fluidized front and the dense core of the avalanche.

The dense core of both avalanches was channelled as thick, powerful streams that appear to gradually widen along the dams, see Figs. 1 and 2, as was previously observed in February 1999 when a smaller avalanche from Skollahvilft was deflected into the ocean (Jóhannesson, 2001; Cui et al., 2007) without causing damage in the settlement. The Skollahvilft avalanche in 2020 entered the harbour of the village and caused great destruction to boats and pier structures. Channelized streams formed below an oblique granular jump are an important aspect of the flow against deflecting dams and can lead to increased run-out distance by hundreds of metres compared with run-out of avalanches in the path without the dam. The associated hazard potential needs to be taken into account in the design of deflecting dams and updated hazard zones after construction of dams extended appropriately in the direction of the streams.

The fluidized fronts appear to have flowed over the dams without much change in flow direction, see Fig. 2, even when they overflowed both a deflecting dam and subsequently the catching dam farther downstream. All the dams at Flateyri are built from loose materials with steepness close to 1:1.25 on the deflecting-dam sides facing the mountain

and 1:1.5 for the catching dam. Overall, the observations at Flateyri show that there may be considerable rest risk associated with the overflow of fluidized fronts on the downstream side of dams, particularly for dams with gentler-sloping upstream sides, although the impact pressure due to the fluidized part of the avalanche may be expected to be much lower than the full impact pressure of the dense core. This aspect of the design avalanche was not addressed in the original design of the dams at Flateyri (VST and NGI, 1996), nor is it typically taken into account in the design of avalanche dams in other countries (Jóhannesson et al., 2009; Rudolf-Miklau et al., 2015), although the possibility of this type of overflow is mentioned and analysed quantitatively in the design report from 1996. The experience at Flateyri highlights a limitation of the current design framework of avalanche dams and a need to improve avalanche models so that danger due to this type of overflow may be addressed in avalanche-dam design.

6. NESKAUPSTAÐUR, MARCH 2023

The town of Neskaupstaður and neighbouring settlements in the Eastfjords of Iceland were hit by a severe avalanche cycle in the last days of March 2023, which put to test protection measures that have been under construction in the village since 1999. Some of the avalanches in the cycle were the largest recorded avalanches in the respective paths, and some were longer than the corresponding avalanches in the catastrophic cycle in December 1974. The design of protection measures in Neskaupstaður is based on a concept of integrated protective structures (VST and Cemagref, 1998) where supporting structures in starting zones are combined with mounds and dams in the run-out zone. It was found that supporting structures can be applied in parts of the starting zones, but in the middle of gullies, the snow depth is too high and rock fall danger and poor soil conditions in other areas makes it impossible to install supporting structures in all the relevant areas of the mountainside. Dams and braking mounds can be constructed in the relatively large run-out zone above the settlement but modelled flow velocities for design avalanches released from the entire starting areas are too high for dams to work properly as the sole mitigation method for the most dangerous avalanche paths. In combination, however, supporting structures and protection measures implemented in the run-out zone were found to provide adequate safety based on traditional design criteria for such measures.

The first avalanches in the cycle were released in the early morning of 27 March (Brynjólfsson et al., 2024), see an outline map in Figure 5. In a time period of probably less than one hour, avalanches with extremely long run-out were released from at least

six avalanche paths above the town. The avalanche cycle was initiated by intense snowfall for only ~6 hours in northerly winds and temperatures around -8°C at the elevation of the starting areas. A wind slab was present in the mountains before the snowfall, but avalanche activity had been minimal in the region. The avalanches in this first phase of the cycle involved relatively little snow mass in comparison with the run-out.

Two of the avalanches on 27 March, from Nesgil and Bakkagil (see Fig. 5), were released above still unprotected areas in the eastern part of the town, while four avalanches with long run-out were released above the central and western part of the town in avalanche paths where protection structures have been constructed (Fig. 5).

Nesgil and Bakkagil: The avalanche from Nesgil reached into the settlement and caused severe damage, while the slightly shorter avalanche from Bakkagil stopped just above the settlement. Windows and doors were broken in an apartment building and some snow flowed into the building (Figure 6). The residents had to be rescued out of the building, and some suffered minor injuries due to broken glass from windows. Cars were thrown around and roofs and walls of some single-family houses were damaged. Field observations indicate that it was the fluidized front of the avalanche that reached the settlement, and that the dense core stopped about 100 m above the uppermost buildings, although a distinction between deposit types was not as obvious as in the Flateyri 2020 avalanches. The Nesgil avalanche broke and uprooted many trees in a reforestation area between Drangagil and Nesgil and uprooted large boulders from the ground, some of which were carried hundreds of metres with the flow. The crown of the avalanches was at ca. 700 m a.s.l., near the top of the mountain.

Skágil: An avalanche from Skágil was released close to the mountain top. The eastern half of the avalanche hit ca. 1.5 ha of decades-old forest in the run-out zone where it broke and uprooted trees, mostly birch, spruce and pine, and subsequently hit a steep 17-m-high catching dam, spraying a cover of snow on the upper damside over the entire height of the dam and depositing an up to 80–90 cm layer of snow with broken tree branches and twigs on the top of the dam. The western half of the avalanche was unobstructed by trees and hit two rows of 10-m-high steep braking mounds that appear to have had a substantial retarding effect on the flow because this part of the avalanche hardly reached the catching dam and did not deposit much snow on the dam face nor on the top of the dam. After some drift snow had melted from the run-out zone in the following days, a distribution of snow clods and debris could be used to map an outline of scattered, thin avalanche debris that appears to have been thrown over

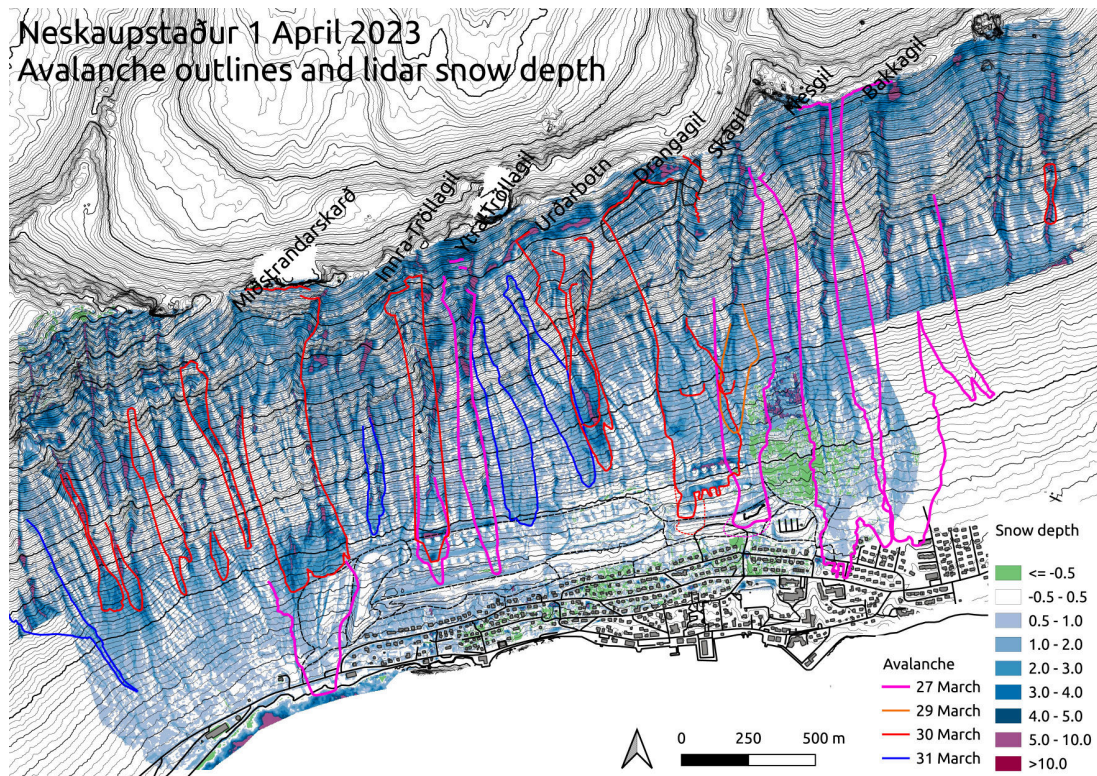


Figure 5: Outlines of snow avalanches in Neskaupstaður on 27–31 March 2023 on the background of snow depth derived from a lidar survey on 1 April 2023. Dashed outlines for avalanches from Skágil on 27 March and from Drangagil on 30 March identify the outer limit of a distribution of snow clods and debris beyond the main dense-flow deposit.



Figure 6: Apartment building below the Nesgöl avalanche path in Neskaupstaður hit by a snow avalanche on 27 March 2023. Photo: Ragnar H. Prastarson, 28 March 2023.

the top of the dam in the impact and landed on the lower dam side without flowing farther (dotted outline in Fig. 5).

Ytra-Tröllagil: An avalanche was released in Ytra-Tröllagil, and the timing can be read from a SM4 snow sensor located in the starting area. The snow depth decreased by approximately 40 cm between measurements at 05:40 and 05:50 AM. The avalanche hit two rows of braking mounds and stopped just above a catching dam.

Innra-Tröllagil: The avalanche was probably released at a similar time as the avalanche from Ytra-Tröllagil. The avalanche hit at least 3 braking

mounds in the upper row, and reached beyond the lower row, however, very little deposit was left by the catching dam.

Miðstrandarskerð: A snowplow driver was the first to notice the avalanche deposit at 05:45 AM. The avalanche had flowed along the inner/western side of a deflecting dam and into the sea. The dam probably only had a minimal effect on the propagation of the avalanche as the main deposit and damaged vegetation were almost entirely located to the west of the dam.

After a couple of days of less snowfall and lower wind speeds, and a $\sim 4^{\circ}\text{C}$ rise in temperature, the second phase of the cycle was caused by additional snowfall on 30 March in E and ENE winds. The largest avalanche in this phase was released from Drangagil, but many other large avalanches are recorded, including a second avalanche from Innra-Tröllagil. These avalanches had in some cases larger mass than the avalanches in the first phase on 27 March and they left thicker snow deposits in the run-out area but they had less powerful fluidized fronts.

Drangagil: A large avalanche was released from Drangagil at 15:30 in the afternoon on 30 March. It impacted both rows of braking mounds and stopped just short of the catching dam. It was witnessed by local people who saw high billows of snow thrown tens of metres into the air in the impact with the mounds. The avalanche left thick piles of snow

Table 2: Area and estimated deposit volume of the main avalanches the cycle of avalanches in Neskaupstaður on 27–31 March 2023. The last column specifies a subjective uncertainty range for the volume.

Date	Path	Area of dep. (ha)	Volume ($10^3 \cdot \text{m}^3$)	Range ($10^3 \cdot \text{m}^3$)
27 March	Bakkagil	14.5	102	76–127
27 March	Nesgil	16.2	115	86–144
27 March	Skágil	10.8	90	67–112
27 March	Ytra-Tröllagil	5.1	39	29–49
27 March	Innra-Tröllagil	4.9	34	21–47
30 March	Drangagil	13.5	181	160–200
30 March	Innra-Tröllagil	9.9	50	35–65

above almost all the braking mounds in both rows, see Fig. 5.

Innra-Tröllagil: An avalanche from Innra-Tröllagil on 30 March impacted the upper row of braking mounds below the gully and deposited thick snow by two mounds, see Figs. 5 and 7.



Figure 7: Snow deposit by a braking mound below the Innra-Tröllagil avalanche path in Neskaupstaður from an avalanche on 30 March 2023. Photo: Sveinn Brynjólfsson, 12 April 2023.

The surface of the avalanche deposits was mapped by UAV lidar and photogrammetry on 28 March (mainly the run-out zone) and again on 1 April (the entire mountainside except the run-out area of Bakkagil) and the deposit volume was estimated by comparison with a DTM of the snow-free terrain after correction for the effect of forests in part of the area as well as the depth of the undisturbed snow below the avalanche (see Fig. 5). Table 2 lists the estimated volume of the deposits of the main avalanches in the cycle.

The snow depth measurements on 28 March show thicker snow upstream of the mounds and dams below the two Tröllagil paths and Skágil than elsewhere in the tongues. Assuming that the snow-depth distribution in the tongues would have been similar as in the tongues of the avalanches on the same day from Nesgil and Bakkagil, one may estimate a volume of snow for each avalanche that was obstructed by the mounds or dams and deposited higher up on the slope than it would have in the absence of the protection measures. By distributing this obstructed volume on the slope below the tip of

the avalanche outline with a similar snow depth as observed for the respective avalanche farther upstream, an estimate can be made of the shortening of the avalanche by the impact with the mounds and/or dam. This computation is of course fraught with uncertainty and gives only an indication of this retarding effect, but the estimated shortening is ca. 60 m for all three avalanches. A similar computation for the Drangagil avalanche on 30 March indicates a shortening on the order of 50 m due to the mounds. The supporting structures in some of the starting areas in Neskaupstaður may be expected to have reduced the volume of the two avalanches released from Tröllagil on 27 March and the avalanches from Drangagil and Innra-Tröllagil on 30 March. The structures in Tröllagil stabilized ca. 2.8 ha of the snowpack in Innra-Tröllagil and ca. 3.1 ha in Ytra-Tröllagil. It is not possible to say whether all this stabilized area would have participated in the release of the avalanches from the two Tröllagil gullies on 27 March but the widespread weak layer and large release areas in other parts of the mountain make it likely that a large part of the stabilized areas would have failed and contributed to the avalanche volume. The snow nets in Drangagil turned out to only partly support the snowpack in the area of the structures on 30 March, as a fracture line through a gap in the lines of supporting structures penetrated into the area with snow nets and caused a partial release from this area. Avalanche snow was nevertheless stopped by the snow nets, which are estimated to have withheld $30\text{--}40 \cdot 10^3 \text{ m}^3$ of snow that would otherwise have contributed to the Drangagil avalanche on 30 March. It is not possible to determine the combined run-out reduction caused by the supporting structures, braking mounds and dams in Neskaupstaður in this cycle but subjective estimates indicate that the run-out of 3–4 avalanches may have been shortened by $>100 \text{ m}$. Since the avalanches stopped 100–130 m above the uppermost residential houses, the observations described above strongly indicate that the protection measures prevented some of the avalanches from reaching the settlement, as of course the avalanche from Nesgil in the same cycle did in an unprotected path. Finally, although this cannot be determined conclusively, the snow nets in Drangagil may have been a contributing factor that prevented an avalanche release there on 27 March when large avalanches were released from many of the other main avalanche paths in Neskaupstaður.

7. DISCUSSION

Observations from the avalanche cycles in January 2020 at Flateyri and March 2023 in Neskaupstaður show that protection measures in the two towns in both cases most likely prevented avalanches from reaching larger settled areas than in fact occurred.

Field observations of the avalanches in the two cycles highlight several problems that need to be addressed in further work to improve safety in these and other settlements in avalanche hazard areas in Iceland and elsewhere. Overflow of fluidized fronts of dry-snow avalanches is a neglected aspect of snow-avalanche dynamics in the current design practice for protection measures in the run-out zone and needs to be addressed by improved design guidelines and evacuation planning to deal with rest risk after the implementation of protection measures. Observations from Neskaupstaður indicate that steep mounds and dams have a substantial retarding effect on fluidized fronts, whereas observations from Flateyri show that obstructions with gentler-sloping upstream sides have little effect on the rapid fluidized flow. Increased hazard due to channelized flow along deflecting dams needs to be taken into account in the revision of hazard zones after deflecting dams have been implemented. This can result in substantial enlargement of hazard zones in a distinct direction where the run-out of avalanches may be increased by on the order of a hundred metres. The concept of integrated protective structures adopted in the planning of protection measures for Neskaupstaður appears to have worked well in March 2023. The partial release of a snow avalanche from a starting zone with snow nets in Drangagil on 30 March 2023 shows that supporting structures have to be carefully designed and installed without gaps that allow the propagation of fracture lines into the supported area. Improvements of the layout of the structures are in progress.

ACKNOWLEDGEMENT

The Icelandic Snow- and Landslide Fund supported the measurements and analysis reported in this paper. We thank the local snow observers of the IMO at Flateyri and Neskaupstaður and their assistants as well as local search-and-rescue volunteers, Örn Ingólfsson, Jón Magnússon, Haukur Sigurðsson, Tómas Zoëga and Hlynur Sveinsson for their efforts in the observations of the avalanches in 2020 and 2023. We also thank Hansueli Gubler at AlpuG and Betty Sovilla at the SLF in Davos for useful discussions about interpretation of the FMCW radar spectra and the dynamics of the 2020 Flateyri avalanches.

REFERENCES

Arnalds, T., Jónasson, K., and Sigurðsson, S. T.: Avalanche hazard zoning in Iceland based on individual risk., *Annals of Glaciology*, 38, 285–290, doi:10.3189/172756404781814816, 2004.

Brynjólfsson, S., Sveinsson, B., Óliver Hilmarsson, Jóhannesson, T., Helgason, J. K., Grímsdóttir, H.: Snjóflóðahrina í Neskaupstað 27.–31. mars 2023 [Snow avalanche cycle in Neskaupstaður 27–31 March 2023; In Icelandic], Report 2024-0xx in preparation, Icelandic Meteorological Office, Reykjavík, 2024.

Cui, X., Gray, J. T., and Jóhannesson, T.: Deflecting dams and the formation of oblique shocks in snow avalanches at Flateyri, Iceland, *Journal of Geophysical Research. Earth Surface*, 112, F04 012, doi:10.1029/2006JF000712, 2007.

Hákonardóttir, K. M., Árni Kristjánsson, and Pétursson, G.: Ofanflóðavarnir á Flateyri – Flóðin 2020: Bakreiknaður þrýstingur á mannvirki frá iðufaldi í snjóflóðum á Flateyri 2020 (Back-calculated impact pressure in the avalanches on Flateyri in 2020), Tech. Rep. ID271911, Verkis, Reykjavík, 2022.

Hákonardóttir, K. M., Lárusson, R., Kristjánsson, Á., and Pétursson, G.: Loading on structures from fluidized avalanche fronts overflowing deflecting dams at Flateyri, Iceland, January 2020, in: International Snow Science Workshop 2024 Proceedings, Tromsø, Norway, Montana State University, 2024.

Hilmarsson, Ó., Jóhannesson, T., and Grímsdóttir, H.: Snjóflóðin úr Skollahvilt og Innra-Bæjargili 14. janúar 2020 [The snow avalanches from Skollahvilt and Innra-Bæjargili on 14 January 2020; In Icelandic], Report 2020-010, Icelandic Meteorological Office, Reykjavík, 2020.

Issler, D., Gauer, P., Schaer, M., and Keller, S.: Inferences on mixed snow avalanches from field observations, *Geosciences*, 10, 2, doi:10.3390/geosciences10010002, 2020.

Jóhannesson, T.: Run-up of two avalanches on the deflecting dams at Flateyri, northwestern Iceland, *Annals of Glaciology*, 32, 350–354, doi:10.3189/172756401781819382, 2001.

Jóhannesson, T. and Arnalds, T.: Accidents and economic damage due to snow avalanches and landslides in Iceland, *Jökull*, 50, 81–94, doi:10.33799/jokull2001.50.081, 2001.

Jóhannesson, T. and Margreth, S.: Adaptation of the Swiss Guidelines for supporting structures for Icelandic conditions, Tech. Rep. G99013, Icelandic Meteorological Office, Reykjavík, 1999.

Jóhannesson, T., Lied, K., Margreth, S., and Sandersen, F.: An overview of the need for avalanche protection measures in Iceland, rit R96004, Icelandic Meteorological Office, Reykjavík, 1996.

Jóhannesson, T., Gauer, P., Issler, P., and Lied, K., eds.: The design of avalanche protection dams. Recent practical and theoretical developments, European Communities, Brussel, 2009.

Jóhannesson, T., Hansson, G., Örn Ingólfsson, Brynjólfsson, S., Jónsson, M. H., Óliver Hilmarsson, and Grímsdóttir, H.: Snow avalanches hitting deflecting and catching dams in Iceland 1997–2018, in: International Symposium on Mitigative Measures against Snow Avalanches and Other Rapid Gravity Mass Flows Siglufjörður, Iceland, April 3–5, 2019, edited by Jóhannesson, T., Gauer, P., Hákonardóttir, K. M., Margreth, S., Pálsson, H., and Sigtryggisdóttir, F. G., pp. 132–139, The Association of Chartered Engineers in Iceland, Reykjavík, 2019.

Margreth, S.: Defense structures in avalanche starting zones: Technical guideline as an aid to enforcement, Tech. Rep. 0704, Federal Office for the Environment (FOEN/WSL), Bern, 2007.

Rudolf-Miklau, F., Sauer Moser, S., and Mears, A. I., eds.: Technical Avalanche Protection Handbook, John Wiley & Sons, Berlin, 2015.

Sovilla, B., McElwaine, J. N., and Köhler, A.: The Intermittency Regions of Powder Snow Avalanches, *Journal of Geophysical Research: Earth Surface*, 123, doi:10.1029/2018JF004678, 2018.

VST and Cemagref: Neskaupstaður. Avalanche defences. Protection plan for the residential area), Tech. Rep. 97.202/97-024, VST & Cemagref, Reykjavík, 1998.

VST and NGI: Flateyri. Avalanche defence appraisal, Tech. Rep. 96.201/964022-1, VST & NGI, Reykjavík, 1996.