International Symposium on

Mitigation Measures against Snow Avalanches and other Rapid Gravity Mass Flows

Siglufjörður, Iceland

3–5 April 2019

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Sponsored by

- The Association of Chartered Engineers in Iceland

Co-sponsored by

- Ministry for the Environment and Natural Resources, Iceland
- Icelandic Meteorological Office
- FSR – the Government Construction Contracting Agency
- Landsvirkjun – the National Power Company
- Landsnet – IceGrid
- Icelandic Road and Coastal Administration,
- University of Iceland
- Iceland Glaciological Society
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FOREWORD

Rapid gravity mass flows pose a threat to settlements and infrastructure and limit the use of land on all continents of the world. In mountainous regions, these natural hazards include snow avalanches, slush- and debris flows, rockfall and landslides. People in modern societies are becoming more concerned with safety, and authorities strive to ensure the safety of settlements, traffic lines and society in general with hazard zoning, planning of settlements, and construction and management of protection measures. Due to high safety demands, the design of permanent protection measures has become more demanding and expensive than before and the question is sometime raised in which situations temporary measures or relocation of settlements should also be considered to improve safety.

Currently, we are witnessing changes in the nature of, and in some cases, an increase in the frequency of natural hazards, for slushflows, debris flows and landslides, which are thought to be related to climate changes. Increased precipitation with rain in the lowlands and snow in the higher altitudes during winter can cause an increase in avalanche activity and increased need to mitigate the hazard. In the Arctic and sub-Arctic, the warmer climate causes more frequent slush flows earlier in the winter than normal.

In high mountain areas such as the Alps, and in the Arctic region, warmer climate leads to an increase in the thickness of the active layer of permafrost which not only results in an unstable top layer but may also reduce the stability of mountainsides. Thicker active layer poses threat to foundations of existing mitigation structures and will make new structures more expensive.

The symposium addresses four different themes; *Risk management*, *Society and Environment*, *Planning, Design, Construction and Management of Protection Measures*, and *Observations and Simulations of Avalanches*. The goal is to introduce the present state of knowledge and get a glimpse of the future as well as try to broaden the view of participants from each group, make them exchange experience and ideas and find ways to cooperate so that we can improve living in areas threatened by avalanches.

The symposium brings together scientists, engineers, architects and representatives of local and central authorities to discuss the state-of-the-art of mitigation measures against snow avalanches and other rapid mass movements. A programme for the construction of protection measures for settlements endangered by snow avalanches and landslides has been ongoing in Iceland since catastrophic avalanches in the Vestfjords in 1995, which claimed 34 lives. It is necessary to appraise the status and performance of such a programme at regular intervals. Professionals in charge of the programme and the responsible local and central authorities need to review the arguments for the protection measures and remind themselves of the consequences of inadequate safety measures. In March 2008, a symposium about mitigation measures against gravity mass-flows was held in Egilsstaðir, Eastern Iceland. A decade later it is again time to call a meeting about the same topic, summarising the status of protection measures in neighbouring countries, the experience gained during the last decade, and the future of hazard management and mitigation measures against rapid gravity mass-flows.

Northern Iceland has two avalanche-prone villages, Siglufjörður and Ólafsfjörður, several power lines and highways through avalanche terrain, and the Tröllaskagi highland is the most popular mountain skiing area in Iceland. Almost exactly 100 years ago to the day, on April 12th 1919, several avalanches struck Siglufjörður and neighbouring rural areas, killing eighteen people and destroying the Evanger herring processing plant on the east side of the fjord. The avalanches caused enormous material damage at several locations, including damage to boats and the harbour of Siglufjörður by a tsunami wave triggered by the catastrophic snow avalanche from Skollaskál Mountain east of the fjord. It is fitting to organise a symposium in Siglufjörður on the centenary of these tragic events, to discuss methodologies and technologies for avalanche protection and see the progress in avalanche safety that has been made in the town of Siglufjörður in recent years.

More than 120 researchers, avalanche professionals and people who work with avalanches and avalanche protection measures in ski areas, road authorities and local communities from 13 countries have registered and almost 60 scientific presentations and will be delivered. The workshop is held during 2 days followed by one-day excursion and a mountain ski tour.

The workshop is sponsored by the Association of Chartered Engineers in Iceland and co-sponsored by the Ministry for the Environment and Natural Resources, the Icelandic Avalanche and Landslide Fund, the Icelandic Meteorological Office, FSR − the Government Construction Contracting Agency, Landsvirkjun − the National Power Company, IceGrid, the Icelandic Road and Coastal Administration, the University of Iceland, the Iceland Glaciological Society, the International Glaciological Society.

We are grateful to financial support by the Icelandic Avalanche and Landslide Fund, the Icelandic Road and Coastal Administration, FSR − the Government Construction Contracting Agency, Landsvirkjun, Landsnet and Húsasmiðjan.

Árni Jónsson, chairman of the organising committee

Tómas Jóhannesson, chairman of the science steering and editorial committee

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International Symposium on Mitigation Measures against Snow Avalanches and other Rapid Gravity Mass Flows – Siglufjörður 3–5 April 2019

Snow 2019 - Iceland

Programme

Tuesday 2 April 2019

17:00 – 19:00	**Registration at Hótel Sigló**
18:30 – 20:00	**Welcome reception sponsored by the municipality of Fjallabyggð/Siglufjörður in the Herring Era Museum**

Wednesday 3 April 2019

08:00 – 09:00	**Registration at the symposium venue (red/blud buildings near Hótel Sigló)**
09:00 – 09:20	**Symposium opening** – Guðmundur Ingi Guðbrandsson, the Minister for the Environment and Natural Resources, Gunnar Birgisson, the mayor of Fjallabyggð/Siglufjörður, Árni Jónsson, chairman of the local organizing committee.
Session	**Risk management, general**
	Chair: Harpa Grímsdóttir
09:20 – 09:40	**Michael Bründl**: Risk management of gravitational driven processes in Switzerland (*keynote*)
09:40 – 09:55	Andreas Drexel: Blons in Vorarlberg, Austria – 60 years sustainable avalanche protection – Experience, setbacks and lessons learned
09:55 – 10:10	Odd-Arne Mikkelsen: Snow2019_NVE.RN_The Norwegian way of preventing nature hazard
10:10 – 10:25	Martin Proksch: An integral avalanche safety concept for Goms region, Valais, Switzerland
10:25 – 10:40	Hafsteinn Pálsson: The importance of the Icelandic Avalanche and Landslide Fund for avalanche-prone areas in Iceland
10:40 – 10:55	*Coffee*
Session	**Risk management, general, continued**
	Chair: Fjóla Guðrún Sigtryggsdóttir
10:55 – 11:10	Magni Hreinn Jónsson: Avalanche hazard mapping and mitigation for settlements in Iceland – An overview
11:10 – 11:25	Hiroki Matsushita: A simple evaluation of dry-snow avalanche hazard using meteorological data
11:25 – 11:40	Bruce Jamieson: Adjusting for uncertainty when combining runout estimates for extreme snow avalanches
11:40 – 11:55	Cam Campbell/Brian Gould: Post wildfire analysis of avalanche hazard in Canada
11:55 – 12:05	*Discussion*
12:05 – 13:00	*Lunch*
Session	**Society and the environment**
	Chair: Tómas Jóhannesson
13:00 – 13:20	**Arne Instanes**: Society and environment in the context of changing climate in Arctic regions (*keynote*)
13:20 – 13:35	Arnold Studeregger: Avalanche commissions in Austria at the interface between locals and authorities. Embedding, decision process and quality assurance
13:35 – 13:50	Fjóla Guðrún Sigtryggsdóttir: Avalanche and landslide hazard zoning committees in Iceland
13:50 – 14:05	Halldór Halldórsson: Protection measures and working with the locals, practical challenges
14:05 – 14:20	Eiður P. Birgisson: Landscape design of snow avalanche protection structures in Siglufjörður, Ólafsfjörður and Seyðisfjörður
14:20 – 14:35	Abdurrahim Aydın: Historical development and future outlook of the avalanche hazard potential of residential areas in the Lake Uzungöl (Eastern Black Sea Region of Turkey) between 2004 and 2050
14:35 – 15:00	*Discussion*
15:00 – 15:20	*Coffee*
Session	**Risk management, general, traffic and ski areas**
	Chair: Magni Hreinn Jónsson
15:20 – 15:40	**Peter Gauer**: Avalanche observations related to probabilities (*keynote*)
15:40 – 15:55	Martin Proksch/Pascal Venetz: From the pilot study to the practical implementation – A case study from the Oberalppass in Switzerland
15:55 – 16:10	Remzi Eker: Evaluation of snow avalanche hazard on the highway using high resolution UAV data: Case of Erzurum-Çat-Karlıova highway, Turkey
16:10 – 16:25	Patrick Siegele: Hazard managing in Austrian ski areas
16:25 – 16:40	Harpa Grímsdóttir: Management of avalanche risk in Icelandic ski areas
16:40 – 16:55	Tore Humstad: Avalanche warning services as an integrated part of winter road operations in Norway
16:55 – 17:10	Geir Sigurðsson: Avalanche management for roads in Iceland
17:10 – 17:25	Trond Jøran Nilsen: Methods for avalanche protection on roads in Finnmark in Northern Norway
17:25 – 17:40	Daniel Germain: Avalanche hazard in urban snow storage sites in Province of Quebec, Canada
17:40 – 18:00	*Discussion*
20:30 – 21:30	Optional evening session with **photos and videos of avalanches and protection measures**

Programme

Thursday 4 April 2019

Session	**Planning, design, construction and management of protection measures**
	Chair: Bruce Jamieson
09:00 – 09:20	**Stefan Margreth**: Effectiveness and maintenance of technical avalanche protection measures in Switzerland (*keynote*)
09:20 – 09:35	Cameron Ross: Avalanche deflection berm and stopping wall at a hydro-electric facility in north-western British Columbia, Canada
09:35 – 09:50	Árni Jónsson: Longyearbyen Svalbard – Mitigation measures for Sukkertoppen and Vannledningsdalen
09:50 – 10:05	Daniel Illmer: Everyday work of an avalanche engineer – Calculation of avalanche loads and protection of small objects in avalanche paths like ropeway towers
10:05 – 10:20	Jón Skúli Indriðason: Experience and evaluation of reinforced soil systems in catching dams in Iceland 1998–2017
10:20 – 10:35	Áslaug Traustadóttir: Landscaping of avalanche dams in Fjarðabyggð and Vestfirðir
10:35 – 10:50	*Coffee*
Session	**Planning, design, construction and management of protection measures, continued**
	Chair: Andreas Drexel
10:50 – 11:05	Rico Brändle: Floating foundations for flexible snow nets on permafrost and creeping slopes – 10 years experience
11:05 – 11:20	Nicolas Villard: Hybrid innovative protection structures with optimized foundations and field adaptation
11:20 – 11:35	Jón Skúli Indriðason: Observed changes in hydrology downstream of large earth fill dams in Iceland. Lessons learned
11:35 – 11:50	Anders Bjordal: Tree Tribes Meeting – how to build a protection dam
11:50 – 12:05	*Discussion*
12:05 – 13:00	*Lunch*
Session	**Observations of avalanches, instrumentation**
	Chair: Árni Jónsson
13:00 – 13:20	**Betty Sovilla**: The avalanche flow regimes and their pressure on infrastructures (*keynote*)
13:20 – 13:35	Philippe Berthet-Rambaud: Attempt to combine few historical data from a 19th century avalanche and recent modelling capabilities for hazard zoning at Tignes Brévières
13:35 – 13:50	Þorsteinn Sæmundsson: Monitoring rock avalanche hazard from the Svínafellsheiði mountainside in SE Iceland
13:50 – 14:05	Engelbert Gleirscher: SNOWCATCHER – full-scale test site in the Stubai Valley – site selection, installation of structure and monitoring system, first results of the avalanche–structure interaction
14:05 – 14:20	Rune Solberg: Landslide detection and mapping by remote sensing
14:20 – 14:35	Tómas Jóhannesson: Snow avalanches hitting deflecting and catching dams in Iceland 1997–2018
14:35 – 14:50	Sveinn Brynjólfsson: Snow avalanches hitting natural obstacles in Iceland: The avalanches at Kisárdalur, Steinsstaðaskál and Upsi in N-Iceland
14:50 – 15:00	*Discussion*
15:00 – 15:20	*Coffee*
15:20 – 16:20	**Poster session**
Session	**Simulations of avalanches, laboratory experiments**
	Chair: Betty Sovilla
16:20 – 16:40	**Chris Johnson**: Interaction of granular avalanches with obstacles and topography (*keynote*)
16:40 – 16:55	Gísli Steinn Pétursson: Analyzing and mitigating the impact of avalanche protection structures on their local wind climate
16:55 – 17:10	Kristín Martha Hákonardóttir: The design of slushflow barriers: Laboratory experiments
17:10 – 17:25	Halldór Pálsson: The design of slushflow barriers: OpenFOAM simulations
17:25 – 17:40	Hafþór Örn Pétursson: Use of RAMMS Avalanche and OpenFOAM to simulate the interaction of avalanches and slush flows with dams
17:40 – 18:00	*Discussion*
18:00	*Closing remarks*
18:30 – 20:00	*Hotel lounge area open for meeting other guests before the banquet*
20:00	*Symposium Banquet*

Friday 5 April 2019

09:00 – 17:30	*Symposium Excursion*
18:00 – 19:00	*Bus to Akureyri airport from Siglufjörður or Dalvík with excursion participants (flight to Reykjavík departs at 20:10)*

Saturday 6 April 2019

09:00 – 16:00	*Ski mountaineering tour*
17:00 – 18:00	*Bus to Akureyri airport with ski mountaineering tour participants (flight to Reykjavík departs at 19:05)*

Programme

Posters, booths, company introductions

Armelle Decaulne: Mass movements in Nunavik: hazard and risk
Andreas Drexel: Adaption of snow bridges in the Großtal avalanche in Galtür, Tyrol, Austria – Constructive and static problems
Susan J. Conway: Using RAMMS (RApid Mass Movement Simulation) to simulate rapid gravity mass flows in martian gullies
Örn Ingólfsson: Using data from automatic snow sensors for avalanche forecasting in Iceland
Árni Jónsson: Planning for highways in avalanche-prone areas in Troms County, Northern Norway
Árni Jónsson: Wind simulation for Longyearbyen mitigation measures
Costanza Morino: Geomorphic signatures of different debris-flow release processes in Ísafjörður, north-western Iceland
Elena Pummer: Hybrid modeling of debris flows – Focusing on initial and boundary conditions
Rune Solberg: Mapping snow surface hoar by optical remote sensing
Brynjólfur Sveinsson: Snow avalanche history of rural areas in Iceland
Þorsteinn Sæmundsson: TDR used for the first time to monitor slope movements in Iceland. A case study from the Almenningar landslide in central North Iceland
FSR – Government Construction Contracting Agency: Protection measures in Iceland – 1997–2018 – Protection dams, supporting structures (three posters)
Exhibitors with booths
Svarmi ehf. Iceland: Use of drones for mapping snow avalanches, landslides and construction areas
CautusGeo, Norway
Trumer Schutzbauten, Austria
Geobrugg, Switzerland
Húsasmiðjan/TAS, Iceland/France
Company introductions
Verkís hf.: Design of avalanche protection measures in Iceland. Verkís Consulting Engineers
Hnit hf.: Design of avalanche protection measures in Iceland. Hnit Consulting Engineers

Historical development and future outlook of the avalanche hazard potential of residential areas in the Lake Uzungöl (Eastern Black Sea Region of Turkey) between 2004 and 2050

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ABSTRACT
The Lake Uzungöl is an important nature tourism area in Turkey and has been declared as a Nature Conservation Park in 1989. The lake areas has continued to face remarkable land use changes in the last decades. The area also suffers from snow avalanches due to its mountainous topography. In the present study, the historical development of residential areas (i.e. from 1955 to 2015) were evaluated using aerial photographs. The Dyna-CLUE model was applied to simulate land use changes between 2004 and 2050. The model was calibrated for yearly changes from 2004 to 2015, and then future projections were created based on the historical development trends of the residential areas. Residential area has increased significantly, especially since 2004. While the residential area increased from 57.35 ha to 108.38 ha between 1955 and 2015, the areas under potential snow avalanche hazard increased from 16.3 ha to 42.3 ha between 1955 and 2015. The projected land use change by Dyna-CLUE model showed that while the residential areas in 2030 were 138.0 ha (86.5 ha under avalanche hazard), those in 2050 increased to 202.3 ha (126.3 ha under avalanche hazard).

1. INTRODUCTION
The Lake Uzungöl, located in the Çaykara District of province of Trabzon, is a prominent nature and tourism destination in the eastern Black Sea Region of Turkey. Due to its rich plant and wildlife diversity and sightseeing potential, many domestic and foreign tourists visit the area. The lake and the surrounding oriental spruce [Picea orientalis (L.) Link] forests present the visitors an attractive landscape. Hence, the Lake Uzungöl was declared as a "Nature Conservation Park" in 1989 by the Ministry of Forestry, a "Tourism center" in 1990, and a "Special Environmental Protection Area" in 2004 by the the Boards of Ministers (Atasoy, 2010). This region has however continued to face remarkable land use changes in the last decades due to many reasons including socio-economic, environmental, and societal changes (Piazza, 2016). The historical shift from agricultural-based society to the service-based society in the region has played an important role in the sharp change of the land use. This dramatic change in land use has occurred since 2004. However, the Lake Uzungöl has been experiencing severe natural hazards due to its heterogeneous meteorological, geological and topographical features. First of all, the lake has been formed by a historical landslide. A snow avalanche hazard indication map in the scale of 1/25 000, generated through a project by the General Directorate of Combatting Desertification and Erosion (ÇEM) is also available (Aydın et al. 2018). According to the snow avalanche hazard indication map, 3239 ha of the project area, which is the 42% of the total area, was located within the snow avalanche hazard zone. The present study aimed to evaluate both historical development and the future outlook of the residential area in the Lake Uzungöl using aerial imageries and dynamic land use change model, entitled Dyna-CLUE.

2. DATA AND MODEL SETUP

The study area covers 7690.5 ha in the Lake Uzungöl and its close vicinity (Figure 1). In order to evaluate historical development in the land use in the area, aerial imageries from 1955, 2004 and 2015 (during the last 60 years), were obtained from the Turkish General Command of Mapping (HGK). Landuse types were digitized based on the aerial imageries, and database was created by classifying landuse types as forest, agriculture, pasture, settlement, open forest and water as six classes in total. Additionally, areal change in landuse types was assessed for time series of the data. The spatial model of land use change were setup for analysing the possible trajectories of land use change in the future (between 2004 and 2050). For this aim, the Dyna-CLUE, a recent version (Verburg and Overmars, 2009) of the conversion of land use and its effects framework (CLUE model) developed by Tom Veldkamp and Louise Fresco in 1996, were employed. Both historical and future landuse maps were then overlapped with digitized snow avalanche hazard indication map, to evaluate interaction of landuse change with snow avalanche hazard (Figure 1).

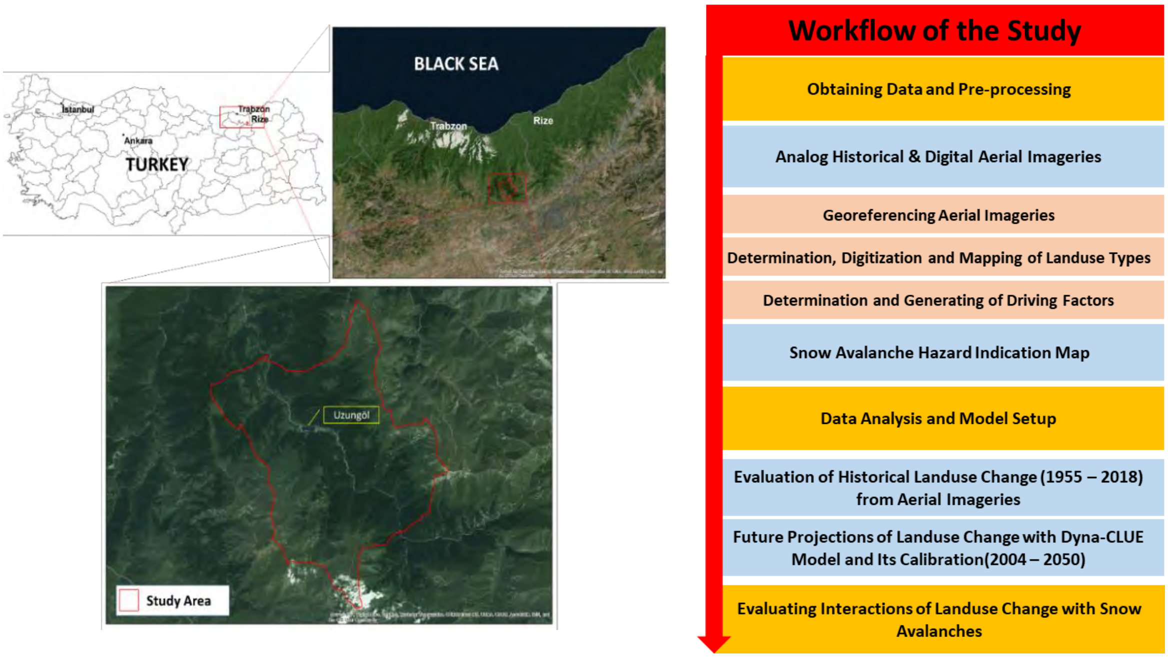

Figure 1 Location of study area (left) and workflow of the study (right).

3. RESULTS

Landuse maps generated for the years of 1955, 2004, and 2015 from aerial imageries were given in Figure 2. The areal size of landuse types determined is given in Table 1. In the study area, forested area covers the largest land use type whereas settlements covers the smallest area. This is mostly due to the fact that the area is located in the eastern Black Sea Region of Turkey. The evaluation of the historical development of residential areas revealed that the residential area increased significantly. While residential area covered 57.35 ha in 1955, it increased to 108.38 ha in 2015. The pace of the increase in the residential area accelerated after 2004 due to the upsurge in the constructions of hotels and pensions in the vicinity of the lake. While the growth rate of residential area for the period of 1955-2004 was 0.24 ha/year, it increased by almost 15-times (i.e. 3.57 ha/year) between 2004 and 2015. The Dyna-CLUE model was setup for the period of 2004 and 2015 for the study, and then calibrated based on the 2015 data. Following model calibration, landuse simulations between 2004 and 2050 were carried out for the future outlook of landuse change (Figure 2).

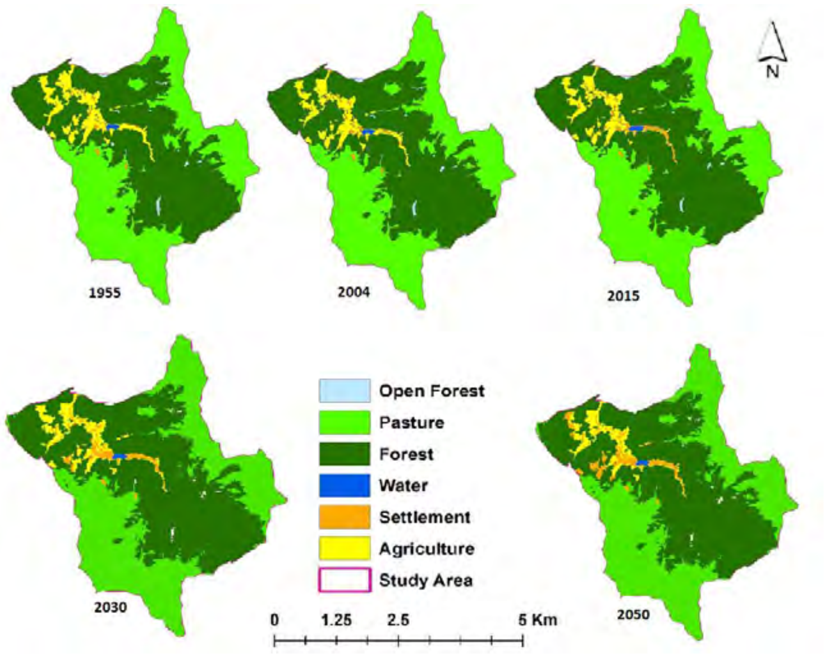

Figure 2 Landuse maps of 1955, 2004, and 2015.

The agricultural area appeared to decrease by 15% between 2015 and 2030, whereas the residential area increased by 63.7% for the same period (Table 1). The projections revealed that in the 20 years between 2030 and 2050, the residential areas increased by 47% while the agricultural areas decreased by 24.1%. In the region, snow avalanche hazard seems to be prevailing in the future as has been in the past. 53% (16.25 ha) of the total residential area (30.5 ha) in 1955 were subject the threat of avalanche. With the increase in growth pace of residential area especially after 2015, a greater area will be endangered by snow avalanches. In 2030, 66% (87 ha) of the residential areas will be under snow avalanche hazard. In the year 2050, this ratio will increase dramatically, and 62% (126.3 ha) of the total settlements (203.8 ha) will be threatened by potential avalanches. Simulation results and landuse maps given in Table 1 and Figure 3 respectively.

Table 1 Areas of landuse types in the study area.

	Year	**Open Forest (ha)**	**Pasture (ha)**	**Forest (ha)**	**Water (ha)**	**Settlement (ha)**	**Agriculture (ha)**	**Total (ha)**
Actual	1955	32.45	3194.36	3954.35	11.82	57.35	440.33	7690
	2004	26.57	3173.94	4016.95	11.82	69.14	392.24	7690
	2015	**20.95**	**3147.93**	**4055.49**	**13.99**	**108.38**	**343.92**	**7690**
Simulation	**2015**	**19.3**	**3174.8**	**4045.8**	**12.5**	**138.0**	**353.5**	**7690**
	2030	19.3	3174.0	4046.5	12.5	138.0	299.8	7690
	2050	21.8	3177.5	4048.5	12.5	202.3	227.5	7690

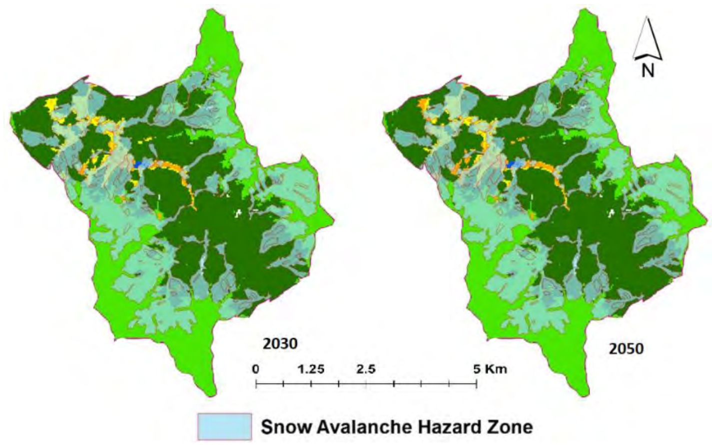

Figure 3 Landuse maps of 2030 and 2050 overlapped with snow avalanche hazard zones.

4. CONCLUSIONS

The Lake Uzungöl with the statues of Tourism Center since 1990 and Special Environmental Protection Area" since 2004 has undergone dramatic land use changes in the last decades. The region also suffers from snow avalanches due to its mountainous topography. The aim was to find out an answer the question of what if the uncontrolled growth of residential areas continues as similar as in the past, how land use change will occur in the future (up to 2050), and how its interactions with snow avalanche hazard will change. For this aim historical aerial imageries were used. Also, Dyna-CLUE model was successfully set up for future projections. Depending on the model, interactions of growth of residential area with snow avalanche hazard were evaluated.

ACKNOWLEDGEMENT
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Attempt to combine few historical data from a 19th century avalanche and recent modelling capabilities for hazard zoning at Tignes Brévières

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ABSTRACT
As a popular ski resort, Tignes (French Alps) is under constant pressure to increase land use including new buildings. In this context, avalanche hazard zoning must be as precise as possible to ensure safety especially for expansion into new areas. One avalanche site, Les Brévières, experienced a remarkable event in 1881. The historical data clearly indicate that most of damages were due to a strong mixed flowing/powder avalanche coming from the Sache mountain. However, the data are sparse and there is the possibility, confirmed by some testimonies, that an avalanche from the opposite mountain side arrived at approximately the same time. To resolve these inconsistencies, a qualification and quantification process has been carried out based on classical expertise combined with numerical modelling approaches: we applied the extended RAMMS avalanche model. The goal is to understand the relative contributions of the dense and powder parts (from Sache side or possibly both sides) and to reconstruct the most realistic conditions to fit the available data and finally define a global hazard zoning consistent with implied hypotheses (including correspondence with pressure and load application height).

1. INTRODUCTION

In France, the main avalanche zoning regulation is based on defining an avalanche event with a 100-year return period. If the return period of the maximum known event is larger than 100-years, the 100-year scenario can be adjusted to include historical information. This implies, of course, that the event is well-documented. A progressive transition allows also to take into account passive protection structures, such as avalanche dams, provided they can be considered as permanent topographic changes.

In many places with little land development pressure or available safe space, qualitative approaches for hazard zoning are usually acceptable and accepted even with large safety margins. In more constrained territory, avalanche hazard requires a more precise and detailed understanding of the terrain and flows behaviour.

The Tignes ski resort in France is a good example of a region under huge land development pressure (amongst the highest real estate prices in France, approximately in the same range as Paris). It contains many confined zones that require careful hazard planning. In this paper we focus on the les Brévieres site which experienced a major avalanche in 1881. We address the problem of how to “manage’’ it, considering both partial historical data and numerical avalanche simulations.

2. TIGNES BREVIERES VILLAGE AND MAIN HISTORICAL AVALANCHE

The Tignes ski resort is consisting of 5 separate villages. Les Brévières is the oldest one and exists from 13th century. One hundred years ago, it was primarily a farming community. In the 1920's the first rumors of a hydro-electric dam appeared and became reality when the dam was built in 1952 becoming the tallest concrete wall in France. There was huge opposition as this project meant that one of the main settlements would be completely buried beneath the newly created lake, strongly reducing the available land near Brévières. However, the hydroelectric dam facilitated the overall development of the Tignes region, including the construction of a ski resort and new villages at higher altitudes.

The village of les Brévières is situated just below the dam at about 1560m asl with buildings mostly along and above the eastern ridge of the Isère river. To the west, it is dominated by the Mont Pourri (3797 m asl) glaciers with the Grande Parei (3350 m) secondary summit exactly opposite it. To the east, the terrain is a slightly gentler and reach la Davie (3000 m).

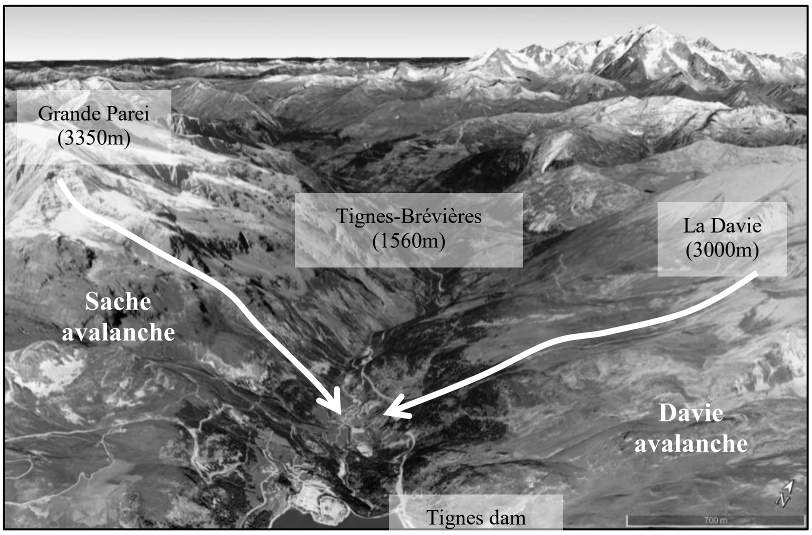

Figure 1 Tignes Brevières situation with the two main avalanches of la Sache (from the west) and la Davie (from the east) – Source: Google Earth

The village is located directly at the convergence of two large avalanche trajectories, la Sache from the west / Grand Parei and la Davie from the east (Fig.1). The final runout of la Davie avalanche was historically protected by a small "splitter" which was replaced and relocated when a road was moved during the construction of the hydroelectric dam. This protection has recently been reinforced and represents a reliable and massive deflective dam. The Sache avalanche trajectory is globally unchanged except a neglectable dam at the exit of the final deep gorge. This situation induced the current avalanche hazard zoning from 2006 (Fig.2): the darkest colours correspond to areas that cannot be developed (existing buildings cannot be modified). Buildings can be built in medium shaded colours zones provided that they respect architectural prescriptions and avalanche impact pressure tolerances.

The French avalanche inventory (known as CLPA - Fig.2) shows two converging and partly superimposed zones corresponding to the Sache and Davie avalanches. The first one appears as a unique zone going far beyond the river (180 m farther and 35 m higher on the opposite valley side) with a possible powder avalanche blast zone. The Davie avalanche stays on the eastern side and shows several branches clearly due to the passive protections. For instance, the south-eastern zone comes from a remarkable event during the XXst century, after the protection improvement whereas the oldest known trajectory is only the northern one.

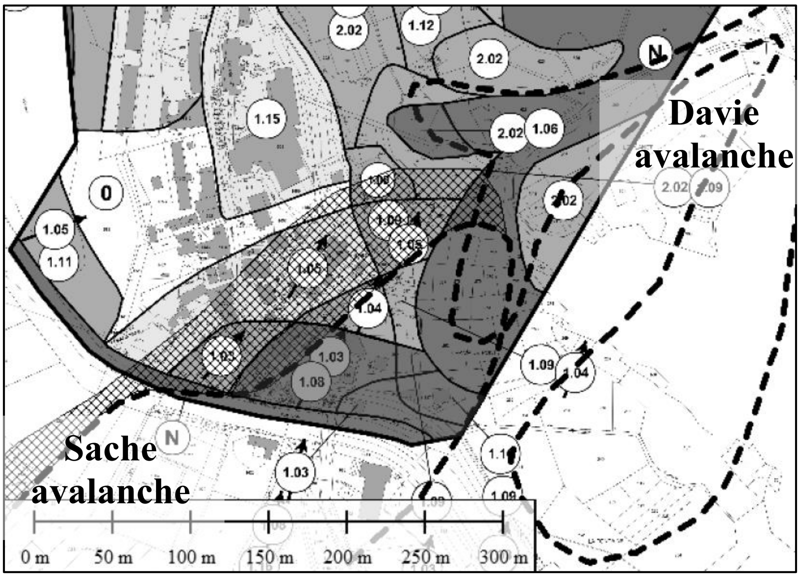

Figure 2 Tignes Brevières avalanche zoning (2006) superimposed with the avalanche inventory limits (flowing part in black dash, powder influence in cross-hatch)

An extreme avalanche event occurred on February 12th 1881: "Catastrophe of the village of Brévières, engulfed by a formidable avalanche descended from Mt Pourri", "The snow depth accumulated on Brévières is estimated at 20 m", "We could not reach the unfortunate buried only by wells and tunnels dug in the hardened snow where the work was difficult and long." as stated some days after by the regional newspaper le Courrier des Alpes.

The avalanche released spontaneously at 6 o'clock in the morning from the ridge of Grande Parei, the avalanche damaged 14 houses on the southern part of the village, buried 37 people and killed 9 of them. At the same time, a few testimonies also indicate that the Davie avalanche occurred in the same days.

Some photos exist, by Paul Mougin which were probably taken a few days after the avalanche: On several of them (Fig. 3), a set of landmarks can be clearly identified to locate and orient these pictures. It confirms the interaction limit near the southern center of the village. A first row of houses were "filled" with snow without being collapsed or carried away. Cottages in the background appear not to seem affected. The Sache final gorge was also clearly overpassed revealing a powerful powder part coming with this avalanche.

However, these pictures do not allow to correctly draw most eastern limits whereas doubts clearly exist about a possible contribution of Davie avalanche. And as this last one is now strongly protected by a reliable deflecting dam (which could allow now to modify/open corresponding zoning where about 20 houses are in the red zone), it is important to clarify what was the exact extension of the Sache avalanche including respective contributions of the pure flowing part and of the powder cloud.

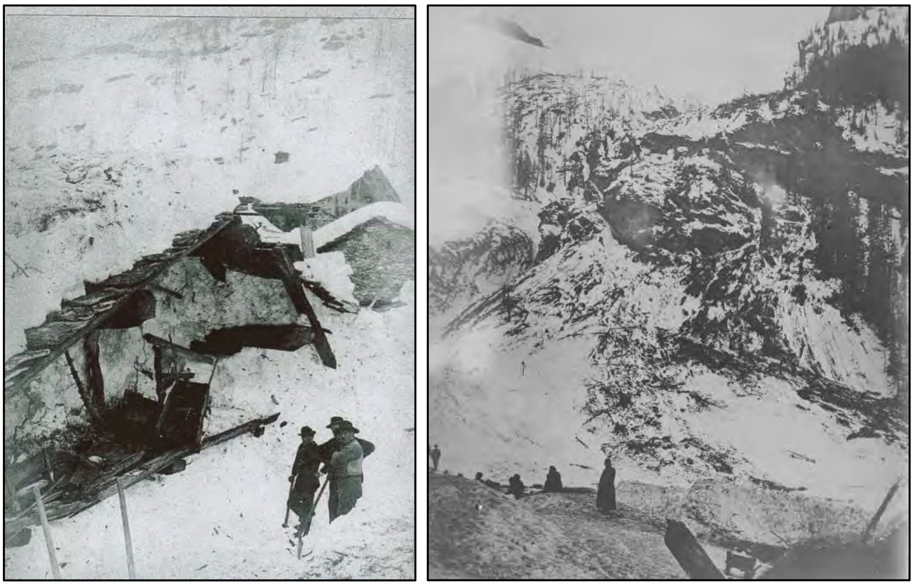

Figure 3 Photos by Paul Mougin of February 12th 1881 avalanche at les Brévières

3. FIRST ATTEMPT WITH RAMMS

From the zoning point of view, the existence of the historical event of 1881 is a crucial point as it constitutes the reference. Of course, its current representativity could be discussed with the climate evolution and including some changes of topography (strong decrease of the top glacier and the corresponding starting zone). But the main point is to better understand how the avalanche run out at that time to fit at best limits with regulation requirements.

A first attempt was carried out with the “all-users version’’ 1.7.20 of RAMMS (Christen et al., 2010) following the usual protocol (statistical assessment of the reference snowdepth in the starting zone considering a 300 years return period scenario, definition of the potential starting zones along the overall trajectory to accumulate them progressively) and including some additional hypotheses: the DEM was manually modify to rub out the modern road platform and the deflecting dam.

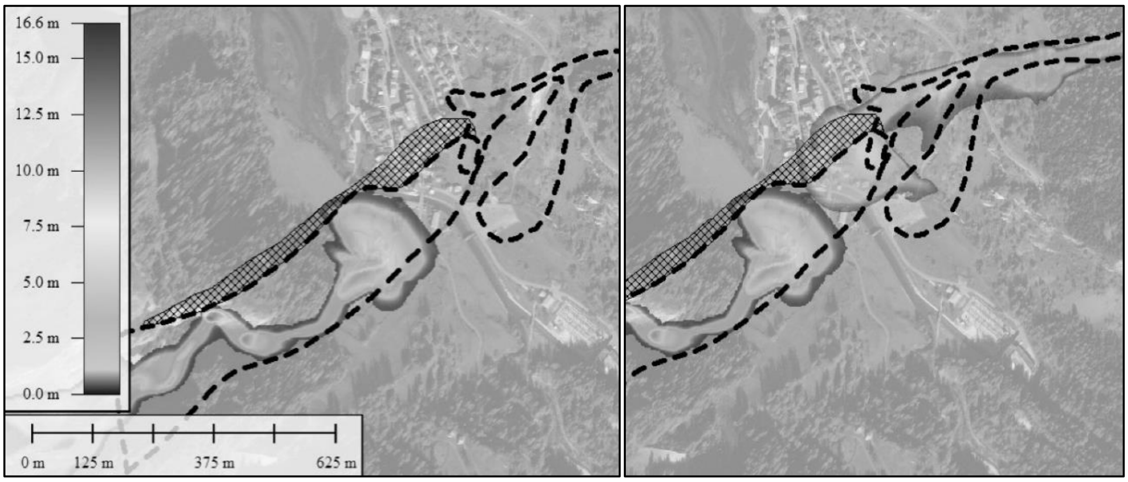

Figure 3 Results (maximum height) with the basic version of RAMMS for the Sache avalanche (left) and including the Davie avalanche (right)

Due to the highly mixed characteristics of the 1881 event, results could be but partial and could not lead to a clear conclusion regarding the respective contributions of the Sache or Davie avalanches. The CLPA avalanche map limits could even be better reproduced introducing the conjunction of both avalanches than in the case of the only Sache avalanche. The operational version of RAMMS cannot properly reproduce this kind of phenomena and therefore could lead to erroneous conclusions if wrongly applied.

4. SECOND ATTEMPT WITH EXTENDED: RAMMS

A second solution could have consisted in "tuning" RAMMS parameters to best-fit one scenario or another. However, the problem with this approach is that it initially chooses indirectly one of the two possible solutions. By doing that, it might even be possible to obtain a sufficiently convincing demonstration for both of the scenarios but finally, not distinguishing between them. This method, that clearly exists in engineering practice, is obviously wrong as it better tries to reproduce the expert opinion by modelling instead of confronting it with unbiased numerical results to reinforce the conclusion.

The "extended" RAMMS model was subsequently applied (Bartelt et al., 2016, Bartelt et al., 2018). At the time of this writing, the extended RAMMS model was being utilized to back-calculate powder avalanche events from a 30-year avalanche cycle that struck Switzerland in early January 2019. Avalanche release conditions and entrainment depths were documented. Because of the immediacy of the events, it was also possible to approximate absolute snowcover temperatures and temperature gradients with altitude. These recent events, and many historical avalanches, have been used to calibrate the RAMMS extended model.

So, the extended model was applied to simulate the historical Sache event by using the calibrated snow parameters of the recent events but assuming (1) more extreme snowcover depths (d0 = 1.5 m) (2) cold snowcover temperatures (T = –7°C) which facilitate the formation of the powder cloud and (3) high snowcover erodibility. The last condition ensured that snow was entrained by the avalanche from initiation to runout. The extreme avalanche had a starting volume of 250'000 m^3 and a total deposition volume of 620'000 m^3. The growth index (by mass) reached 5.5; 14% of the total mass was suspended in the powder cloud. The avalanche increased in mean temperature by approximately 5°C (Vera Valero, 2015).

Fig. 4a depicts the inundation area of the avalanche core (velocity); Fig. 4b the map of the powder air-blast. Unlike the operational RAMMS model, we find the modelled mixed flowing/powder avalanche penetrates deeply into the runout zone. The 3 kPa pressure line is in good agreement with the mapped destruction in the village. The width of the inundation area is larger than the corresponding CLPA zone. This is clearly due to the overflowing of a ridge above the village of les Brévières which permits the formation of a second flow arm which is registered also as a possible trajectory. Here the deposit region clearly mixes with the opposite avalanche trajectory of la Davie. The calculations indicate that an extreme avalanche could descend from the Sache track and accurately represent the documented destruction pattern.

The primary difficulty in modelling the destruction of the village is overcoming a 50 m high gully wall. This cliff deflects the avalanche away from the village; however, there are model scenarios where the fluidized avalanche core can overcome this wall and directly impact the village. It is unlikely that the DEM model of today, accurately represents the terrain of 1881. Changing terrain clearly makes the investigation of historical events a problem.

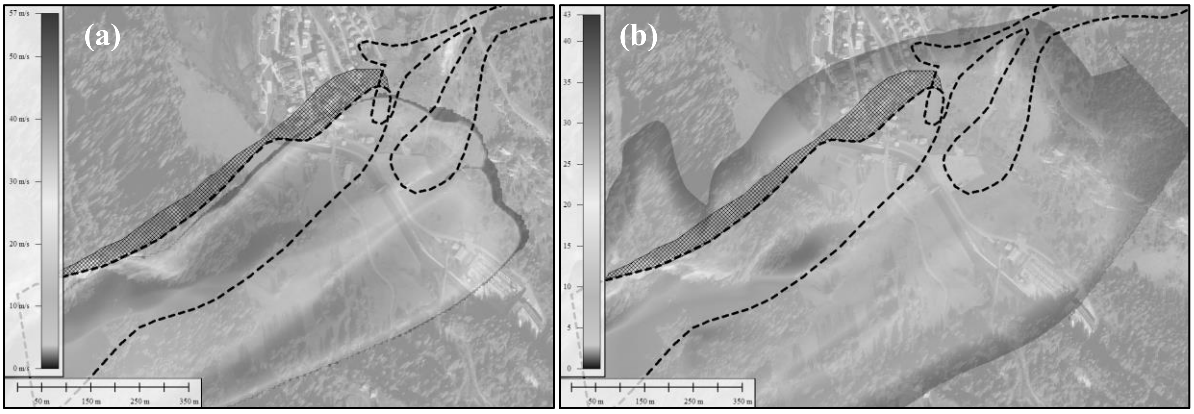

Figure 4 Extended RAMMS results: avalanche core velocity (a) and powder air blast (b)

5. CONCLUSIONS

Beyond controversy, this example shows the usefulness of such advanced tools in engineering practices not to replace but to feed engineers conclusions: for that, the community needs to develop a consistent methodology to account for entrainment, including thermal energy fluxes, in mixed flowing/powder avalanche dynamics models. This includes methods to define snowcover depth (including spatial variation and changes in altitude), erodibility and temperature for 10, 30, 100 and 300-year avalanche events. Efforts in Switzerland are presently directed at modifying calculation procedures used to define avalanche release depths. That is, historical data from measurement stations will be used to define the entrainment conditions. However, there is little information on how to constrain snowcover temperature. Progress in this area would be helpful for avalanche practice.

ACKNOWLEDGEMENT

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Landscape design of snow avalanche protection structures in Siglufjörður, Ólafsfjörður and Seyðisfjörður

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ABSTRACT
The vast scale of snow avalanche protection structures has a great impact on the surroundings and is therefore prone to meet some resistance from the local community. The main challenge is therefore to adapt and integrate the structures into the landscape. A vital part of making the project socially acceptable, is to soften the visual impacts and give the structures an alternative purpose. In Siglufjörður, Ólafsfjörður and Seyðisfjörður, the structures are designed to function as recreational areas for the communities, thus giving the new landscape more meaning – creating a place!

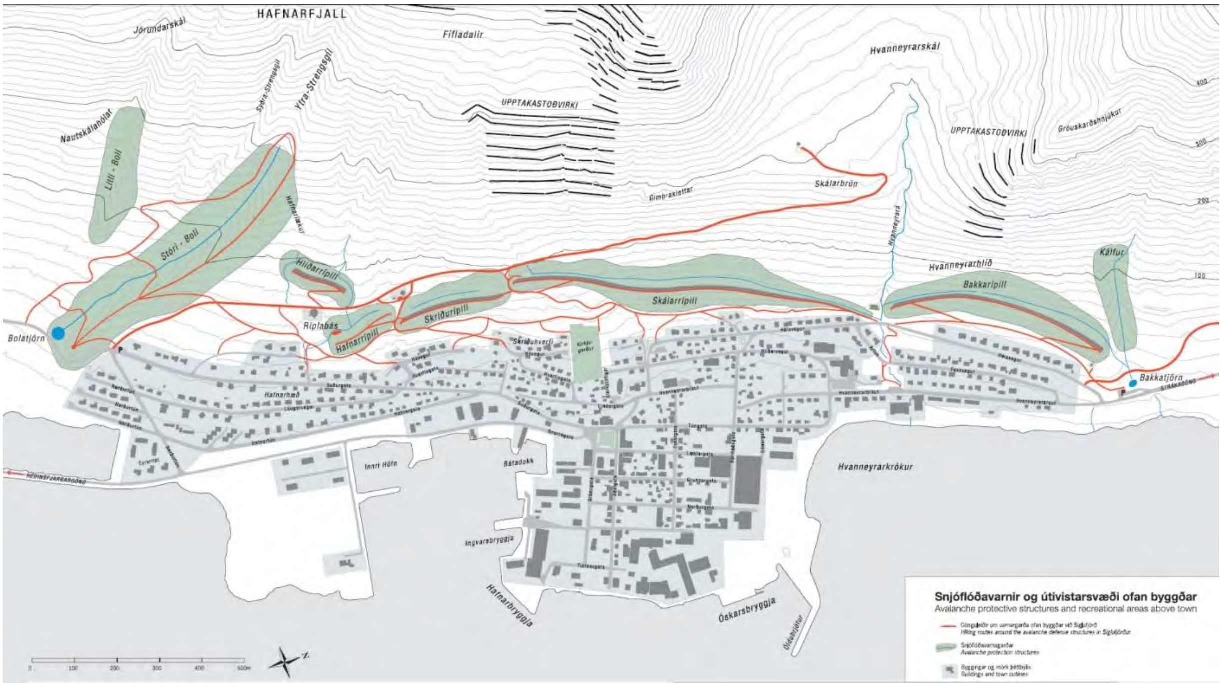

Figure 1 An overview map from an information sign about the avalanche protection structures in Siglufjörður.

1. INTRODUCTION

Since 1901, more than two hundred lives have been lost in Iceland because of snow avalanches and landslides. In 1995, two snow avalanche catastrophes resulted in massive destruction and 34 fatalities in the small towns of Súðavík and Flateyri. After these devastating losses, the nation rallied to action. In 1997, the legislature passed an "Act on Protective Measures Against Avalanches and Landslides" to begin appropriate planning and constructions and reduce risk.

The law established preventative measures including hazard zoning, land use and planning criteria, snow observations, avalanche warnings, and evacuation plans. Since then, Iceland has embarked on the implementation of defence structures in the areas of greatest vulnerability.

The design of avalanche defence structures is, in principle, based on the civil engineers' and geotechnical specialists' ingenuity. One might therefor ask what the role of landscape architects is in the design process. To answer that question, the vast scale of such projects needs to be taken into consideration and the large impact the, sometimes invasive structures, have on the local landscape and the appearance of the environment.

2. SOCIAL ASPECTS

Drastic changes in the landscape close to the communities concern the inhabitants directly and they can, therefore, be expected to have different views on mitigation projects involving large avalanche protection dams. People's attitudes towards the project are often negative at first, and even though a risk assessment is available, many believe that action is unnecessary or excessive. People tend to be rather negative towards the invasive alteration of the landscape so close to home. Therefore, the social aspects need to be taken into consideration and not just the technical aspects of the design.

The Icelandic Avalanche and Landslide Fund for avalanche-prone areas has recognized this issue and, therefore, a part of the budget includes environmental improvements and reclamation of the area in order to adapt the structures to the existing landscape and make the project more socially acceptable. For this reason, landscape architects are included in the design team and our role is to make recommendations about the shape of the structures and land reclamation, give advice on the implementation of the project and present the projects visual effects on the surroundings, to the community. The goal is to reduce negative impacts of the projects by utilizing the opportunities that arise to create new recreational areas and experiences.

Figure 2 Catching dams above the town of Siglufjörður, N-Iceland. The ends of the dams are formed like sloping bastions with a public viewpoint.

3. DESIGN

For centuries, grass and rock were the main building material in Iceland. Even small structures such as the ruins of old farms still stand out in the landscape in many places and bear witness to ancient residence. When it comes to extensive structures such as avalanche protection structures, great care needs to be taken in their implementation. The structures need to fit as well as possible in the existing landscape and their appearance must be acceptable. By thinking of the project, not only as building protective structures for safety reasons, but giving the structures and the surroundings an alternative purpose as a recreational area, the project is much more likely to have a positive impact on the community.

In Siglufjörður, the recreational areas consist of over 9 km of hiking paths, green open spaces, new forestation and open playgrounds. The design team realized that these gigantic structures could not be hidden, nor could they count on tall-growing trees to camouflage them from view. Therefore, they chose rather to make an architectural statement or landmark out of the structures while adapting them to the shape of the mountain. In order to avoid the structures from looking too dominating, their width varies thereby creating a variable form on one side of the wall, contrasting its steep dominating form on the other side. The landscaping and final design of all the structures was based around the concept of a waving line in the landscape. While the dominating upper aspect of the dams must be steep in order to deflect or stop avalanches, their visual impact is offset by a smoother lower edge. Varying in width, this serves to give them an organic, ridged, yet undulating form. The ends of the structures are formed like a sloping bastion with a public viewpoint at the top, giving them an architectural appearance.

3.1 The path network

An important aspect of the recreational area is the path system. The network of hiking paths connects the different areas together and has many connection points to the town's existing pedestrian walkways, for ease of access to the area. The paths run around and on top of the structures providing scenic views over Siglufjörður. An informal path on the crown of Stóri-Boli provides access to the mountainside. Wherever possible, former construction roads have been incorporated in the path system, which contributes to minimizing construction costs. Dedicated rest areas are strategically placed to welcome tourists and locals to the site. The rest areas are equipped with information signs with essential information about the project. Car parking is provided in connection to the rest areas for motorists.

Figure 3 Stóri-Boli, deflecting dam, in Siglufjörður, N-Iceland. An informal path to the mountainside.

In Ólafsfjörður, skiing has been an inseparable part of daily life throughout the years. With modern communication and travel, skiing is still a very popular recreational activity and in the last decades the inhabitants of Ólafsfjörður have been amongst the most energetic skiers in the country. Tracks for cross-country skiing, which function as hiking paths during summer, have been developed on the mountainside in the outskirts of the town. The deflecting dam above Hornbrekka health clinic, is placed midst among the cross-country skiing tracks. It was, therefore, emphasized by the municipality, that a connecting path should be constructed to connect the areas on either side of the dam.

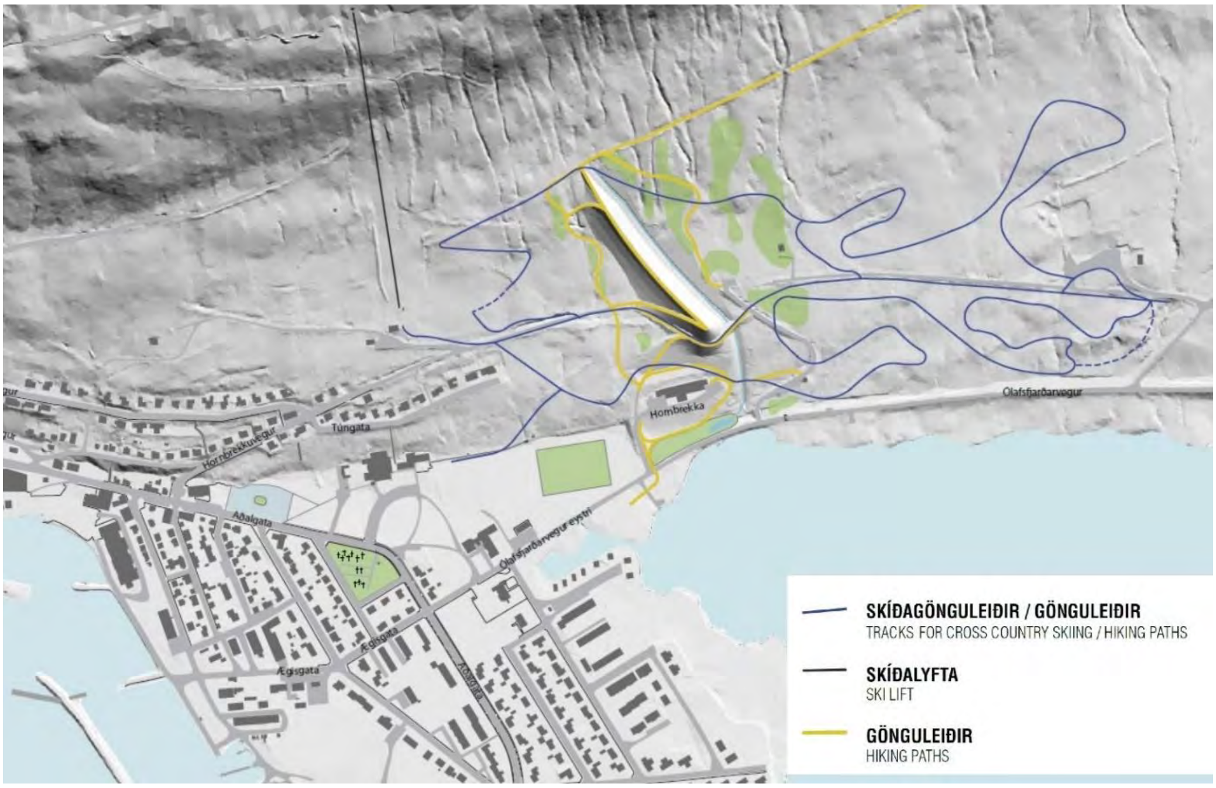

Figure 4 An overview map from an information sign about the avalanche protection dam in Ólafsfjörður, N-Iceland.

3.2 Cultivation

It is important to reclaim the vegetation. It helps the structures to blend into the environment, minimizing the visual impact and prevents soil erosion. The tall protection structures, with their steep slopes, need special care to ensure a successful cultivation. In Siglufjörður and Ólafsfjörður, a long-term cultivation program helped to start the cultivation, following the reclamation of the local vegetation.

4. VISUALIZING THE PROJECT

It can be of great value to be able to visualize the project beforehand. This is useful in the design, to determine the visual impact of the structures and the optimal placement and shape of the structures. The visualizations are also useful for presenting the project to the local community. Reynir Vilhjálmsson, who lead the team of landscape architects in Siglufjörður, made many hand-drawn sketches during the design process.

Figure 5 A hand-drawn sketch by Reynir Vilhjálmsson of a catching dam in Siglufjörður, N-Iceland.

As technology has progressed, computer-generated images have now, for the most part, replaced the hand-drawn sketches. In Seyðisfjörður, a computer model was constructed where the planned deflecting and catching dams were fitted into the existing landscape.

Figure 6 A computer-generated perspective image of planned snow avalanche protection structures in Seyðisfjörður, E-Iceland.

5. CONCLUSION

By thinking of avalanche protections projects, not only as safety measures but an opportunity to create an inviting landscape, the sometimes invasive structures are more likely to be accepted by the local community. The avalanche protection structures in Siglufjörður and Ólafsfjörður are an active part of a recreational area with various opportunities for outdoor activities. The structures are designed to adapt to the landscape by mimicking natural forms found in the surroundings and using local materials. The planned structures in Seyðisfjörður are designed with the same principles in mind.

The Icelandic Avalanche and Landslide Fund for avalanche-prone areas has included these environmental improvements in the projects budget, thus making these visions a reality. A design team with broad expertise has been involved in the design of these projects from the start, which has resulted in projects that are well received by the community, and outdoor recreational areas which is frequently used by the inhabitants. The project in Siglufjörður has been reviewed by several journals and it was nominated for the Rosa Barba European Landscape Award in Barcelona in 2003.

Figure 7 Stóri-Boli, deflecting dam in Siglufjörður, N-Iceland.

Tree Tribes Meeting – how to build a protection dam

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ABSTRACT

This area, in the north of Norway, is also called "The Three Tribes Meeting", where Sami, Norwegians and people with Finnish background lives.

State directives have historically often been perceived as the abusers of locals, which therefore perceive the state as a common enemy.

Folk belief in this area is strong, so strong that they are willing to fight against the State and science that ignores people's faith and ancient legends. Here are people who relate to it's not all that can be explained, and who lives with it.

Try turning it, and think from their point of view, we are ignoring the nature and what is destined. We explain with knowledge, while they relate to what cannot be explained. There are two completely different views on the world that meet, and both parties think they are right. And it is in this thrill we are now operating.

The settlement on Samuelsberg is exposed to avalanches, the state will build a protection dam, but parts of the population are opposed.

The protection dam is now being built of rock masses obtained from a new tunnel nearby.

Floating foundations for flexible snow nets on permafrost and creeping slopes – 10 years experience

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ABSTRACT
Increasing effect of climate change is felt on permafrost ground at high altitude. Not much research is available, as not much infrastructure is installed at such high altitudes and the access is often difficult. The only relatively common infrastructure, especially in Switzerland, is represented by cable car stations, mountain huts and avalanche mitigation measures. The example of the flexible high tensile steel wire snow nets installed at Wiisse Schijen (test site for permafrost monitoring of the WSL) in 1990 showed the importance of taking ground destabilisation, due to permafrost change, into account. After 17 years, instead of an estimated ~80 years, significant repairs were necessary to keep the system up (Phillips et al. 2008), anchors were for example exposed due to soil creep. This led to the development of so-called "floating" foundations, a specially constructed baseplate for the posts, to accommodate for creep over the years. These floating foundations were installed at Wiisse Schijen in 2008 and subsequently used for all flexible high tensile steel wire snow nets.

This contribution now summarises the experience acquired over 10 years at Wiisse Schijen in permafrost ground evolution and behaviour of the flexible snow nets and worldwide.

Risk management of gravitational driven processes in Switzerland

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ABSTRACT

Over the past 30 years, dealing with natural hazards in Switzerland has changed from being hazard-oriented to using a risk-oriented approach. After a series of catastrophic events, the National Strategy Natural Hazards was published in 2004 and updated in 2018. Following this strategy, various methods and tools were developed. We present some of these developments and give an example of risk-oriented planning for structural avalanche protection measures using the tool EconoMe. The results of the quantitative risk assessment and the benefit-cost-analysis indicate that the planned measures can be recommended for subsidisation.

1. INTRODUCTION

Over the past 30 years, several catastrophic natural hazard events and the expected increase in number and frequency of such events due to climate change have changed the natural hazard policy in Switzerland. With the floods in 1987, causing damage of 1.5 billion CHF (inflation-adjusted to 2018) in several regions of the Swiss Alps (BWG and LHG, 1991), it became apparent to authorities and politicians that investment in protection measures against natural hazards had to be adjusted according to the meaning and the value of the objects at risk. Equally, it became clear that structural measures alone where not enough. Only in combination with other types of mitigation measures, including land use planning, biological (e.g. protection forest) and organisational measures, could the impact of damaging events be reduced to an acceptable level. Since the early 1990s, dealing with natural hazards in Switzerland has developed from a strategy of hazard defence into a risk-oriented approach.

Here, we provide an overview of recent developments due to this strategy change. We concentrate on achievements in Switzerland, but the general trend of setting the focus on risk reduction instead of hazard defence can be observed throughout several Alpine countries.

2. NATIONAL STRATEGY NATURAL HAZARDS AND FOLLOW-UP PROJECTS

The aftermath of the avalanche winter of January/February 1999, the flood in May 1999 and the winter storm Lothar/Martin in December 1999 confirmed the necessity of a paradigm shift of natural hazard policy. As a consequence of these events and in response to an initiative in Swiss parliament, the National Platform for Natural Hazards PLANAT elaborated the Strategy Natural Hazards Switzerland (PLANAT 2005) and proposed the risk concept as a guiding model for dealing with natural hazards in Switzerland. The strategy aims to achieve a comparable security level for all natural hazards throughout Switzerland by measures that are economically viable, environmentally friendly and socially responsible. Following this strategy, two action plans with several projects were started implemented between 2005 and 2011 to close gaps in natural hazard risk management. In 2018, the PLANAT strategy was updated and supplemented with the concept of resilience (PLANAT, 2018). In the following, some key results are presented.

A guideline entitled "Risk Concept for Natural Hazards" (RIKO) is one result of the PLANAT action plans. The guideline's first part explains the general risk concept for natural hazards while in the second part, examples show how risk-based planning of protection measures against snow avalanches, debris flows, floods, rock fall, landslides but also non-gravitational processes such as hail, storms and earthquakes can work in practice (Bründl, 2009).

The guideline "Effectiveness of Protection Measures" (PROTECT) proposes criteria to determine whether protection measures may be taken into account for hazard mapping as well as a step-by-step procedure of how to do so. This guideline is organised in the same manner as the guideline RIKO: a general description in the first part and practical examples for different processes in the second (Romang, 2008). Three steps are suggested by which mitigation measures have to be assessed: (1) A general assessment indicates whether a mitigation measure may be relevant for a hazard assessment; (2) the reliability of a mitigation measures is assessed according to its structural safety, serviceability and durability; (3) the effectiveness of a mitigation measure is assessed according to its reliability. These steps enable practitioners to then give a recommendation on whether the evaluated measure may be considered for the reduction of hazard zones. A practical example of an assessment using PROTECT is given by Margreth (2018) and treats the hazard zones of the Vallascia avalanche in Ticino, Switzerland.

One of the main objectives of the PLANAT strategy is to achieve a comparable security level throughout Switzerland. The report "Security Levels for Natural Hazards" (PLANAT, 2014; 2015) provides a uniform definition of the objectives and suggests security levels for objects at risk (Fig. 1).

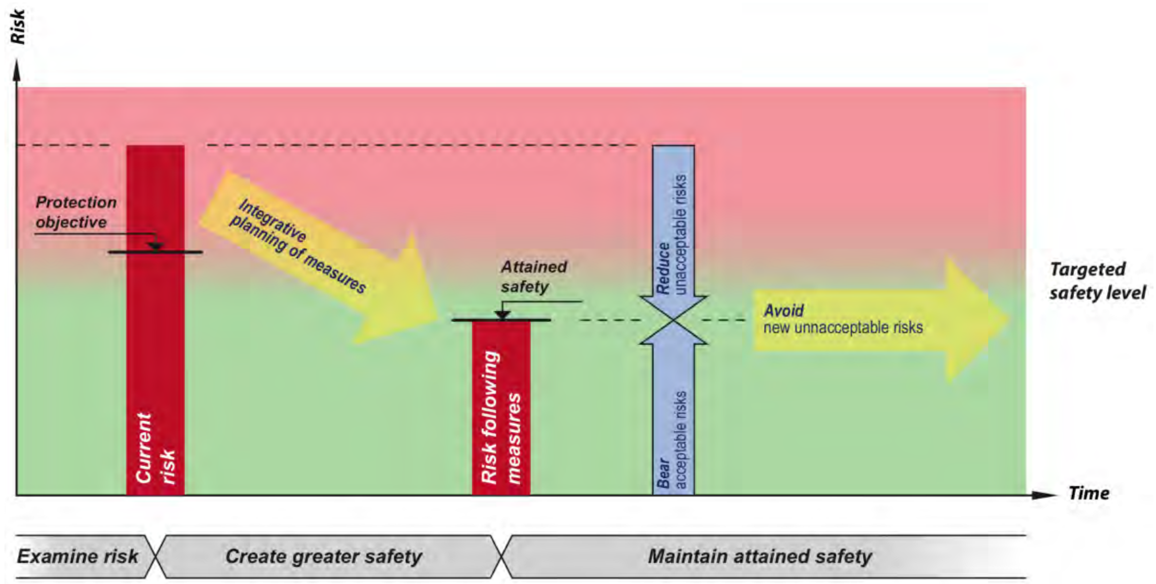

Fig. 1 Procedure to achieve the desired level of security (PLANAT, 2014).

Three categories of objects have to be protected: people, major material assets and the environment. The protection of people has the highest priority. The suggested security level for people states that the general risk of death to an individual should not be significantly increased by natural hazards. Thus, the individual risk of a person to die due to a natural hazard event should be lower than the lowest average probability of death for any age group of Swiss society. Major material assets such as buildings have to be resistant and must provide a high level of protection to the people within and their belongings. The residual risk should be acceptable by risk carriers such as insurances. The risk to infrastructure, to objects of considerable economic importance and to essential natural resources should be so low that the existence of present and future generations is not endangered. Cultural goods must be protected to permanently conserve their cultural value. Meanwhile, no explicit security level is defined for the environment.

3. EVALUATION OF THE EFFECTIVENESS AND THE ECONOMIC EFFICIENCY OF PROTECTION MEASURES

Increasing challenges to maintain and even improve the security level under the constraints of limited financial resources have prompted the Federal Office for the Environment in Switzerland to define criteria for prioritising mitigation projects. Based on the risk concept for natural hazards RIKO, the tool EconoMe was developed and introduced in 2008 to assist authorities and practitioners in the evaluation of the effectiveness and efficiency of mitigation projects (Bründl et al., 2009; 2016). Since 2008, EconoMe has been continuously developed. Operational users of EconoMe include cantonal authorities and private engineering companies. EconoMe guides the user step-by-step through a quantitative risk assessment to calculate the individual risk of a person as well as the collective risks to people, buildings, infrastructure, agricultural areas, forests and parks. The risk reduction induced by mitigation measures is then put into relation with the cost of said measures. Working steps are (1) gathering all documents and describing the area under investigation, (2) hazard assessment, (3) definition of measures, (4) assessment of the damage potential, (5) analysis of consequences (calculation of damage and risk), (6) display of risks and costs and (7) documentation of the assessment (Bründl et al., 2016). The order of the working steps is interchangeable for a user during assessment editing. Business interruption and indirect costs according to definitions provided by Meyer et al. (2013) are not taken into account.

For a first, rough assessment of the potential benefits of a mitigation measure, EconoMe-Light was developed and introduced in 2015 as an online and offline tool. EconoMe-Light allows for a simplified risk assessment and evaluation of the economic efficiency of potential mitigation measures. Practitioners and authorities use EconoMe-Light to evaluate whether the planning process of the mitigation measure should be continued. However, an EconoMe-Light assessment is insufficient grounds with which to request a subsidy from the Federal Government. This requires a full assessment with EconoMe.

In EconoMe, risk to people is calculated as individual risk, expressed as probability of death per year for an individual, and as collective risk, denoted as the number of fatalities per year. To calculate a total collective risk, the number of fatalities per year and the damage to material assets, given in Swiss Francs, must be in the same unit. EconoMe uses the value of statistical life (VSL) to monetise a prevented death with 5 million CHF (4.4 million Euro as of January 2018; Rheinberger, 2011).

Protection projects, for which an application for a subsidy is submitted to the Federal Office for the Environment FOEN, are examined according to several criteria. First, they are assessed with EconoMe concerning their effectiveness (risk reduction) and economic viability. Projects with objects in which the individual risk of death is greater than 1×10^{-5} per year have the highest priority. A project's economic efficiency, calculated as a benefit-cost-ratio in EconoMe, should be larger than one to be considered for a subsidy; for highest priority, a ratio larger than two is required. This means that the quantified risk reduction by mitigation measures must be twice as high as the cost of the measures. A further subsidy criterion is the provision for ecological aspects. Projects can also earn credit points if they are planned in a participatory process (FOEN, 2018).

4. EXAMPLE FOR A RISK-BASED ASSESSMENT OF MITIGATION MEASURES

We show a typical evaluation of the effectiveness and the economic efficiency of an avalanche defence structure using EconoMe. The example is a real case example but data were slightly adapted and location names are not provided due to data protection reasons.

4.1 Situation

The area under investigation is a community in the Swiss Alps endangered by avalanches. Several events in the past hit buildings and infrastructure and caused damage and fatalities. In response to these events, avalanche defence structures were put in place. However, due to protection deficits, additional measures were recently planned. Their effectiveness and economic efficiency were assessed in order to apply for a subsidy from the Federal Government. We present the main steps of the evaluation using EconoMe.

4.2 Hazard Assessment

The risk assessment is based on a 30-, a 100- and a 300-yearly scenario. For each of these scenarios, intensity maps for the situation without (Fig. 2) and with additional measures are calculated by a numerical avalanche model and cross-checked by the expert in charge.

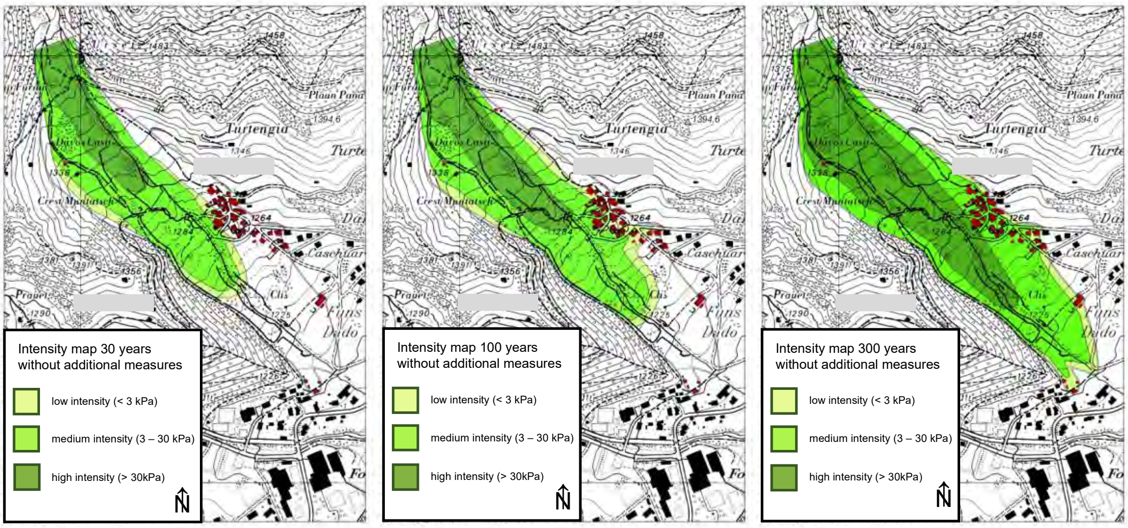

Fig. 2 30-, 100- and 300-yearly scenarios without additional measures.

4.3 Damage Potential

In EconoMe, risk can be calculated either using user-adapted values, which must be documented, or using default values, e.g. for the monetary value of objects (restoration costs) and the average number of people in buildings (2.24 people/apartment or single-family house). Risk to people is monetised by a VSL of 5 million CHF. In this example, various types of objects are endangered. In total, a damage potential of 19 million CHF is exposed (Table 1).

Table 1 Damage potential within the area of investigation.

Objects at risk	**Damage potential**
Number of people	69.77
People monetised (VSL 5 million CHF/averted fatality)	348,850,000 CHF
Buildings	14,930,800 CHF
Cantonal and communal roads	2,154,600 CHF
Telecommunication infrastructure	7,500 CHF
Agriculture and forests	1,999,200 CHF
Sum	19,092,100 CHF

4.4 Mitigation Measures at the Planning Stage

Avalanche defence structures already exist in the release zones. To further reduce the prevailing risk, permanent (steel) and temporary (wood) defence structures are planned in combination with afforestation. With an investment sum of 1,600,000 CHF, annual costs for maintenance of 16,000 CHF, a life span of 80 years and an interest rate of 2%, the annual costs result in 52,000 CHF per year.

4.5 Collective and Individual Risks

Both individual and collective risks are calculated. The risk assessment revealed that for several people, the threshold for individual risk of 10^{-5} per year is exceeded. This means that there is a protection deficit and cost-efficient measures must be put in place to reduce risk. Fig. 3 shows the calculated individual risk without and with additional measures.

The collective risk without and with additional measures for all objects at risk is shown in Table 2. The numbers suggest that all risk is eliminated for the 30-yearly scenario, while risks in the 100- and 300-yearly scenarios are greatly reduced. In total, 97% of the risks are reduced (Table 2).

4.6 Benefit-Cost-Ratio

The benefit-cost-ratio is calculated as the ratio of risk reduction and cost of measures. With a risk reduction of 58,420 CHF per year (Table 2) and measure costs of 52,000 CHF per year (section 4.4), this results in a benefit-cost-ratio of 1.1, which means that the project is economical viable by a narrow margin. Since the mitigation measures reduce individual risks to an acceptable level, the project is recommendable for subsidisation.

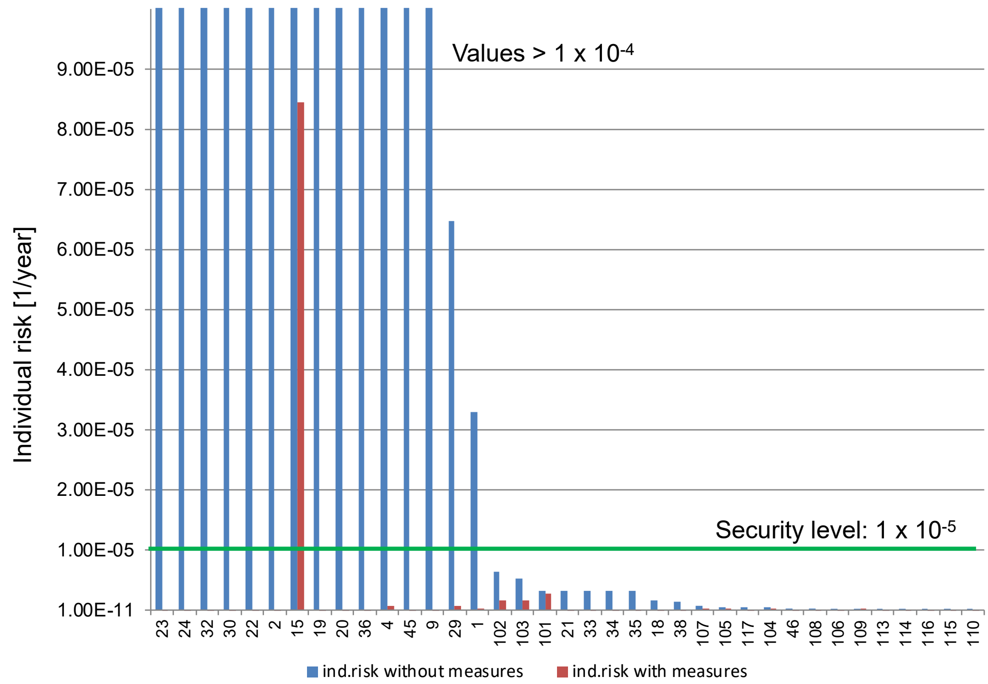

Figure 3: The individual risk of people in objects at risk for the situation without additional measures (blue columns) and with additional measures (red columns). The planned measures reduce the individual risk to an acceptable level except in the case of one building.

Table 2 Collective risks per object categories without/with measures in CHF per year. Risk reduction achieved by measures amounts to 58,414 CHF per year. Risk to people is monetised with 5 million CHF per prevented fatality.

	People	**Buildings**	**Roads**	**Agriculture and forests**	**Collective risk**
Scenario 30	21 / 0	23 / 0	328 / 0	212 / 0	584 / 0
Scenario 100	827 / 7	1,320 / 0	695 / 45	644 / 11	3,486 / 62
Scenario 300	43,423 / 481	11,434 / 772	857 / 468	720 / 306	56,440 / 2,027
Sum	44,271 / 488	12,777 / 772	1,879 / 513	1,576 / 317	60,504 / 2,090
Total risk reduction					58,420

5. CONCLUSIONS

Over the past decades, the natural hazards coping strategy in Switzerland has changed from a hazard-oriented to risk-oriented approach. Mitigation strategies should combine all available types of measures, such land use planning (hazard maps, relocation) as well as structural, biological (e.g. protection forest) and organizational measures (e.g. artificial release, road closure and evacuation). Especially organizational measures have become more important in recent years due to technical developments, such as sophisticated alarm and warning systems. In Switzerland, planning mitigation measures is based on a risk-oriented approach which aims to sink the individual risk to people below a defined threshold and to reduce collective risks with cost-efficient measures. Additional criteria for obtaining a subsidy from the Federal Government are making provisions for the environment and planning measures in a participatory approach (social acceptance). Although there is no explicit corresponding study, authorities argue that equal amount of protection is achieved with less money using a risk-oriented approach compared to the results of a hazard-oriented approach.

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Snow avalanches hitting natural obstacles in Iceland: The avalanches at Kisárdalur, Sveinsstaðaskál and Upsi in N-Iceland

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ABSTRACT

Several avalanche dams have been built to protect settlements in Iceland during the last 20 years, greatly improving the safety of people and property in the areas below the dams. The dams are both deflecting dams and catching dams, with height in the range 10–22 m. Several of the dams have been hit by snow avalanches, resulting in up to 13 m vertical run-up on the deflecting dams and one case where a catching dam was overrun without anyone coming to harm. No large avalanche, in comparison with the design avalanche, has so far hit the man-made dams to properly test the rather crude avalanche dynamics assumptions used in the design of the dams. However, several large snow avalanches have in recent decades hit natural obstructions in Iceland. Some of them provide indications about the dynamics of avalanche flow against obstructions that may be useful in the context of avalanche dam design. Here we report on three such avalanche paths where simulations with avalanche dynamics models have been used to interpret observations about the extent, run-up and other available information about notable avalanches. Two large avalanches in N-Iceland, at Sveinsstaðaskál in Skíðadalur and Kisárdalur in Fnjóskadalur, have overrun 8–12 and 50–60 m high opposing gully sides respectively that are almost perpendicular to the flow direction. The gullies both have rather steep sidewalls, shaped not unlike catching dams. The paths have 700 and 340 m vertical drop, respectively, from the starting zone to the impact with the opposing gully side. The slope angles from the top of the starting zones to the gullies are 25 and 24 degrees, respectively, and the alpha angles to the tip of the avalanche tongues in the run-out areas below the impact with the gullies are 22 and 17 degrees, respectively. A third location investigated here is the 10–20 m high Upsi landslide deposit in Eyjafjörður, which is formed like deflecting dam with a 27° deflecting angle, and is frequently hit by snow avalanches. Three farms are located in the shelter provided by this landslide and two more farms stand farther down in the run-out zone of the avalanches. Avalanche simulations are used to back-calculate impact velocities of large avalanches at these three locations and investigate to what extent the observed geometry of the avalanche deposit can be reproduced. The simulations of the Sveinsstaðaskál avalanche indicate that avalanches at this location can easily overtop the 8–12 m high obstruction that is nearly perpendicular to the flow direction, which is consistent with traditional design assumptions of catching dams. The simulations of the Kisárdalur avalanches indicate that avalanches traveling at 45 m/s can overtop the 50–60 m high obstruction that is nearly perpendicular to the flow direction, which is also largely consistent with traditional dam-design assumptions.

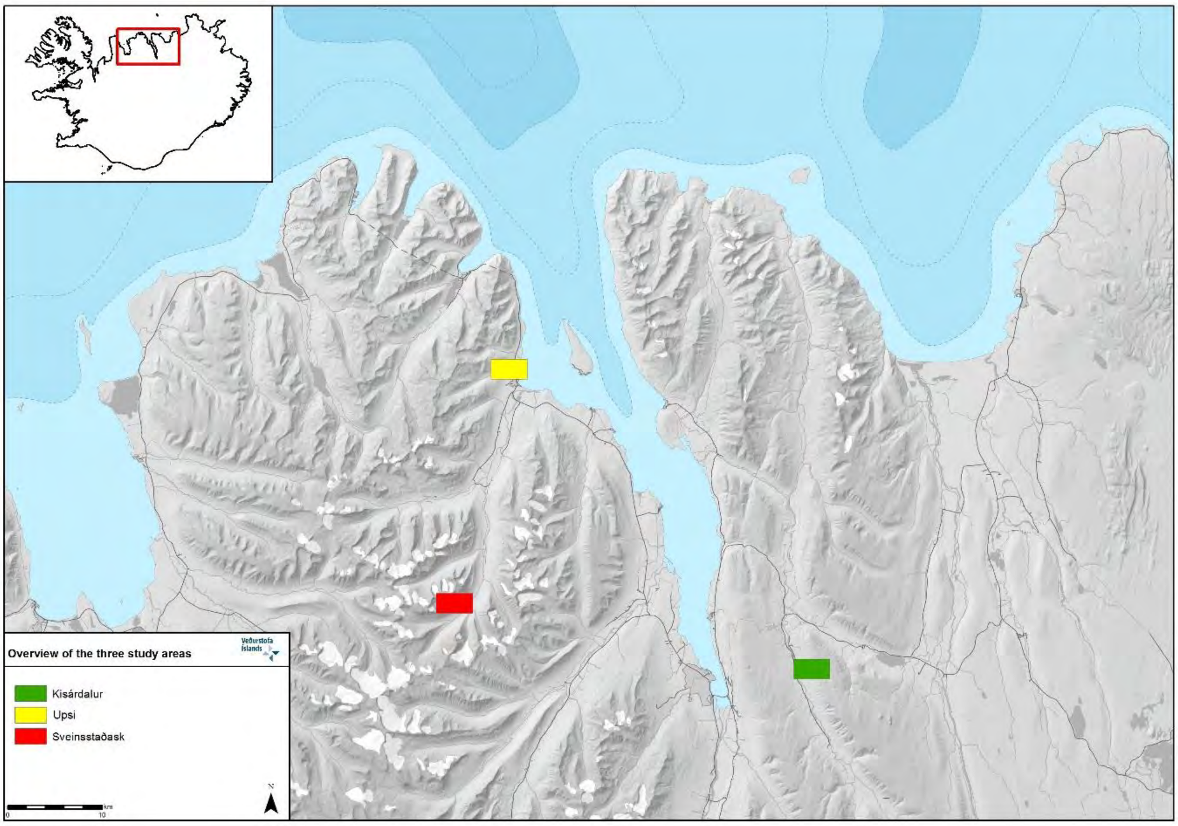

Figure 1. An overview of the three study sites. The terrain at Kisárdalur and Sveinsstaðaskál below the avalanche starting zone is formed like natural catching dams, whereas the lower part of the avalanche path at Upsi is formed like a deflecting dam.

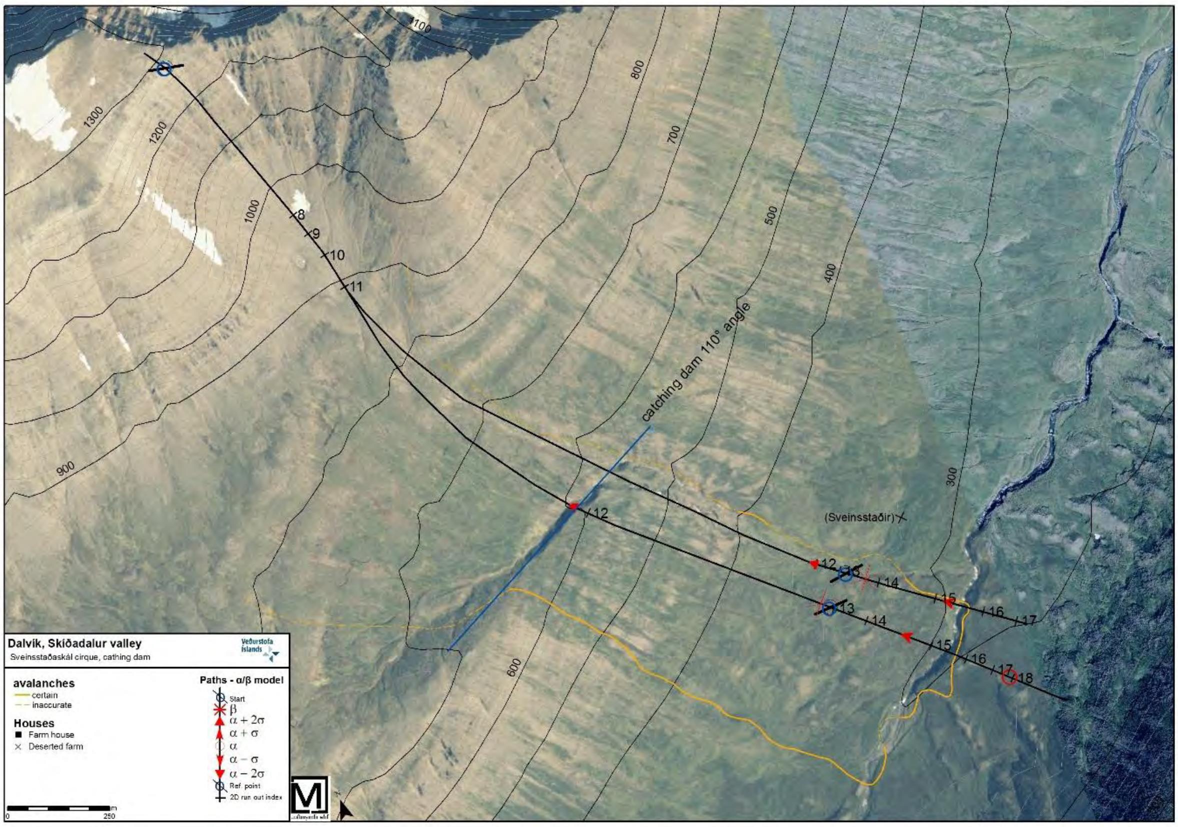

Figure 2. Only one avalanche from the Sveinsstaðaskál cirque in the avalanche database of the IMO is reported to have reached down to the bottom of Skíðadalur Valley but local farmers hold knowledge about more avalanches reaching this far. An avalanche in November 2017, with a fracture line at the rim of the cirque, hit a catching-dam-like, 8–12 m high opposing gully side. The avalanche left almost no snow deposit in the gully but the lower flank was covered with an iced snow surface and fine-grained rock debris indicating high-energy impact. The run-out zone had maximum width of 520 m and was covered with rather thin but even snow debris, typically 10–100 cm thick, with a maximum depth of 300 cm. The abandoned farm Sveinsstaðir, just north of the avalanche tongue, was located in between two large avalanche paths as the run-out zone of another and even more active avalanche path is located just north of the farm. People were living on the farm for some decades during the 19th and early 20th century without any recorded avalanche accidents. That is unfortunately not the case for all farms in the valley. Probably the avalanche danger at Sveinsstaðir was obvious enough for the inhabitants to build the farm at a relatively safe location.

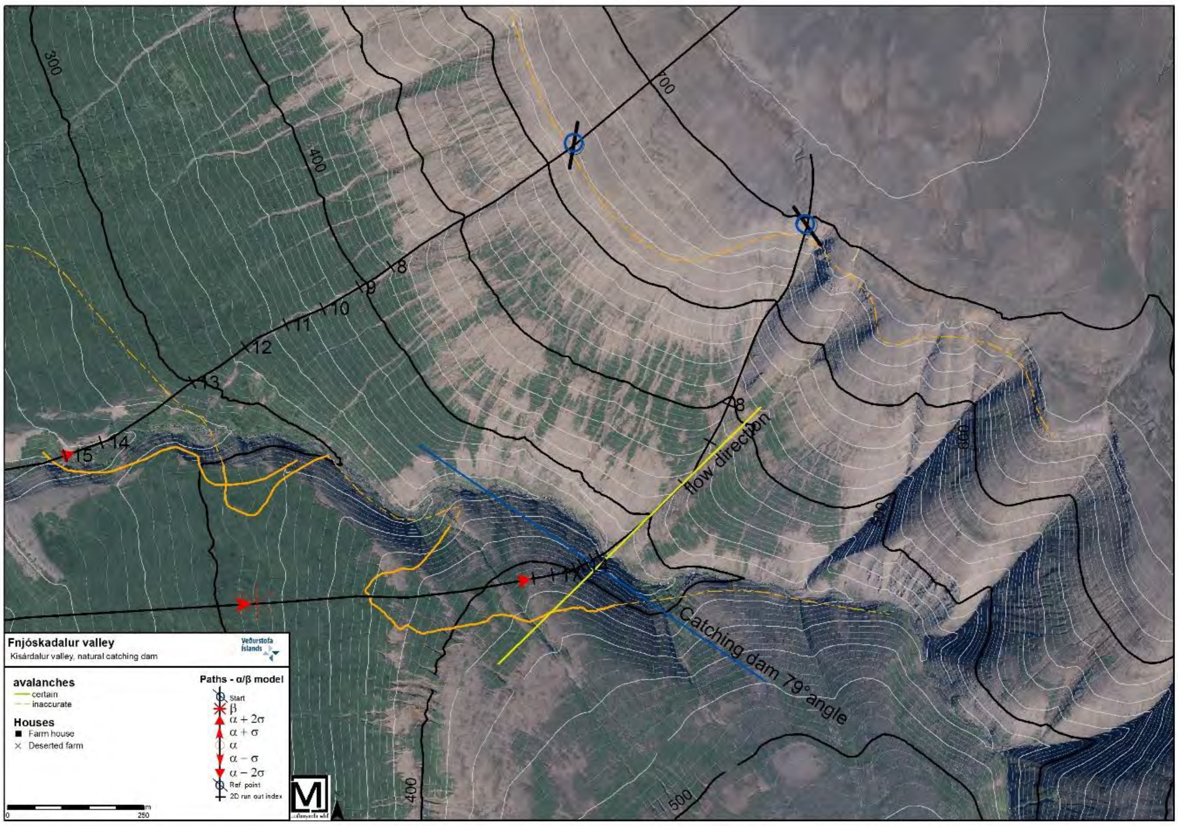

Figure 3. As in Sveinsstaðaskál, only one avalanche is reported having overrun a catching-dam-like opposing gully side at Kisárdalur, Fnjóskadalur Valley. The gully is 50–80 m deep where the avalanche from October 1995 rushed across from a starting zone on the north side of the Kisárdalur Valley. The maximum, vertical run-up of this remarkable 3-km wide slab avalanche was almost 70 m on the south side of the gully. The avalanche tongue was deflected towards west by the south side of the gully which is oriented approximately 11° from perpendicular to the flow direction. Another tongue, coming from the open slope just north of Kisárdalur, reached across the gully farther down where the vertical run-up from the gully bottom is approximately 10 m. The avalanche spread turf and rocks over a large area, making it easy to map the run-out for a long time after it fell.

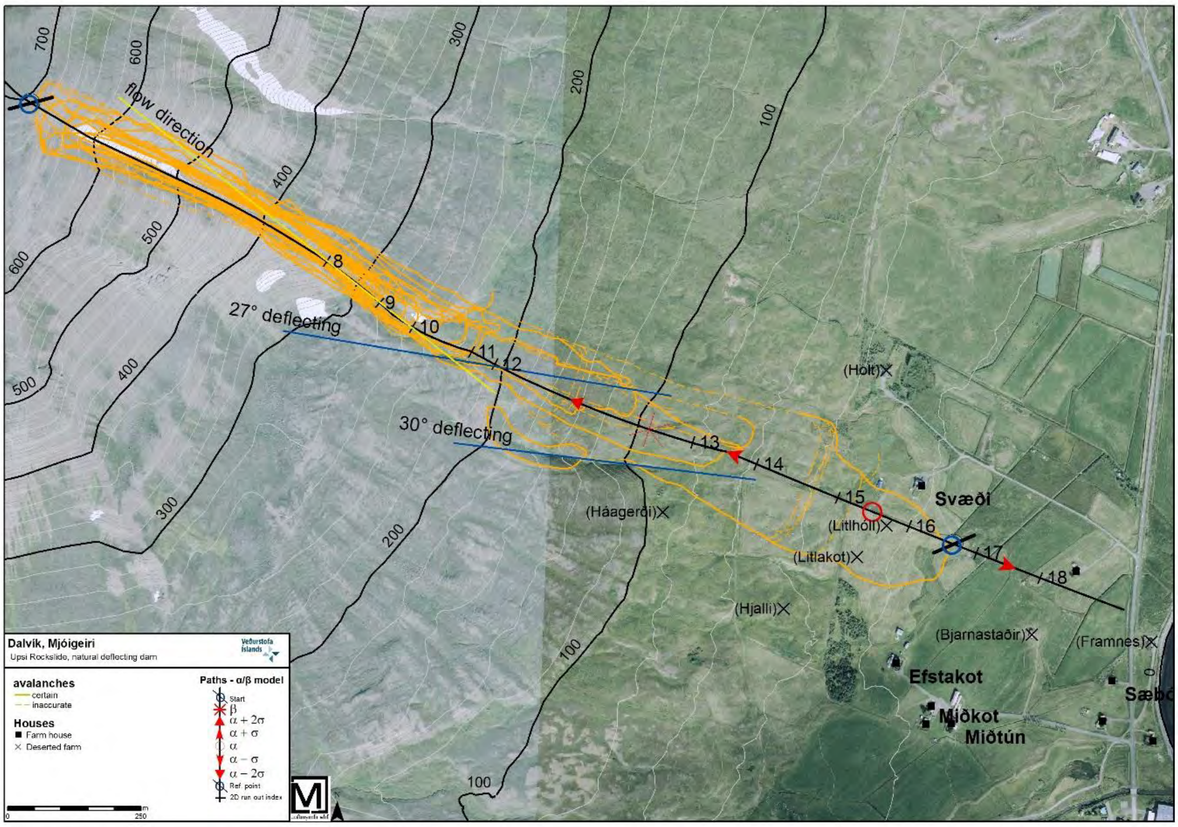

Figure 4. Many avalanches are mapped from the gully Mjóigeiri in the Bæjarfjall Mountain, just north of the village Dalvík. Several of them have damaged the powerline, that used to cross the run-out zone, and fences for livestock many times. The largest recorded avalanche was released in February 1973 and hit the sheep house at the farm Svæði and stopped about 120 m below the farm, only 30 m south of it. The 10–20-m high Upsi landslide deposit lies with an approximately 27° angle from the flow direction of avalanches from the Mjóigeiri Gully. The landslide has several times been observed to deflect avalanches from Móigeiri towards north and is expected influence the hazard at the farms below. The three farms south of Svæði seem to be sheltered by the deflecting effect of the landslide but the Svæði itself seems to be more endangered as the avalanches are deflected towards that farm. There are no indications or records about avalanches overrunning this natural deflecting dam.

Using RAMMS (RApid Mass Movement Simulation) to simulate rapid gravity mass flows in martian gullies

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ABSTRACT

Martian gullies are young alcove-channel-fan systems, some of which are geomorphologically active today. The present-day flows in gullies are generally more mobile and deposit on substantially lower slopes than would dry grainflows. Yet, these flows have been observed to form in the absence of liquid water and are generally believed to be triggered and fluidized by CO_2 sublimation. However, initiation and flow conditions are currently unknown. We employ the RAMMS (RApid Mass Movement Simulation) debris flow and avalanche model to back-calculate and infer initial and flow conditions of recent flows in three gullies in Hale Crater on Mars. We infer minimum release depths of 1.0–1.5 m and initial release volumes of 100–200 m^3. Entrainment leads to final flow volumes that are 2.5–5.5 times larger than initially released, and this bulking is necessary to match the observed flow deposits. Back-calculated dry-coulomb friction ranges from 0.1 to 0.25 and viscous-turbulent friction between 100–200 m s^{-2}, similar to debris flows on Earth. This suggests that CO_2 sublimation fluidizes recent flows in gullies to a similar degree as water in terrestrial granular debris flows.

Mass movements in Nunavik: hazard and risk

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ABSTRACT

In Nunavik, Northern Québec, Canada, slope processes are active within rolling plateau landscapes. Escarpments are seldom; however snow avalanches and sudden mass movements are obvious from the study of slope deposits. According the archives and literature, Kangiqsualujjuaq, one of the 14 Inuit villages in Nunavik, has been stricken by a dreadful snow avalanche: nine people died and 25 were injured on the night of December 31st, 1998-January 1st, 1999. At this time, the inhabitants were gathered to celebrate New Year's Eve in the school gymnasium that was located within the deposit zone of a short snow-avalanche track. The memory of this event is locally long-lasting, however, the perception of hazard is impeded by the lack of systematic data collection regarding slope activity in locations where hazard could easily shift to risk due to the vulnerability of settlements or short transportation corridors around settlements or within National Parks.

From the case study of three sites, within the village of Kangiqsualujjuaq, in the surrounding of Umiujaq and in Lac-à-l'Eau-Claire inside National Park Tursujuq, we documentt the constraints of slope processes on the village expansion, and the methods developed to monitor changes on slopes all year-round, from the setting of automatic time lapse cameras to morphometric properties slope deposits.

Adaption of Snow Bridges in the Großtal Avalanche in Galtür-Tyrol - Austria, Constructive and Static Problems

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ABSTRACT
The dimensioning of the heights of supporting structures is subject to great uncertainties. For example, uncertain meteorological data, short series of measurements, wind drift or the influence of the wind field on the created construction. The design variable of the "extreme snow height" (H_{ext}) shows an enormous high bandwidth depending on the applied method. The data basis at the beginning of the construction of defense structures in the starting zone was even lower than today. Therefore, the supporting structures of many older construction sites have been dimensioned for too low snow heights and are snowed over and thus overloaded in snowy winters. An alternative to new construction is to raise the existing steel snow bridges. This approach is explained using the case study of the “Großtallawine” (Great Valley Avalanche) (Galtür-Tyrol-Austria). Two building types were developed: the type of construction "Rigid" and the construction type "Flexible". These two variants differ in their different girder connection. The load assumptions and statics are described in detail. The advantages and disadvantages are discussed and the costs are shown. The increase of supporting structures is a practical and economical alternative with regard to labor and costs. The type "Flexible" has proven to be more suitable for practical use. However, the prerequisites for an increase must be met. The special conditions of each construction field must be considered, the described procedure is not transferable one to one to each construction field.

1. INTRODUCTION (BACKGROUND AND AIMS)

1.1 The catchment area and its construction history

The catchment area is located on the orographically left side of the Paznaun valley in the municipality of Galtür, Tyrol, Austria. The area of the avalanche starting area extends from 2,300 - 2,700 m above sea level and covers an area of approx. 8 ha. To date, 11 avalanches have been documented.
In 1967, after a major event that injured 4 people, damaged 5 houses and destroyed 30 cars, a construction project was drawn up. ÖAM supporting structures with effective height of grate of Dk = 3.0, 3.5 and 4.0 m were erected on different foundations. The majority of the supporting structures to be raised were constructed using so-called "rust foundations". This is a buried grate rigidly connected to the girder, the tension and compression forces are dissipated like a "dead man anchor". Fig. 1 shows the erection of a ground plate supporting structure using an excavator. The screes were terraced. In the 80s, individual simple elevations of 0.5 m were already carried out. A U-shaped steel was welded to the beams (see Fig. 2).

The 2010 project led to the extension of the defense structures in the starting area against the SW (towards the valley) with an effective height of grate Dk= 4.5 - 5.0 m and to the new construction of the top row of supporting structures as a replacement for the steel snow bridges, which were largely destroyed by rockfall. Furthermore, it was planned to replace the existing plants with an effective height of Dk= 3.0 m by new ones with Dk= 4.5 m.

	
Figure 1: Installation of a supporting structure with high of 3.5 meters, the foundation will fixed with a will be filling with soil material.	Figure 2: First easy increases of the supporting structures in the begin 80ths of the last century.

1.2 Problems

The dimensioning of the heights of supporting structures is subject to great uncertainties. Reliable meteorological data with sufficient measuring network density and sufficiently long measurement series are not always available. The wind drift or the influence of the wind field on the construction must be considered in advance. The data basis at the beginning of the construction of defense structures in the avalanche starting zone was even lower than today. Apart from the uncertain data basis, the design variable of the "extreme snow depth" (H_{ext}) still represents the greatest uncertainty. Here there is a wide range of methods for determining H_{ext}. The following methods are to be mentioned here: Lauscher (1969), Wakonigg (1975), Fliri (1992), Leichtfried (2010), extreme value statistical evaluations (with height extrapolation), consideration of strong wind influence. The range of H_{ext} for this construction site varies between 240 and 797 cm depending on the chosen method. The latest approach, according to Hölzl, Schellander and Winkler (2017), which has determined snow depth gradients for the whole of Austria, yields values for the construction site of around 400 cm for H_{ext}. Margreth et al. (2011) point out that after completion of the supporting structure, further observations of the snow distribution over several years are necessary before it becomes clear whether the choice of the plant height was actually correct As can be seen from Fig. 3, the snow bridges erected in 1976- 1982 are repeatedly "snowed over", even in "normal" winters. The reason for this is the strong influence of wind on the snow distribution in the construction site. The remediation and supplementary project 2010 now requires the following alternatives to be examined: demolition and new construction of parts of the supporting structures and an increase of the existing ones.

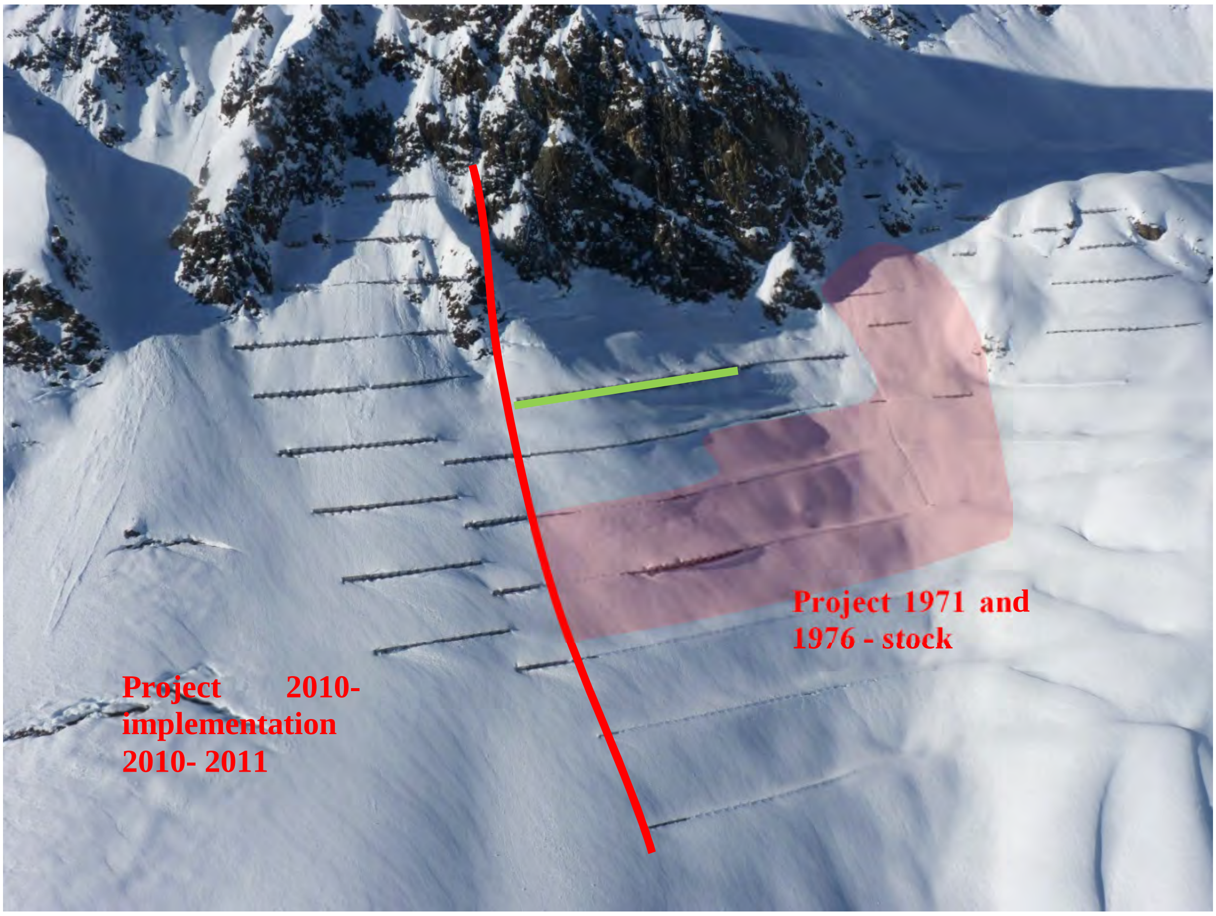

Figure 3: The project field in snowy January 2012. The area with a red background is the one in which the steel snow bridge increasions have taken place in recent years. The green line represents the (local) top row of the supporting structure. This had to be replaced due to severe rockfall damage.

2. METHODS

In order to avoid the costs of the removal and the new construction as well as the associated expenditure, the possibility of increasing the existing steel snow bridges was examined. Two construction types were developed. These differ only in the area of the girder connection: joint "g1" in Fig. 3.

In general, the supporting structure was designed and optimized in such a way that the existing structure only receives a minimal additional load as a result of the supporting structure's increase.

The static calculation of the two-dimensional system was carried out with the help of Dlubal's engineering software. For the structural analysis and design by civil engineer Rainer Zangerle, Kappl. Eurocode 3 and Ö- NORM EN 1993-1-1 were also used. The two variants of increasing and the considerations associated with them are explained below.

2.1 Load assumptions and detailed statics

The load acting on the (elevated) steel snow bridges was determined analogously to the Swiss Guideline for defense structures in the avalanche starting zones (2007). These load assumptions are based on two load models, as shown in Figure 4. (Since the construction field consists of closed support rows, the marginal forces are not taken into account)

Load case 1: Fully snowed-in support system, with evenly distributed snow pressure, the point of application of the resultant is halfway up the supporting structure.

Load case 2: Partially backfilled supporting structure by a set snow cover with a snow height of 77% of the supporting structure height. The resultant impacts on this load model is in the amount of 38.5% of the supporting structure height. The specific snow pressure is increased by a factor of 1.3 due to the snow cover set.

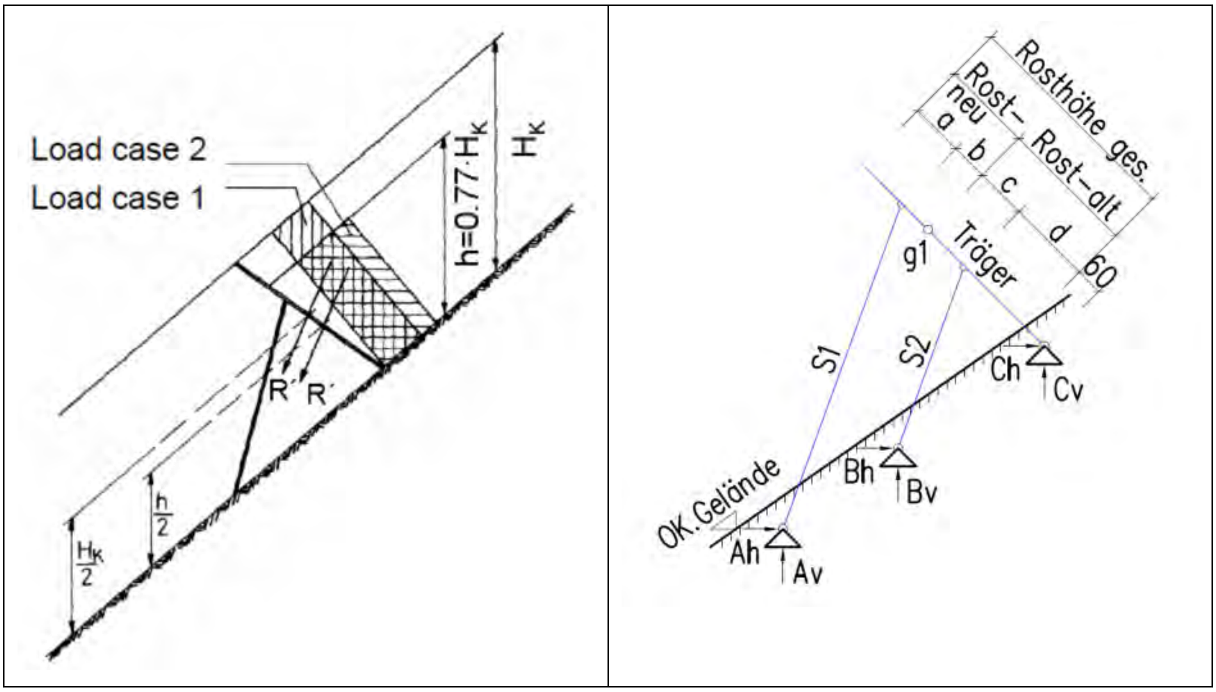

Figure 4: left: Point of attack of the resultant and specific snow pressure distribution in both load models (from Margreth, 2007).
right: Static system of the increasing supporting structure. (*Gelände= surface, Träger = girder, Rosthöhe = height of the crossbeam, Rost = crossbeam, neu = new, alt = old;)*

For the increases, the three new grate heights (1.18, 1.61 and 2.00 m in Figure 3 on the right) were worked out (a and b are variable, depending on the projected increase of the effective height of grate). The higher load, caused by the increase in height, must be absorbed as far as possible by the existing structure. In the course of the calculations, the existing supporting structures and the associated increases were tested with regard to stability and support reactions. Special attention was paid to sufficient static design of the existing girder and supports. Furthermore, the respective maximum support lengths were determined in relation to the greatest load. The load case 2 with a set snow cover was regarded as decisive for the increase. In this case, the resultant force is high due to the higher effective height, but the increase element is not loaded. This assumption was confirmed by the analysis of the support forces. In the old snow bridges the supports are underdesigned. Due to the "special" foundation (rust foundation) with terraces on the mountain side (see Fig. 1) and the associated reduction of the snow pressure parallel to the slope, this dimensioning weakness is not fully bearable.

2.2 Construction types

For the "Rigid" type, the existing girder is raised by means of welding plates on both sides of the girder web (see Fig. 4). For this increase, an IPE 270 (elevation 1.18 m) was welded to an IPE 300 beam on site. The welding plates as a rigid connection provide additional relief for the existing supporting structure, as the pressure is diverted into the ground via two supports. However, the full bending moment cannot be transmitted through the joint. In advance, the moment above the support was regarded as critical, as the new pressure foundation of the "S1" heightening support could settle strongly and the stresses arising as a result would overload the supporting structure. In the course of the construction, however, the subsoil proved to be sufficiently stable. A disadvantage is the more expensive "construction costs". The elevation elements were lifted individually from the access road by crane. A helicopter lift would be another option.

Figure 4: Construction Type rigid	Figure 5: Construction Type flexible

The "Flexible" type is connected by means of fasteners and bolts in the same way as the supporting structures are connected to the micropile. After preliminary work (drilling, welding on the reinforcing straps), the elevation elements can be lifted like works with helicopter (Fig. 5). In this type of construction, the connection is designed as a joint and does not relieve the existing structure. Due to the "play" of the joints, the construction can follow slight settlements of the pressure foundations and stresses or "constraints" in the girder can be avoided. However, the "play" of the joint is limited, the girders have a distance of approx. 1 cm to each other.

2.3 Costs

In the Regional Office Upper Inn Valley (Gebietsbauleitung Oberes Inntal), the new construction of a 4.5 m plant amounts approx. 950 € / running meter. The costs of removal and incurred transport costs are not taken into account here. The increase cost 450 €/running meter in 2012 and was reduced in 2013 by optimizing the workflow to 410 €/running meter.

3. RESULTS

Through the increases described above, it was possible to convert the existing, too low construction relatively inexpensively into such with an effective height that is up-to-date and the state of the art. An increase in supporting structures is profitable in terms of labor input and labor costs. If the prerequisites for an increase exist (sufficient foundation, existing support structure sufficiently dimensioned for increases), the procedure presented here is in any case an expedient, economic and economical alternative.
Of the two increase variants, the type "Flexible" has proven to be more practicable. This is not least because a faster work progress can be achieved here. The increases were already successful in the winter of 2012. Edge forces were not considered in the design, which is why the procedure described here cannot be transferred one to one to another construction site. Particular attention must be paid to the performance of the tension foundation.

4. CONCLUSIO

The determination of the extreme snow height for the dimensioning of snow bridges is still subject to great uncertainty. In particular, the influence of wind on a construction field or its influence by the executed construction can be determined only after implementation of the measures. The described designs show a possibility for the adaptation of existing steel snow bridges. However, an examination of the existing support structure prior to such an adaptation is inevitable. Increasing the effective height of grate will result in higher loads that the base of the structures may not be able to handle. This would increase the probability of failure. However, the shown methods, are an economically way to adapt existing support structures made of steel.

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BLONS IN VORARLBERG, AUSTRIA- 60 YEARS SUSTAINABLE AVALANCHE PROTECTION: EXPERIENCE, SETBACKS AND LESSONS LEARNED

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ABSTRACT:
In 1954, the largest avalanche accident in the history of the second Austrian Republic occurred in the small Walser community of Blons in Vorarlberg. The avalanche disasters of 1951 and 1954 heralded modern avalanche protection in the Alps.
In addition to the development of various support structures in the avalanche starting zone, some of which are still in operation today, special attention was paid to the "green protective wall" - the protective forest above the residential areas in the municipality of Blons.
Sustainable avalanche protection is a permanent task for an exposed alpine valley. Competence, consistent action and the factor time are the way to success, especially in the conversion of over-grown protection forests and their refoundations. 100 years are often not enough to build protective stocks near the upper timberline.
This article provides an overview of the natural conditions of the Great Walser Valley (Vorarlberg / Austria) and explains the events of the year 1954. Subsequently it reports about the forest and technical protection measures taken over time and the associated risk assessments.
KEYWORDS: Sustainable Avalanche Protection, Protection Forest, Avalanche Hazard in Blons / Vorarlberg.

1. INTRODUCTION

In the avalanche winter of 1954 in Vorarlberg 125 people were killed, 57 of them in Blons in the Great Walser Valley. In total, 13 avalanches occurred there. The avalanche paths are shown in the event picture of 1954 (Figure 1).
Just over 60 years after this catastrophe, technical, forestry and spatial planning measures, which are explained below, were taken to protect the local community of Blons.

Figure 1: The avalanche disaster of Blons in Vorarlberg on 11.01.1954 [Source WLV Vorarlberg].

2. WALSER AND THE GREAT WALSER VALLEY

In the 13th century, the Walser, an Alemannic ethnic group from the Valais, moved to the now named after them "Great Walser Valley". The wandering movement fell into the medieval warm period. The Walser cleared the steep slopes and built their classic scattered settlements and alpine pastures. Due to the subsequent climate deterioration in the small ice age, first avalanche accidents of the year 1497 are registered in the chronicle.

The Great Walser Valley is aligned to the wet weather conditions from the west (Atlantic Ocean) and thus often affected by large amounts of snow. Although the individual farms were set up at favored locations, the remaining, non-cleared protective forest was pushed back further and further over time due to overpopulation and overuse. The highest elevation of the avalanche catchment areas of the municipality of Blons is the Falvkopf with 1849 m above sea level. The potential natural timberline is in the Great Walser Valley in the range of about 1900 m above sea level. The avalanche starting zones are thus potentially forestable. The natural forest communities are formed in the montane stage by spruce - fir - beech forest and spruce - fir forest. In the subalpine stage, in the range of 1500 m above sea level and above, the sub-alpine spruce forest prevails, often with tall bushes in the undergrowth. These stocks, which were largely outdated during the 1970s and 1980s, are very difficult to rejuvenate due to strong competition (Figure 2). The municipality area of Blons is built on rocks of the Vorarlberg Flysch. The rocks are easily weatherable and prone to erosion. Almost the entire forest area must therefore be considered in addition to the avalanche protection as a soil and erosion protection forest. A profound and interlinked rooting horizon of the faltering stocks is therefore especially in steeper locations of high conservation importance. In other words, in the long term local sustainability with respect to the local susceptibility to soil erosion can only be ensured by sufficiently stabilizing tillering. The silver fir [*Abies alba*] with its deep-reaching tap root system (up to 2 m) is the only tree species at this altitude capable of ensuring sufficiently deep-reaching stabilization of the soil structure of such cohesive soil types. The root system of the spruce [Picea abies] extends at these locations, especially on marl or marl slate, rarely deeper than 50 cm. However, it forms a dense topsoil rooting.

Figure 2: Outmoded protection forests in the high montane / subalpine altitude are in the decay phase and very difficult to rejuvenate [Source: WLV Vorarlberg].

3. HAZARD SITUATION

Figure 3 shows the forest cover situation of the Walser scattered settlement around 1958. Figure 4 gives an overview of the relevant main avalanche catchment areas in Blons and shows the forestation situation of the year 2006.

	
Figure 3: The municipality of Blons 1958 with low afforestation [Source: WLV Vorarlberg].	Figure 4: The avalanche catchment areas of Blons in 2006. The increase in forest cover is easy to see. [Source: WLV Vorarlberg]

The main avalanche paths "Hüggenlawine", "Eschtobellawine" and "Mont Calf-Avalanche" extend over the entire, south-exposed valley flank of the municipality of Blons. The "Hüggen" and the "Mont-Calf-avalanche" are surface avalanches while the "Eschtobel avalanche" has a canalized avalanche path.

4. THE AVALANCHE WINTER OF 1954

Between the 10th and 12th of January 1954, several avalanche accidents occurred in Vorarlberg. The trigger was extreme snowfalls of more than 2 m of fresh snow within 24 hours. 280 people were spilled, 125 of them died. In the municipality of Blons, one third of the houses were destroyed and one third of the village population, a total of 57 people, lost their lives. The avalanche disaster led to an unprecedented wave of helpfulness and solidarity. The first airlift in the history of Austria was built in Blons. In addition, the two avalanche winters of 1951 and 1954 resulted through their numerous personal and material damages in the development and establishment of modern avalanche protection.

5. THE TECHNICAL PROTECTION MEASURES

The first avalanche protection measures in Blons were probably object protection measures such as roof terraces and splitting wedges. More details are not known. First organized avalanche protection measures in the avalanche starting zones of Blons were established between the years 1906 and 1908. These were Arlberg Rakes (Arlbergrechen) over a length of 1.2 km. Figure 5 shows this type of construction with an effective height of 2 - 2.5 m. The partially already ailing support structures were largely destroyed during the avalanche winter of 1954. The securing of the "Hüggen avalanche" was resumed in 1954. In the process, further types of constructions were developed. The so-called "snow-hanging bridges" (Schneehängebrücken in Figure 6) and, subsequently, the basic structure of the still common snow bridges made of steel. Significant development steps in this type of construction can be found in the foundation. Thus, the originally concreted foundations for micropile foundations and shallow foundations have developed (Figure 7).

Figure 5: Arlberg Rake in the avalanche starting zone of the Hüggenlawine in the year 1906 [source: WLV Vorarlberg].

Figure 6: "Snow-hanging bridges", Dk = 3m, mounting after snowfall in the 60s of the last century in the avalanche starting zone of the Hüggen avalanche [Source: WLV Vorarlberg]

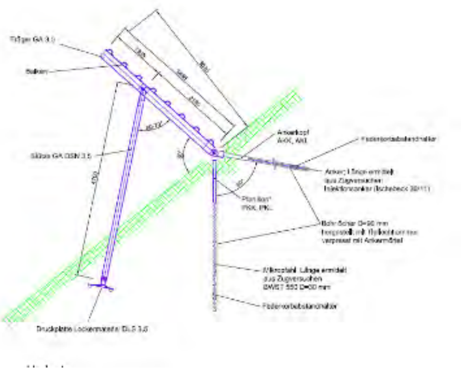

Figure 7: Construction type of modern state-of-the-art snow bridges [Source: WLV Vorarlberg].

Figure 8: The overloaded support structures in the avalanche starting zones of the Hüggenlawine and the Etschtobellawine in February 1999 [Source: WLV Vorarlberg].

In the main starting zones of Blons, about 6.5 km of avalanche defense works (snow bridges made of steel, hangings, combined steel-wood works, etc.), 315 creeping snow constructions and 745 running meters of wind drift barriers fences have been erected. The support structures in the starting zones have proven them-selves in the last 60 years. In the snowy winters of 1967 and 1999, the functionality of the technical constructions of the starting zones could be proven. However, the level of impact of the construction was exceeded in the avalanche winter of 1999 (Figure 7).

Sustainable avalanche protection can only be achieved in wooded areas with adequate forest tillering.

In addition to the protective measures mentioned in the starting zones, protective measures were also taken in the transport area and in the deposit area (dams and object protection measures), which will not be discussed further here.

6. SUSTAINABLE AVALANCHE PROTECTION

In Austria, the Forest Engineering Service for Torrent and Avalanche Control has been responsible for protection against alpine natural hazards since its foundation in 1884. The maxim of the natural hazard management located there is the consideration of the problem for the whole catchment.
Permanent technical protection measures are subject to a certain limited lifetime. In order to achieve sustainable avalanche protection, a combination of different measures such as spatial planning and land-use approaches (forestry) is necessary.
In the starting zone of the Hüggenlawine in the years 1906 to 1908 20,000 pine and 15,000 spruces were planted.

High altitude reforestation was a completely new field of work at that time. There was little empirical value for such exposed reforestation sites. Today it can be seen that about 90- 99% of the plants have failed from this first reforestation.

Further afforestation efforts were made after the avalanche winter of 1954. The clearings were reforested extensively and overaged protection forests were rehabilitated with artificial afforestation. Frequently the rejuvenation was initiated in the protection of technical constructions.

In the municipality of Blons, around half a million forest plants have been planted in the last 60 years. Four fifths of them are spruce [*Picea abies*], the natural main tree species in this sub-alpine area. The forest area in Blons has been increased from about 520 ha in 1971 to 601 ha in 2009.

6.1 Experiences and setbacks

Comparing the forest stands of Figures 3 and 4, the afforestation offensive and 60 years of permanent care seem to be successful. However, the afforestation areas have hardly any protective stocks.
The following problems can be mentioned here:

- Incorrect provenance in early reforestation and the use of large, fast-growing plants (see the consequences in the creeping snow problem).
- Black snow mold [*Herpotrichia nigra, H. juniper*]: Due to the area planting at the beginning of the large afforestations with approx. 10,000 plants / hectare, the small relief was paid too little attention. This led to a widespread spread of the snow mold.
- Creeping snow: Snow creeping and gliding lead to the following damage patterns in the afforestations
  - pull the rootball out of the soil
  - trunk cracks (Figure 9):
  - snow breakage and snow pressure (Figure 10)

Trunk cracks in particular pose major problems for the further development of the stock, as this damage to the stem can provide potential break points for later snow or wind breakage. Lederle (2017) notes that around 90% (!) of the plants are affected at the construction site of the Hüggen avalanche. Although it has been tried for over 60 years to prevent sliding and creeping movements of the snow (Figures 11 and 12).

Figure 9: Strongly drawn trunk cracks, usually these are shorter than 50 cm [Source: WLV Vorarlberg].

Figure 10: Heavy snow pressure damage on ca. 25-30 cm thick trunks after the avalanche winter 1999 [Source: WLV Vorarlberg]

Figure 11: Creeping Snow Construction Dk 1.5. There must be built about 250- 350 pieces per hectare [source: WLV Vorarlberg]

Figure 12: Combined steel-wood works consist of a simple foundation, a slight rust of steel elements and a bed of robinia or chestnut wood, and are expected to last about 30 years, with a effective height (Dk) of 2 to 3 meters [source : WLV Vorarlberg]

Hoofed game (red deer, roe deer and chamois): A close-to-nature silviculture is not possible without the naturally adapted hoofed game stocks (cf. Lederle and Scheier, 2002). The hoofed game bites (special attention must be drawn to the selective biting of the fir [*Abies alba*]), beats, sweeps and peels the forest plants. Rejuvenation of montane mixed forests and the application of subalpine spruce forests can only be achieved with consistent wildlife management. The solution of the existing conflict of interest between hunting and forestry, the so-called "Wald-Wild-Problem" (forest-game-problem) poses major challenges for politics.

In particular, the hoofed game is a limiting factor for the silver fir, so that it has not been able to achieve a sufficient proportion of white fir 20-30% in the established forest stands.

6.2 ***Risk assessment***

In Austria the danger assessment for torrents, avalanches and possibly erosion is based on the hazard-zone map of the Austrian Service for Torrent and Avalanche Control. In 1975, this area-wide appraisal was fixed in the Forestry Act as part of forestry spatial planning. The hazard zones are distinguished here into two intensity classes. In the case of avalanche danger, only the avalanche pressure parameter is decisive. With an avalanche pressure above 10 kPa a high intensity is given and these areas are indicated as "red zone". The "yellow zone" has a low hazard and represents ranges between 1 and 10 kPa. (cf. BMLFUW, 2011)

Hazard zoning is an important planning tool. This applies both to in-house planning (setting of measures, financing, expert activity, etc.) and to external planning such as spatial planning or construction. Consideration in spatial planning ensures that no new settlements are built in hazardous areas. Here is the principle of avoiding the danger. The consequence for Blons was a partial abandonment of scattered settlements and a concentration of residential properties in the most avalanche safe places (Figure 9).

The hazard zones are only indicated for the so-called "space relevant area". A review of the threat is foreseen at least 15 annually or after changes in the catchment areas.

The hazard-zone map of Blons was revised in 2011. With the help of modern avalanche simulation programs it was possible to simulate hazard scenarios such as the partial failure of the technical constructions of the starting zone. (cf. GZP Blons, 2011).

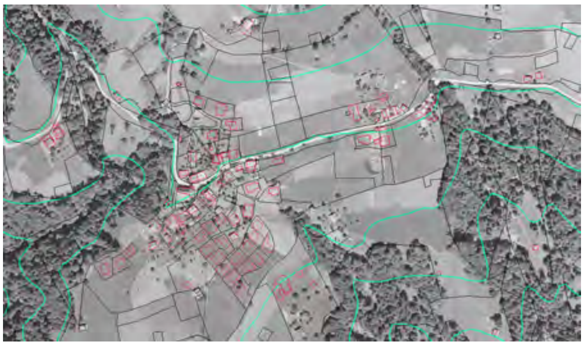

Figure 9: Settlement concentration at the avalanche technically safest place in Blons. The red framed areas are the residential buildings as of 2016. The aerial photo is from the 1950s. The turquoise lines represent contour lines. [VOGIS]]

7. RESULTS AND CONCLOUSION

The Austrian Service for Torrent and Avalanche Control, a department of the Federal Ministry of Sustainability and Tourism pursues a sustainable avalanche protection in Austria. Regardless of political will and the associated provision of financial and human resources for (costly) avalanche protection, the following three points are crucial for sustainable hazard prevention:

1. Competence

As described above, the implementation of sustainable protection measures requires a high level of technical and forestry knowledge. This requires a competent and dedicated staff and further education. However, some insights are only apparent in the practical implementation of the measures during the course of a working life. It is indispensable to pass on this wealth of experience. For example, in Blons, over the years, it has been found that a misplaced provenance of forest plants leads to scarcely protective stock.

2. Consistent action

Successes in high-altitude afforestation and protection forest regeneration require consistent and constant care. However, success can often only be measured after decades. The more important it is to have clear management objectives that look at both the individual tree and the protection forest as a whole. These goals must be consistently implemented in the next generation. Considering natural hazards in spatial planning requires a high degree of assertiveness. It is necessary to resolve conflicts that arise through the interference with the right of ownership of the population.

3. Factor time

The time factor must be seen in the context of sustainable hazard prevention. As can be seen in the example of afforestation and protection forest management in Blons, over a period of 60 years large areas of forest cover, mainly spruce, could be planted. However, these areas are not yet able to withstand the snow pressure due to the poor quality (trunk cracks, etc.). Until these areas have been planted effectively, a further, comparably long period, permanent reforestation and protection forest management, including the maintenance and repair of the technical protection infrastructure, must be expected.

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Evaluation of snow avalanche hazard on the highway using high resolution UAV data: case of the Erzurum-Çat-Karlıova highway, Turkey

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ABSTRACT

Snow avalanches that disrupt traffic and create serious safety problems are frequent events during winter season on the Erzurum-Çat-Karlıova highway in the eastern Anatolian Region of Turkey. The snow deposition on the highway during the winter averages 5-6 m. However it can accumulate as high as 9 – 10 m during the season (e.g. the winter of 2002 – 2003). Serious health and safety issues arise during snow clearance: a fatal accident (i.e. dozer operator) occurred during clearing avalanche debris off the road at the 75+800th and 76+300rd km of the highway in 2013. In the present study, potential snow avalanche release zones were determined, and then 2D snow avalanche simulations were carried out. A high resolution digital elevation model (DEM) was created through images from an unmanned aerial vehicle (UAV) using a camera with 12 MP and structure from motion algorithm. In total, 30 potential snow avalanche release zones, varying between 0.11–1.36 ha were determined. Simulations were performed using three different scenarios with 30–, 100–, and 300–year recurrence intervals for the avalanche release zones determined. The avalanche hazard was then evaluated. The simulations demonstrated that even snow avalanche with a 30–year recurrence interval may cause serious problems for the traffic safety and transportation. These results will help make a decision on how mitigation measures could be planned and designed.

1. INTRODUCTION

Snow avalanches pose a threat to the settlements, the infrastructure and the road network in the mountainous environments. Avalanches can have both direct and indirect negative impacts on the motorways including collusions between mass of avalanches and vehicles, traffic artery blockage as well as severe damages to the structure of the road (Kristensen et al. 2003). It is considerably costly for the governmental agencies, to minimize avalanche risks on the motorways with technical mitigation measures, including using snow supporting structures in the zones of avalanche starting zones, and avalanche galleries (Zischg et al., 2005). Due to great costs of reliable mitigation measures and limited financial resources, utilizing an integrated approach involving active, passive and organizational measures is required for an efficient and sustainable policy (Bründl et al., 2004). Collecting accurate information on the location and the extent of avalanche events is important for both forecasting and designing/planning mitigation measures. Traditional methods involving observations of individual experts in the field provide isolated information with a very limited coverage (Bühler et al. 2009). In the field of snow science, remote sensing has been used as an advanced tool in order to eliminate the shortcomings of the traditional methods. Recently, small unmanned aerial vehicles (UASs) continuously gain preference in remote sensing applications in scientific and practical areas as an alternative remote sensing platform (Nebiker et al., 2008) and/or a new photogrammetric measurement tool (Eisenbeiss, 2015). Snow avalanches that disrupt traffic and create serious safety problems are frequent events during winter season on the Erzurum-Çat-Karlıova highway in the eastern Anatolian Region of Turkey. The snow deposition on the highway during the winter averages 5-6 m. However it can accumulate as high as 9 – 10 m during the season (e.g. the winter of 2002 – 2003). Serious health and safety issues arise during snow clearance: a fatal accident (i.e. dozer operator) occurred during clearing avalanche debris off the road at the 75+800th and 76+300rd km of the highway in 2013. In this study, it was aimed to understand snow avalanche potential and problem in the region and to propose solutions against avalanche hazard. Potential snow release zones and snow avalanche simulations were assessed in different scenarios. The main input, high resolution digital elevation model (DEM), was created from unmanned aerial vehicle (UAV) images.

2. MATERIAL AND METHOD

2D snow avalanche simulations were performed based on three different scenarios with 30–, 100–, and 300–year recurrence intervals for evaluation of snow avalanche hazard on the Erzurum-Çat-Karlıova Highway (Turkey) (Figure 1). For this, ELBA+ (Energy Line Based Avalanche) software (Volk and Kleemayr, 1999) were used. ELBA+ simulations are based on the Voellmy model containing two parameters: the Coulomb friction μ and the velocity squared dependent turbulent friction ξ. In addition to these two parameters, release areas (m2), release height (m), snow density in the release zone (kg/m3) and Digital Elevation Model (DEM) data are necessary inputs for simulations, with entrainment and resistance areas being optional. In order to obtain high resolution DEM data, UAV flights were carried out by using DJI Mavic Pro (Figure 2), allowing for the capture of 12MP DNG and RAW images. All flights were planned with Android-based DroneDeploy software. UAV images were then processed using structure from motion algorithm on Photoscan Agisoft 1.3.2 to create high resolution DEM and orthophoto. Before UAV flights were carried out, a total 12 of ground control points were surveyed on the field with RTK-GPS (Figure 2). Following processing UAV data, snow avalanche release zones were determined based on topographic parameters using high resolution DEM data and field observations. 2D snow avalanche simulations were then carried out based on three different scenarios with 30–, 100–, and 300–year recurrence intervals. Depending on the simulation results, some avalanche mitigation measures were proposed.

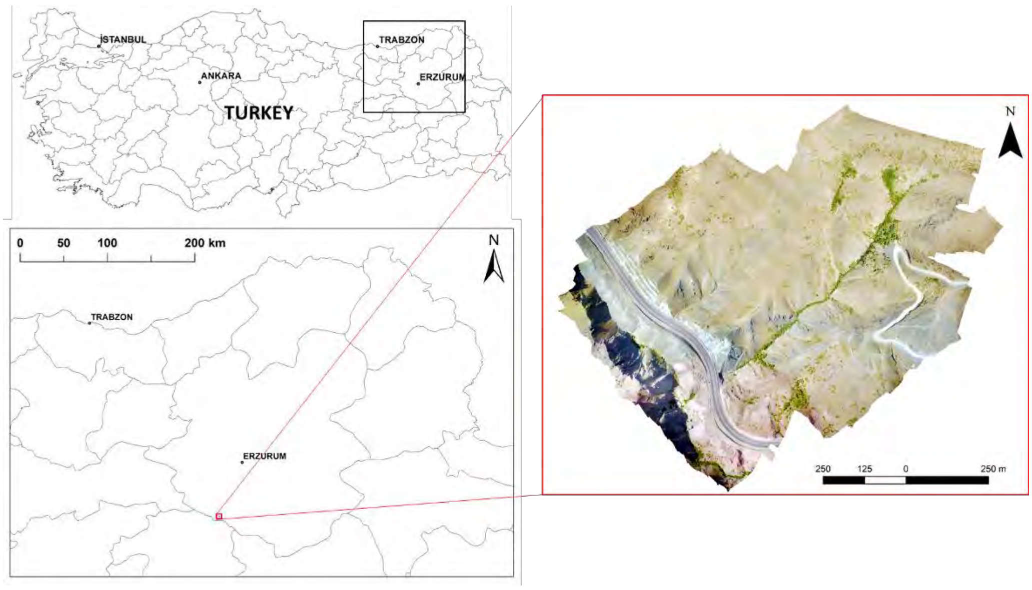


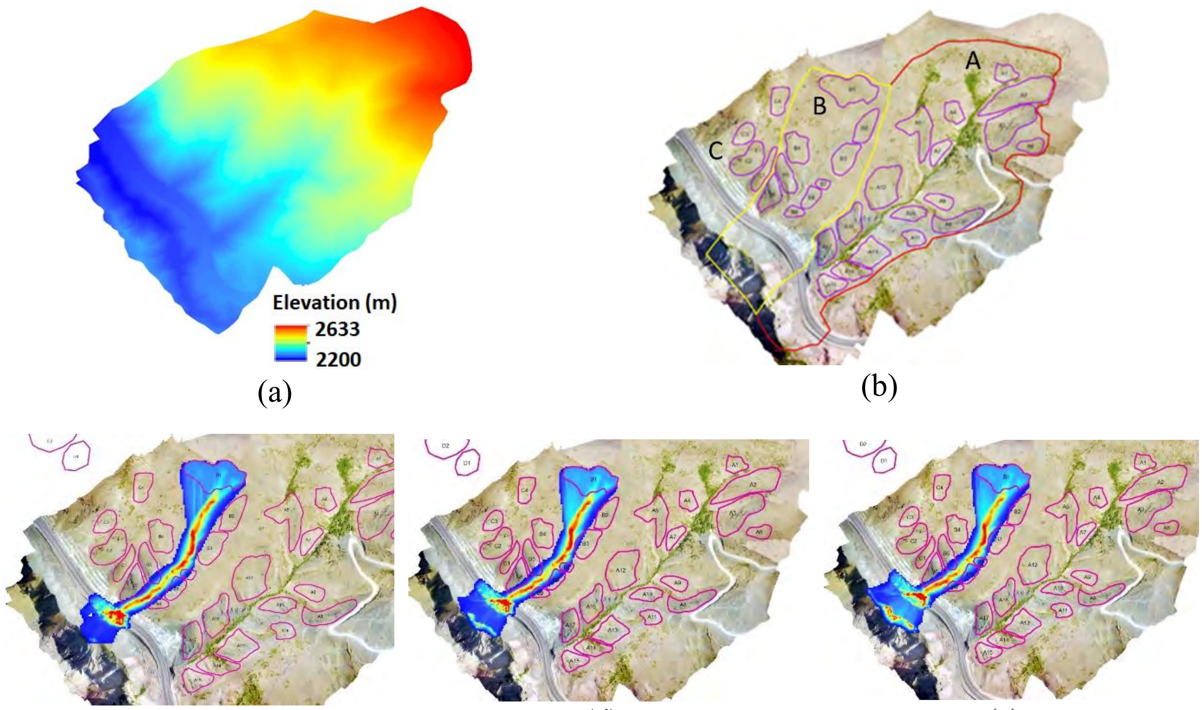
Figure 1 Location of study area.

(a) (b) (c)

Figure 2 (a) DJI Mavic Pro model UAV, (b) an example of flight plan, (c) GCP surveyed.

3. RESULTS

The high resolution DEM and orthophoto generated from 585 of UAV images are given in Figure 3. DEM data were generated in different spatial resolutions; 20 cm, 1 m, 2 m, 5 m, and 10 m to evaluate effect of spatial resolutions on the simulation results. In the study area, in total, 30 potential snow avalanche release zones varying from 0.11 ha to 1.36 ha were determined (Figure 3). The study area were categorized into two sub-catchments, called as A, B, and C (Figure 3). While 17 of release areas were located in catchment A, 9 of them were located in catchment B, and remains are located in catchment C. 2D snow avalanche simulations were made for each release zones in each scenario of the 30–, 100–, and 300–year recurrence intervals. Thus, in total, 90 avalanche simulations were run. Three examples of simulations for each recurrence intervals are given in Figure 3.



(a) (b)

(c) (d) (e)

Figure 3 (a) DEM, (b) orthophotos with snow avalanche release zones determined, (c) 2D snow avalanche simulation result with 30-year recurrence interval, (d) 2D snow avalanche simulation result with 100-year recurrence interval, (e) 2D snow avalanche simulation result with 300-year recurrence interval.

For the 30-year recurrence interval, the results indicated no avalanche that can reach up to the road for the catchment A. However for both catchment B and C, snow avalanches had a considerable potential to reach up to that road and could pose a threat to the traffic safety. In the case of the scenario with 100-year recurrence interval, there was only one snow avalanche that had the potential to threaten the traffic safety for catchment A. The remaining release zones in catchment A did not potentially pose a threat to the road. However all potential snow avalanches in catchment B and C could reach up to the road, posing a great potential risk to the traffic safety. For the 300-year recurrence interval, five snow avalanches in catchment A could potentially reach up to the road. Depending on the analysis in the area, two alternative mitigation measures were proposed. The first alternative for mitigation is to construct a 715-me avalanche tunnel that over the highway. The Second alternative is to build snow bridges with 4 m in height and 3034 m in length against avalanches potentially threatening the road safety.

4. CONCLUSIONS

Snow avalanches that disrupt traffic and create serious safety problems are frequent events during winter season on the Erzurum-Çat-Karlıova highway in the eastern Anatolian Region of Turkey. Nevertheless, neither active nor passive mitigation measures were planned or carried out so far. In this study, it was aimed to understand snow avalanche potential and problem in the region and to propose solutions against avalanche hazard. Potential snow release zones and snow avalanche simulations were assessed in different scenarios. UAV based high resolution data were successfully used for this aim. Depending on the evaluations, mitigation measures were proposed.

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Avalanche observations related to probabilities

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ABSTRACT

Delineation of avalanche endangered areas or the design of appropriately dimensioned mitigation measures according to the respective regulations while accounting for the possible (economic) consequences is a challenge. Mitigation measures may be very effective for the design event, but may have little or no effect on events that exceed the design event. Even if a mitigation measure reduces the hazard in a certain area, an extension of human activity in this area may increase the social risk. Planning and design of avalanche mitigation measures requires information about avalanche intensity (e.g. impact pressure or velocity) and the corresponding occurrence probability. In this paper, a series of avalanche observations are presented that can help to derive estimates of those probabilities.

1. INTRODUCTION

Oftentimes avalanches are referred to as "Geissel der Alpen", meaning scourge or whip of the Alps. But avalanches are not confined to the Alps. They have endangered and still do endanger the population and their infrastructure in all mountainous areas with at least seasonal snow cover.

Hazard zoning and extensive construction of mitigation measures (such as supporting structures in the starting zones or avalanche dams in the run-out areas) have reduced the number of fatalities in settlements and on roads in areas, where those measures have been implemented. In the Alps, the Winter 2018/2019 has probably shown again that these measures are successful. Despite of two to three meter of snow within seven days in the many precipitation areas, which probably corresponds to a return period of 15 to 30 years, relatively few damages to buildings were reported in the news. Nonetheless, three avalanches, which all hit and slightly damaged hotels, made the news in Switzerland, Austria, and Germany—fortunately without fatalities.

In Norway, for example, hotels belong to safety class S3, which implies that they should only be built in areas where the nominal annual probability for avalanches is less than $2 \cdot 10^{-4}$ (return period > 5000 years) [TEK17 (2017)]. Typical residential buildings belong to safety class S2 for which the annual avalanche probability should not exceed 10^{-3} (return period > 1000 years). There are no explicit specifications concerning impact pressure corresponding to this return period, but it is sometimes taken as 1 kPa. Today's major challenge is to delineate avalanche endangered areas or to design sufficient mitigation measures according to the respective regulations while at the same time accounting for the possible (economic) consequences [Wilhelm (1996), Bründl and Margreth (2015)].

Avalanche hazard is influenced by the combination of various parameters, such as:

- terrain (slope, exposition, roughness, ...);
- vegetation (stand density, tree diameter, undergrowth, ...);
- precipitation (frequency, amount, intensity, rain, snow, ...);

- wind;
- snowpack properties (maritime, continental, ...);
- avalanche type (dry, wet, …), dynamics, run-out distance.

Each of those parameters is related to a probability distribution that needs to be defined and appropriate estimates of the combined probability need to be made. In addition to historical records and longtime observations, numerical models can be useful tools, but keeping in mind that the uncertainties related to model simulations might by higher than the desired accuracy by the regulations. These models include snow cover models such as Crocus [Naaim et al. (2013)] or Alpine3d [Mott et al. (2010)] but also avalanche models like RAMMS [Christen et al. (2010)], SAMOS-AT [Sampl and Granig (2009)], and MN2D [Naaim et al. (2002)]. Models may be especially useful in regions where little historic information is available. As mentioned before, the uncertainties of the models might be higher than the desired accuracy—therefore, their application requires extensive experience from practitioners to assess the model results.

2. AVALANCHE OBSERVATIONS RELATING TO PROBABILITY

In this paper, avalanche observations are presented that can be related in one way or the other to probabilities or help to derive those probabilities.

2.1 Probability to observe a natural avalanche

One of the main challenges with regard to hazard assessment is to estimate avalanche probabilities and avalanche size for a given path. Little data are available to quantify these probabilities as it requires sufficiently long-term observations of all avalanche events. One example of this kind of observations is represented by a data set of approximately 80 surveyed avalanche paths around the Rocky Mountain Biological Laboratory (RMBL), Gothic, Colorado (an area of approx. 60 km^2) during a period 37 years.

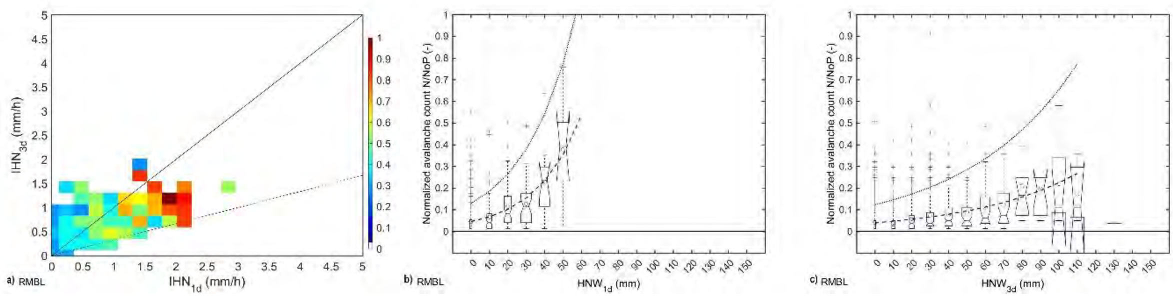

Figure 1 a) Normalized conditional probability ($\log_{10}$-scaled) of observing an avalanche given the mean precipitation intensity of the last day and last 3 days. The continuous line resamples constant intensity during the last 3 days and the dashed line precipitation only during the last day. b) Normalized number of observed avalanches versus one-day new snow water equivalent HNW_{1d} (total number of avalanche paths surveyed NoP = 81). The dashed line shows a fit of the mean value and the dotted line of the 0.95-quantile. c) Normalized number of observed avalanches versus three-day new snow water equivalent HNW_{3d} (number of avalanche paths surveyed NoP = 81).

Figure 1 shows how precipitation or its intensity may relate to the probability of natural avalanches. That recent loading intensity (either as precipitation or snow drift) is a major driver for natural avalanche activity is commonly known, however, little work has been done on the quantification. Figure 1 suggests that especially recent intense loading is important for high avalanche activity. This is, e.g., also reflected in recent experiments by [Birkeland et al. (2018)].

2.2 Fracture depth and avalanche size

Not only how often one has to expect an avalanche in a given path but also what is the expected fracture depth and avalanche size/mass are important parameters in hazard assessment. In modern avalanche models, fracture depth and avalanche size are required as initial parameters.

Based on data from Rogers Pass, [Schaerer and Fitzharris (1984)] proposed an empirical relationship between the mass of avalanches and the most significant determining factors, which can be expressed as

$$M_m = C(S-R)A^n, \tag{1}$$

where M_m, is the total mass of a maximum avalanche for the return period m; S is an index of the amount of snowfall in the avalanche path; R is a factor describing roughness of the ground; A is the surface area of the catchment; C is an avalanche mass coefficient that is a function of the return period, m, as well as of the incline and wind exposure of the starting zone, and n is an empirical exponent.

Nowadays, Geographical Information System (GIS) provide valuable tools to delineate potential releases areas and ease the evaluation of size of catchments [Maggioni (2005), Bühler et al. (2018), Veitinger (2015)].

[Brown et al. (1972), Jamieson and Johnston (1990)] as well as [McClung (2009)] emphasized a relation between the fracture depth D_{REL} and the release size. [McClung (2009)] proposed the relation

$$M = 225 C_0 D_{rel}^{3.2} \tag{2}$$

for the release mass M in tonnes, where C_0 is a constant of the order of 10. The difference between total mass and release mass relates to the mass that the avalanche may erode along the track. For simplicity, the avalanche release depth of major avalanche is often linked to the three-day new snow HNW_{3d} [Salm et al. (1990), McClung and Schaerer (2006)]. This approach may give reasonable fracture depth for major avalanches, but may give a wrong impression of their return periods (see e.g. the discussion by [Schweizer et al. (2008)]). To obtain a better relationship between avalanche release probability and fracture depth/avalanche size, a better understanding of the release mechanism of natural avalanches is required. Recent advances in the understanding of the fracture process of snow [Schweizer et al. (2016)] can help to provide better estimates of return periods and avalanche size.

Based on a simple slab model [Lackinger (1989)], [Gauer (2018a)] used a Monte-Carlo simulation approach, to obtain estimates of avalanche release probabilities and probability distributions of the expected fracture depth (snow water equivalent) depending on climatological conditions. In an extension, he also accounted for forest.

Figure 2 shows some examples of preliminary results of those Monte-Carlo simulations and comparisons with observations.

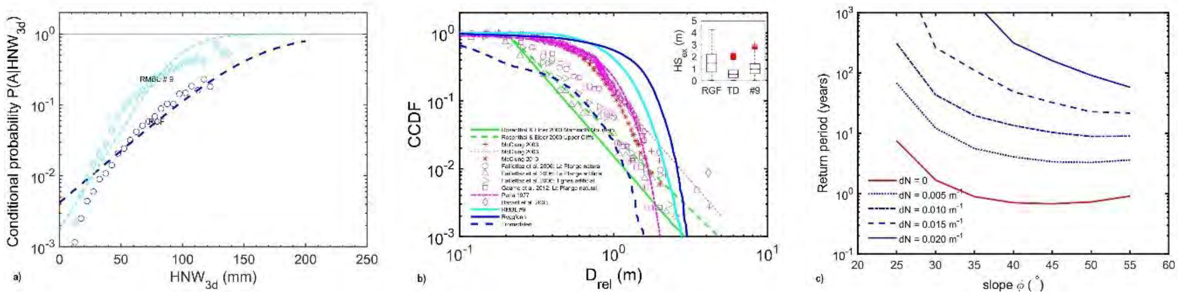

Figure 2 a) Distribution of the conditional probability $P(A|\mathrm{HNW}_{3d})$. Comparison of observations (lines) and simulations (dots) for data from Gothic, Colorado (RMBL #9 and Ryggfonn, Norway (RGF). b) Complementary cumulative distribution function of D_{rel}. Comparison between simulations for Ryggfonn (RGF, Norway), Tromsdalen (TD, Norway), and Gothic (#9, Colorado) and observations or proposed relations in the literature. The boxplot shows the snow height distributions for the three simulations reflecting different climatic conditions. c) Comparison of the nominal return period versus mean slope angle of the release area with the forest stand factor dN as parameter (dN is given by the breast height diameter in m times the number of trees per m^2).

2.3 Scaling behavior of maximum front velocity of major avalanches

Avalanche velocity is an important intensity factor; it is decisive for the dimensioning of mitigation measures, like dams or reinforced buildings [Jóhannesson et al. (2009)], but also for defining warning times.

A scaling analysis using a simple mass block model, supported by observations and measurements of snow avalanches, indicates that the maximum front velocity of major avalanches scales with the total drop height as $U_{max} \sim \sqrt{gH_{sc}/2}$ and that the mean velocity is $\overline{U} \approx 0.64U_{max}$. Here, H_{sc} is the maximum drop height, i.e., for major avalanches usually the altitude difference from the release area to the valley bottom. The analysis also suggest that the effective friction depends on the mean slope angle.

Furthermore, the observations may also help to estimate run-out probabilities. Figure 3 shows exceedance probabilities (i.e. the probability to observe a value larger than a given one) for a series of observed $U_{max}/\sqrt{gH_{sc}/2}$ [McClung and Gauer (2018)] and expected α values according to the α–β model [Lied and Bakkehøi (1980)]. The assumption of the empirical α–β model is that the data on which the model is based reflect rare avalanches; that is events with return periods of the order of 100 years. With that in mind, exceedance probability in Figure 3 b) might be multiplied by a factor of the order of 10^{-2} to obtain annual probabilities. The CCDF of U_{max} can be approximated reasonably well by a Generalized Extreme Value (GEV) distribution.

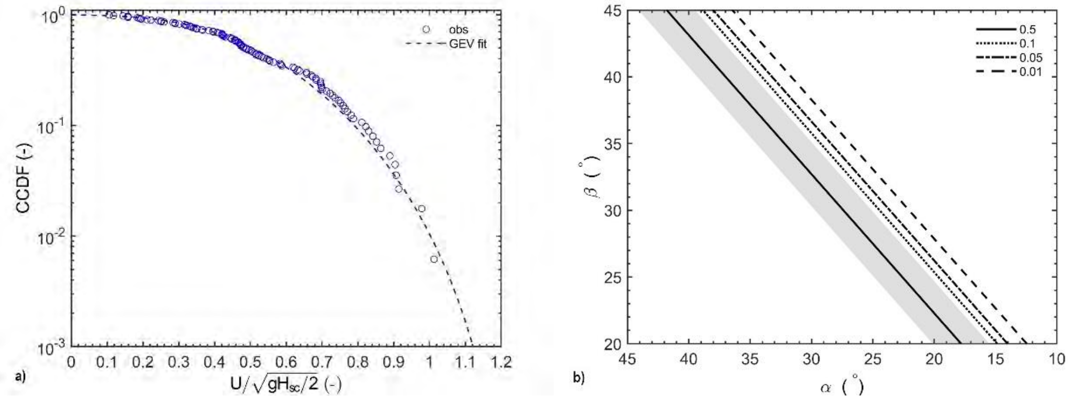

Figure 3 a) Complementary Cumulative Distribution Function (CCDF, survivor function) of observed values of $U_{max}\ /\sqrt{gH_{sc}/2}$ and b) estimated exceedance probability of α versus β according to the α−β model [Lied and Bakkehøi (1980)] for major avalanche events.

Figure 4 shows the calculated (dimensionless) velocity of a mass block moving with a constant retarding acceleration along a cycloidal track. The retarding acceleration is chosen in such a way that the mass block stops at, respectively, the β-point (which is close to the $\alpha_{\mathrm{m}}+1\sigma$ -point), the α_{m}-point, or at the $\alpha_{\mathrm{m}}-1\sigma$ -point. In these cases, the corresponding dimensionless maximum velocity $U_{max}\ /\sqrt{gH_{sc}/2}$ is approximately 0.76, 0.86, and 0.96, respectively.

According to Figure 3, such maximum velocities are attained or exceeded by, respectively, 12%, 6% and less than 2% of all avalanches occurring in the path. Comparing these results with the observations in Figure 3 suggests that the simulated run-outs as well as the velocities agree with the assumption that the velocity curves in Figure 4 reflect major dry-snow avalanches that are relevant for dimensioning of mitigation measures.

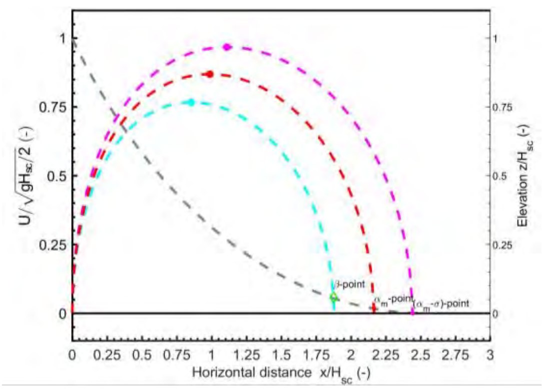

Figure 4 Velocity of a mass block moving with a constant retarding acceleration along a cycloidal track (gray dashed line; steepness in release area is $\phi_0 = 40°$) and reaching 1) the β-point (cyan dashed line), 2) the α_{m}-point (red dashed line), and 3) the $\alpha_{\mathrm{m}}-1\sigma$-point (magenta dashed line). The corresponding maximum velocities are marked with a dot •.

Simple dimension criteria for avalanche catching dams relate the required height of the free board H_{fb} to the avalanche velocity (see for example Chapter 8.4 in [Rudolf-Miklau et al. (2014)])

$$H_{fb} = \frac{U^2}{2g\lambda} + h_f \tag{3}$$

where λ is empirical constant with a value typically between 1 and 3 depending on the avalanche type (dry or wet) and h_f is the flow height. In the case of the example in Figure 4, an avalanche stopping at the α_m-point has still a velocity of approximately $0.55\sqrt{gH_{SC}/2}$ at the β-point. Now planning a catching dam at β-point, one could directly relate the required free board to the drop height H_{SC}

$$H_{fb} = \frac{H_{SC}}{12\lambda} + h_f \tag{4}$$

That is, the required free board in this case would be of the order of 5% of the drop height for dry-snow avalanches, which leads to technically impractical dam heights for drop heights in excess of ca. 500 m.

2.4 Estimates of the reach of the powder part of avalanches

Most of the present-day avalanche models only account for the run-out of the dense or fluidized part of the avalanche. However, a destructive effect of the suspension cloud or air blast of the avalanche can often be observed a considerable distance beyond the more obvious deposits of the dense part.

Avalanche observations from Norway, Austria and Switzerland, which distinguish between the dense (fluidized) flow and powder part, are analyzed to obtain probability information about the reach of the powder part [Gauer (2018b)]. Figure 5 show estimates on the survival probability of α_{PSA} versus β. The data provide useful hints for avalanche practitioners about the reach and the corresponding probabilities of the powder part of avalanches.

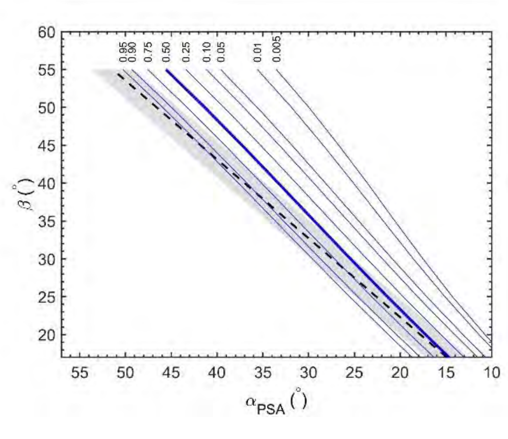

Figure 5 Estimated survival probability of α_{PSA} versus β. For comparison, the dashed line shows the relation angle $\alpha_m = 0.96\beta - 1.4^\circ$ of the dense part and the gray-shaded area marks the corresponding $\pm\sigma$-range.

3. CONCLUSIONS

A quantified avalanche risk management and planning of mitigation measures requires extensive knowledge of all individual processes involved as well as their interactions. Especially regarding a consistent quantification of the interactions of individual processes, be it with regard to the recurrence periods or the vulnerability of objects, there is still a need for research.

ACKNOWLEDGEMENT

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Avalanche hazard in urban snow storage sites in Province of Quebec, Canada

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ABSTRACT

Snow avalanches are a severe natural hazard, threatening recreation, transportation, industries, property and lives in Canada with more than 700 fatalities since the mid-1800s. Of these, many incidents were reported on the short slopes of eastern Canada. Indeed, archival research, coroner's investigations and newspaper searches indicate that avalanches are the second most deadly natural hazard after landslides in the Province of Quebec. Most of these accidents have occurred near residential or public buildings, highlighting the danger related to snow mass wasting on very short slopes (< 70 metres of relief), but also their potential in infrastructural damage. In addition, there is no structural protection nor any systematic daily forecasting procedures to reduce avalanche risks, as compared to western Canada. In January 2017, a fatal avalanche accident occurred in an urban snow storage site. The inventory of these avalanche-threatened areas has not been completed but it is likely that they are more widespread than previously thought. Indeed, it appears that all the major cities in the Province of Quebec are struggling with this problem in several snow storage sites resulting from the cleaning of the roads. The preliminary results about snow characterization and stability in storage sites are presented and discussed.

Snowcatcher – full-scale test site in the Stubai Valley

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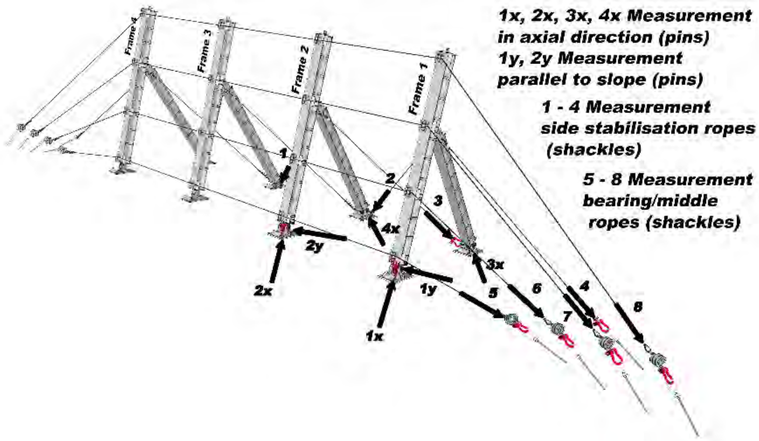
ABSTRACT
Avalanche protection structures such as snow bridges, rakes and nets in release zones, as well as dams for catchment or deflecting structures in run-out and deposition zones, have been successfully employed for many years. More recently, the idea of using flexible-net catchment fences as lightweight, space saving and economic alternatives, aimed at shortening the run-out distance of avalanches, has been proposed. A full-scale structure, the so-called Snowcatcher, was installed and instrumented with several load measuring pins, which record the dynamic forces caused by an avalanche. Two avalanche events were recorded and allow to investigate the temporal force evolution and observed peak values. The results indicate significant differences in the measurement results. It appears that the difference in size and structure-avalanche interaction, as well as the existence of debris material in the avalanche flow is of major importance for the observed forces. This additional debris material blocks the net surface, making it impermeable and prevent snow particles from passing the net surface. Further the debris – structure impact leads to peak forces that may damage parts of the structure.

1. INTRODUCTION
Permanent avalanche mitigation measures are either constructed in the release zone (e.g. snow bridges) or in the lower avalanche path/runout zone (e.g. dams) (Rudolf-Miklau and Sauermoser, 2011; Pudasaini and Hutter, 2007). Under certain topographical conditions one advantage of constructing measures in the runout zone, as opposed to the release zone, is the possible reduction of construction lengths, due to an often smaller avalanche width in the path. This has a major impact on the project implementation, especially with regard to space and time savings, resulting in lower construction costs and often less ecological impact. At present, the most common method of retarding an avalanche in motion are avalanche protection dams, which were subject to several scientific studies (e.g. Baillifard, 2007; Domaas et al., 2002; Hákonardóttir, 2004; Jóhannesson et al., 2009). Flexible rope nets for the protection against rockfall are common and have previously been investigated, (Gottardi and Govoni, 2010; Peila and Ronco, 2009; Volkwein, 2005). While rockfall nets are optimized to absorb high punctual impact energies, avalanche pressure acts over a much larger area and longer time period (Margreth and Roth, 2008). Therefore, results from rockfall and avalanche experiments on flexible wire rope nets can hardly be compared to each other. A mitigation barrier against debris flows constructed with supporting frames, similar to the prototype presented here, is described in Bichler et al. (2012). Herein a new mitigation measure against avalanches is proposed. For areas endangered by smaller avalanches the Snowcatcher presents a viable alternative to avalanche

(a) *Avalanche path*



(b) *Positions of measurement devices and force directions.*

Figure 1: Test site overview

dams using flexible wire rope nets. Therefore, a full-scale prototype of the Snowcatcher was instrumented with several load measuring pins, which record the dynamic loads caused by an avalanche. The motivation of the measurements is (i) to investigate the resulting forces in the structure due to an avalanche and (ii) to observe the influence of net structure on the avalanche flow.

2. SNOWCATCHER TESTSITE

Since a major goal of our project is to analyse the effectiveness of a new protection measure against avalanches in motion, a location that meets several requirements had to be found. An avalanche path in the Stubai Valley (approx. 35 km from Innsbruck) was considered as location with advantages regarding avalanche frequency, avalanche size and reachability in winter. The location of the Snowcatcher allows easy access, being close to a forest road on 1300 masl in a narrow east-facing avalanche path, see *Figure 1*. The release zone of the avalanche is between 2000 and 2400 masl which leads to a vertical gap larger than 700 m. The release volumes of expected avalanches are in a range up to 35.000 m³ corresponding up to a destructive size 3-4.

2.1 Snowcatcher Structure

The prototype of the Snowcatcher was designed to withstand impact pressures up to 50 kN/m², which corresponds to an avalanche simulation with a release volume of 7000 m³ and a snow density of 300 kg/m³. The structure of the Snowcatcher consists of the following parts:

- Omega-Net: This structural element catches the avalanche. It is a specially braided net with a mesh size of 185 mm and a wire diameter of 9 mm.
- Ropes: Bearing and middle ropes stretch the net and redirect forces from the structure to the lateral anchors. Side stabilisation ropes account for the lateral stability of the structure.
- Brake elements: They expand at a certain force level and limit the load in ropes and anchors during an avalanche event.
- Supporting structure: It is constructed as a three-hinged frame in the form of a λ, called "Lambda Frame".
- Anchors: Hollow bar anchors IBO R51 were used to transmit loads from ropes and frames into the ground. The length of each anchor is approximately 9 m.

(a) incoming avalanche *(b) interaction with structure* *(c) avalanche deposit*

Figure 2: A sequence of the powder avalanche from 2019-01-13

Four Lambda Frames are installed with 4 m spacing, resulting in an overall width of the Snowcatcher of 12 m. The height of the net supporting beam is 5.3 m and the angle of the beam to the terrain is 85°, whereas the terrain angle is 25°. Lower angles between net surface and terrain reduce the effective height of the system and complicate the snow removal of avalanche deposits in the Snowcatcher. In contrast to currently used net structures, the Snowcatcher doesn't have upslope retaining ropes, what allows the emptying of the deposit volume with machinery during the season.

2.2 Instrumentation

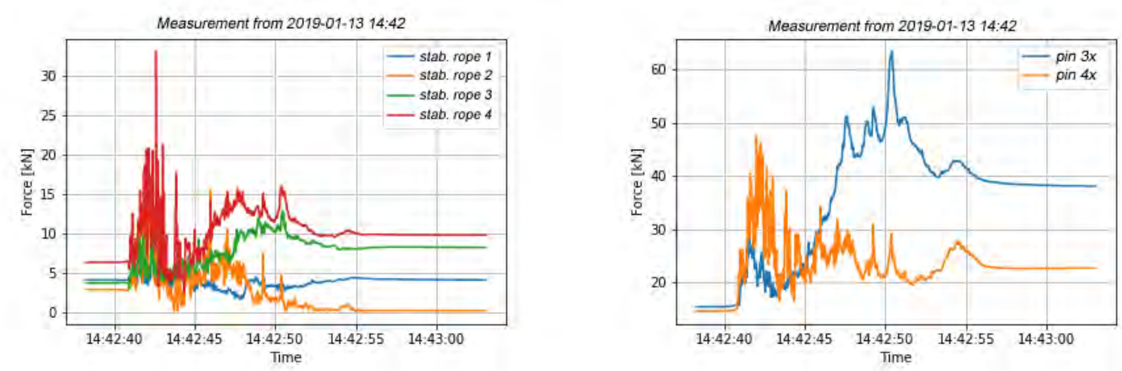
Several load measurement devices are installed in the system to record dynamic forces exerted by an avalanche. Two Lambda Frames of the structure (frame #1 at the edge and frame #2 in the middle) are instrumented with load measurement pins (four pieces) similarly to the set up of Rainer et al. (2008). The arrows (*Figure 1*b) indicate the direction of the force measurement in the Snowcatcher. eight shackles record tension forces in selected ropes of the system. Data loggers with a rate of 100 Hz collect the data from all sensors. Further two cameras are installed to record the avalanche interaction with the Snowcatcher. Camera #1 is situated 30 m lateral to the structure and camera #2 is placed in a distance of 250 m. The recording frame rate of both cameras is 100 fps.

3. AVALANCHE EVENTS

In this contribution we focus on 2 different avalanches that occurred in an avalanche cycle in January 2019. One avalanche occurred on 2019-01-13 at 14:42 and the other one the following morning 2019-01-14 at 4:34. The avalanches differ in size, related volume and the interaction with the structure. This includes the direction of impact and the interacting cross section which specifically depend on the change of the flow path due to previous deposits.

3.1 Avalanche Event 2019-01-13 14:42

After a heavy snow fall an avalanche release led to a powder snow avalanche that hit the Snowcatcher, see *Figure 2*. The maximal tension force in the ropes reached a value of 33 kN (*Figure 3*a). The highest compression forces were measured in pin #3 at the foot of the bracer of the Lambda Frame #1. Here forces raised to a value of 63 kN (*Figure 3*b). The videos of camera 1 indicate a front velocity of 25 – 30 m/s before the powder cloud hit the Snowcatcher. Turbulences and a side passing suspended snow leads to a bad visibility and therefore the assessment of the velocity after the interaction with the Snowcatcher is not possible. Nevertheless, the video of camera #2 shows a deflecting and retarding effect of the structure to the avalanche. The pictures indicate that the net surface remained permeable, leading to particles passing the net surface. This is in correspondence to the results of laboratory



(a) tension forces in the side stabilisation ropes *(b) compression force in the bracer (Lambda Frame)*

Figure 3: Force measurements of the powder avalanche event 2019-01-13

experiments performed by Gleirscher and Fischer (2013). During the event the electric chord of shackle #5 was damaged, hence no measurement of this device exists. The volume of the avalanche deposit is estimated to approximately 1000 m³ which corresponds to an avalanche size 2.

3.2 Avalanche Event 2019-01-14 4:34

This avalanche event happened in the early morning. Due to the darkness at this time no video data is available. The deposit volume is estimated to approximately 5000 m³, indicating a destructive size of 3 and therefore a bigger size than the avalanche characterized in 3.1. Further the deposit of this avalanche shows many branches that block the permeable net surface *(Figure 4)*. The maximal deformation of the Omega-Net was observed in the field between frame #1 and frame #2 and the maximal force occurred in frame #2, leading to the assumption that here the avalanche had the biggest impact. The maximal tension force in the side stabilisation ropes reached a value of 190 kN and for bearing/middle ropes a value of 83 kN. While the bearing/middle ropes are equipped with braking elements, limiting the forces in these ropes, the side stabilisation ropes are fixed without braking elements. During the avalanche event, the side stabilisation rope #4 broke probably due to an interaction with a trunk. Immediately before the fracture the measurement in this rope indicates a force increase from 40 kN to 190 kN in between 10 milliseconds *(Figure 5a)*. 83 kN was the maximum value of the forces recorded in the bearing/middle ropes *(Figure 5b)*. The measurements in the pins #1 and #2 show similar courses *(Figure 5c)*. The axial force has a negative sign, which indicates a tension force in the beam. The values in pin #1 (referring to frame #1, see *Figure 3*) are considerably higher than in pin #2. Highest values in axial- and slope parallel-direction are -142 kN and 137 kN in pin #1. *Figure 5d* indicates a remarkable higher compression force (298 kN)in pin #4 referring to frame #2 than in pin #3 (174 kN) referring to frame #1. This effect might ascribe to a higher force application point in frame #2 than in frame #1.

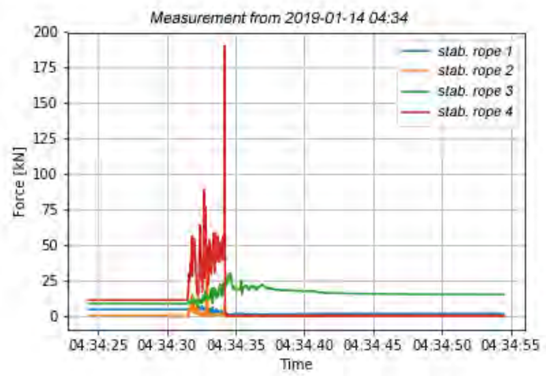
4. RESULTS AND OUTLOOK

This study is an attempt to better understand the interaction of snow avalanches with flexible net structures. A prototype of a new mitigation measure with several load measuring pins was installed in an avalanche path to record forces during an avalanche event. We want to provide a first step in analyzing the forces acting in parts of a mitigation structure that could be a novel

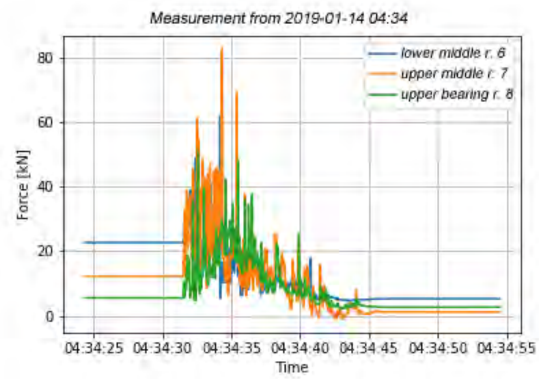
(a) branches in the net

(b) deposit of the avalanche

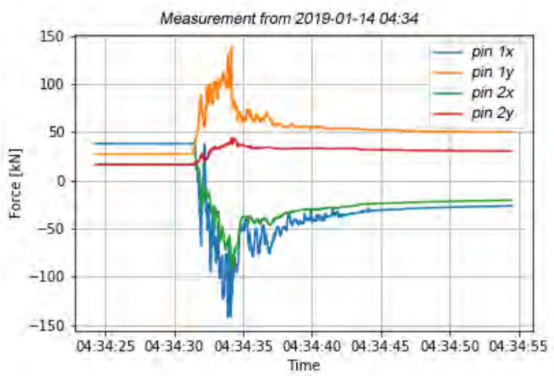
Figure 4: The test site after the avalanche event from 2019-01-14



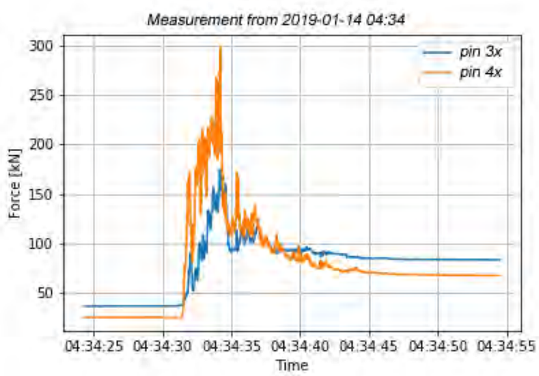
(a) tension forces in the side stabilisation ropes



(b) tension forces in the bearing/middle ropes



(c) axial, slope parallel forces in pin 1 and 2



(d) axial forces in pin 3 and 4

Figure 5: Force measurements of the avalanche event 2019-01-14

measure against avalanches. Herein we highlight two avalanches that differ in size and avalanche–structure interaction. The interaction of a powder avalanche (destructive size 2) with the Snowcatcher led to maximal rope forces of 33 kN and to maximal compression forces of 63 kN in the measuring pins, which account for the base plates of the Lambda Frames. Another avalanche event represents a destructive size 3 avalanche. This event led to remarkable higher forces in the structure. Because of that, plastic deformations of parts of the structure were observed: One side stabilisation rope broke probably due to debris impact at a peak load of 190 kN. Further six brake elements were permanently strained. The maximal force at the base plates of the Lambda Frame was recorded in pin #4. The compression force reached a value of 298 kN.

ACKNOWLEDGEMENT

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Post wildfire analysis of avalanche hazard in Canada

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ABSTRACT

In recent years, western Canada has suffered some of the worst forest fire seasons in history in terms of areal extent of forest burned. Fires have impacted several mountainous areas near towns and highways that have been previously assessed for avalanche hazard. Along with slope incline, forest cover is considered a key terrain feature when considering where avalanches may initiate and flow, due to its effect on the radiation balance and the structural support it provides. Forests also provide a retarding effect to avalanches in motion reducing the momentum and shortening runout distances. Once burned, these characteristics can be altered for several decades, bringing into question the level of protection provided by remaining stems. Furthermore, in the short-term dead trees can be uprooted or broken by a flowing avalanche, increasing the density and impact pressure of the flow. Considering these factors, avalanche paths affected by wildfires require reassessment to determine and quantify the effect of deforestation on avalanche hazard. Factors involved in re-assessing avalanche hazard for burnt paths are explored and two examples of reassessments are provided.

Management of avalanche risk in Icelandic ski areas

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ABSTRACT

Ski lifts have been operated for decades in Iceland but most ski areas are small, and run by local municipalities as non-profit organisations. Snow avalanches have damaged buildings, ski lifts, and other equipment in ski areas in Iceland, but, so far, no fatal avalanche accidents have occurred within the boundaries of the ski areas. In Ísafjörður, a very large snow avalanche destroyed ski lifts and ski huts in the 1994, and again in 1999 when the area was being rebuilt. It was then relocated to a safer place. In Siglufjörður, an avalanche caused extensive damages to ski lifts in 1988 which lead to relocation of the ski area. In the new location, an avalanche damaged a ski lift in 1995. Avalanches have also hit ski lifts in other areas, for example in Oddsskarð on the east coast, and in Bláfjöll, the largest ski area in Reykjavík, without causing serious damages.

The first regulation on avalanche hazard mapping and monitoring for ski areas was enacted in Iceland in 2009. The regulation requires lower ski lift stations and the surrounding area, where people gather in queues, to be in a relatively safe location (outside C-zone in the hazard map) and the same applies to ski huts and parking lots as well as manned ski lift top stations. Apart from that, lift lines, top stations and ski runs can be located in avalanche zones. Every ski area with one or more avalanche starting zones within its boundary is required to have an avalanche safety plan.

Protection measures and working with the locals, practical challenges

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ABSTRACT

The challenge Icelanders faced after the deadly avalanches at Súðavík and Flateyri 1995 is still our mission. That is to protect our inhabitants in towns and villages threatened by snow avalanches and landslides. We lost 34 people in the two catastrophic avalanches. And we have lost much more people in earlier decades in the 20th century.

Even after horrible events like these, it is a challenge for local politicians and those that are responsible for the safety of the inhabitants to convince many of them about the need for evacuating their home in an endangered area for a while during an avalanche cycle or even about building protection measures close to their house. And then relocating a part of settlements, or even a whole village like Súðavík, can be a difficult task also. In Hnífsdalur, NW-Iceland, part of the settlement was relocated, and it did hurt that small community at least emotionally for the inhabitants.

After my experience during the years between 1998 and 2010 as Mayor of Ísafjarðarbær in the Westfjords, I believe that we must increase the speed of the construction of avalanche protection measures in Iceland. There are still many projects waiting to be implemented. The Icelandic Avalanche and Landslide Fund has sufficient means to cover the remaining work but the Parliament has not allocated high enough budgets to complete projects according to plans that were made by the Icelandic government after the deadly avalanches 1995.

The design of slushflow barriers: Laboratory experiments

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ABSTRACT

We report on a series of laboratory experiments to study the interaction of slushflows with catching dams. The aim of the experiments is to identify an engineering design that effectively stops a slushflow upstream of a catching dam. In the experiments, we use water as a substitute for slush. The chute flow is scaled with the Froude number and the barrier height is scaled with the depth of the chute flow and the Froude number. We find high run-up (splash) and thus high impact forces may be inferred, during the initial impact of the flow with an impermeable barrier, resulting in overtopping of the dam. The splash is followed by semi-steady fountaining, with overflow until an abrupt transition to a hydraulic jump occurs and overtopping ceases. The high initial splash may be interpreted in terms of high pressures that develop during the impact due to the incompressibility of water as opposed to granular flow. We note the importance of reducing the initial splash to minimize overtopping and shorten the transition to a hydraulic jump state. A row of relatively low, steep braking mounds upstream of an impermeable, steep dam is extremely effective. We find that energy dissipation does not take place at the upstream mound face, but rather downstream from the mounds, due to turbulence. A permeable or partly permeable steep rock dam or a rock berm is also effective to reduce overtopping.

1. INTRODUCTION

Slushflows occur when water-saturated snowpack is mobilized. Slushflows are common in Norway, Iceland, Alaska, other Arctic regions, as well as in Japan, and may become more common in lower altitude Alpine regions, due to global warming. Erik Hestnes at the NGI in Norway has studied Norwegian slushflows for over three decades (Hestnes, 1985, 1998). In a recent paper, Hestnes and Kristensen (2011) identify three types of slushflows, based on the triggering mechanism: 1) Liquefaction of a wet snow slab, 2) release of a slab avalanche into an increasingly wetter snowpack and 3) avalanches into lakes.

The resulting flows may be highly turbulent and travel with steep flow fronts (see Figure 1), much like dam-break floods. Gude and Scherer (1998) studied slushflows in Spitsbergen and North Sweden. They used the Froude number of the flows to distinguish between minor, $Fr < 1$ and larger slushflows or slushtorrents, $Fr > 2$. Wave-like instabilities on the free surface have been observed for flows with Fr close to 1 (surges or roll waves, Sovilla et al., 2012) and more than one release from the same starting zone is common, with the lower part releasing first and the upper part following (Hestnes et al., 2011; Ágústsson et al., 2003b). The speed of large slushflows is generally lower than the speed of dry snow avalanches, which may be due to high basal resistance in the flow track. The flows generally entrain snow, soil and rocks on the way and the flowing mass increases substantially downslope.

Large slushflows may be highly destructive, exerting dynamic pressures on obstacles of the same order as large dry-snow avalanches.

The present study is motivated by the challenge of stopping slushflows above the villages of Patreksfjörður and Bíldudalur in Nortwestern Iceland. Residential houses are threatened by slushflows with volumes of 10–50 thousand cubic meters and both towns have been hit by slushflows from prominent gullies in the mountainsides (Ágústsson et al., 2003a; 2003b). A catastrophic slushflow was released above Patreksfjörður in January 1983, claiming three lives and damaging 16 houses, see Figure 1. Back calculations of flow speeds suggest a speed of the slushflow of 10 to 15 m/s (Jóhannesson and Hákonardóttir, 2004; Gauer, 2004). Channels to direct the flows through the residential area, to the ocean were proposed in earlier appraisal studies (Sigurðsson et al., 1998), thereby splitting the towns in two and removing several houses in the way. The proposals were rejected by the town council due to the undesired impact on the town's appearance. The channel in Patreksfjörður would also have cut access to the hospital from the western part of town, during and after a large slushflow. In 2015, Stefan Margreth of the SLF in Switzerland, was brought in for consulting. He recommended investigating the feasibility of a catching dam as an option for the protection of this part of the town, including detailed studies of the retarding effect of such structures against slushflows (Margreth, 2015). Hestnes and Sandersen (2000) discuss mitigation measures in the track of slushflows. They recommend catching dams to restrict the run-out of slushflows and breaking structures as used for retarding debris flows, for retarding the flows, upstream of the dams. They do not suggest stopping such flows.

Figure 1 A slushflow in Western Norway in May 2010 (Hestnes et al., 2011). A newspaper clip from Morgunblaðið of slushflow-debris in Patreksfjörður, Northwestern Iceland in January 1983.

A few experimental studies on the velocity profile and viscosity of slushflows have been conducted (Jaedicke et al., 2008; Upadhyay et al., 2010). Jaedicke et al. (2008) additionally measured impact pressure on an obstacle in the flow path, measuring the highest pressures as the flow front hit the obstacles. Small scale experimental studies of granular flows have shown similarities between granular flows and shallow water flows and indicate that shallow-water theory may be directly applied to calculate phenomena such as shocks (hydraulic/granular jumps) in the interaction with obstacles (Savage, 1979; Brennen et al., 1983; Gray et al., 2003; Hákonardóttir and Hogg, 2005). Dissimilarities have also been observed in small scale experiments with water. Hákonardóttir and Hogg (2005) report on short-lived water jets moving up obstacle faces in the initial impact, with run-up or splashing exceeding the run-up calculated from energy conservation. This behaviour is not observed to the same extent in impacts of granular flow with obstacles. The difference is ascribed to the incompressibility of water, whereas the granular flow front is dilute and compressible. Similar splashes may be observed in violent and destructive ocean wave impacts on harbour walls, see Figure 2.

Figure 2 Stay away from the seafront: Waves crash against the promenade in Aberystwyth, Wales, as strong winds and high tides continue in western Britain. Taken from the Daily Mail article 2534511.

The goal of the experiments presented in this paper is to identify an engineering design that effectively stops slushflows upstream of an approximately 10 m high catching dam, where a 1–3 m thick slushflow at the speed of 10–20 m/s may be expected (Froude number between 2 and 5). We draw upon experience in the design of dams and mounds for retarding dry-snow avalanches (Jóhannesson et al., 2009) of ocean breakwaters (van der Meer and Sigurðarson, 2017; Bruce et al., 2009; Najafi-Jilani and Monshizadeh, 2017), wave impact theory (Cooker and Peregrine, 1995), and the design of obstacles (baffle/chute blocks) in dam spillways and bottom outlets of hydropower plants to dissipate the energy of the flow (Peterka, 1984).

2. THEORY

2.1 Scaling

The Froude number of a free-surface flow, upstream of an obstacle, is an important dimensionless parameter which is given by

$$Fr^2 = \frac{u^2}{g\,h\,\cos\xi}\,, \qquad (1)$$

where u is flow speed, h is flow depth and ξ is the slope angle. The Froude number is commonly used to scale free-surface fluid flow, if viscous effects are negligible. It measures the speed of the flow relative to the speed of the small-amplitude surface waves. Issler (2003) suggests that for dry-snow avalanches Fr is in the range 5 to 10. We find that the Froude number for large slushflows that may be expected in Patreksfjörður, Northwestern Iceland, is between 2 and 5 on the debris cone, where catching dams may be located (see discussion in section 1).

2.2 Splash

Hákonardóttir and Hogg (2005) observed pressure-induced splash in the initial impact of high Froude number water flows and dams. The splash height may be calculated from pressure impulse by Cooker and Peregrine (1995).

2.3 Energy conservation

The maximum run-up of a snow avalanche on a catching dam has traditionally been determined from point-mass energy conservation (Salm et al., 1990; Rudolf-Miklau et al., 2015).

2.4 Ballistic trajectories

Jets of fluid or granular flows over relatively low obstacles (H/h_1 = 1–5, where H is obstacle height) have in laboratory experiments been observed to follow ballistic trajectories.

2.5 Hydraulic jump

The flow depth for an upstream propagating hydraulic jump may be determined from classical analysis of two-dimensional hydraulic jumps, mass and momentum fluxes are conserved across the jump, but mechanical energy is dissipated (Hager, 1992). The hydraulic jump for flows with Froude numbers between 2.5 and 4.5 is unstable and oscillating. Dissipation of energy flux over the jump is 0.15 to 0.45 (Hager, 1992). Interestingly, the hydraulic jump for flows with Froude numbers between 1.7 and 2.5 is weak with series of small rollers.

3. EXPERIMENTAL SETUP AND DESIGN

Slushflows are a partly-saturated mixture of water and snow, with a range from almost pure water to very wet snow mixed with mud and rocks. We use water to study slushflows, since slush is hard to produce in a consistent manner and scale in the laboratory. By using water, we enhance the difference with granular flows and the interpretation of the results is simplified.

The experimental chute is approximately 9 m long and 1.2 m wide, with a 6 m^3 tank at the upstream end, 1.5 m higher than the horizontal part of the chute, see Figure 3. Water is released from the tank with a quick release valve, to imitate dam break. The system is based on the design of wave simulators, to recreate run-up of ocean waves on flood banks at a large scale (van der Meer, 2001). The valve is 1 m wide and 0.3 m high. Water is released from the tank onto a chute, with obstacles for testing on a level section near the end of the chute, see Figure 3.

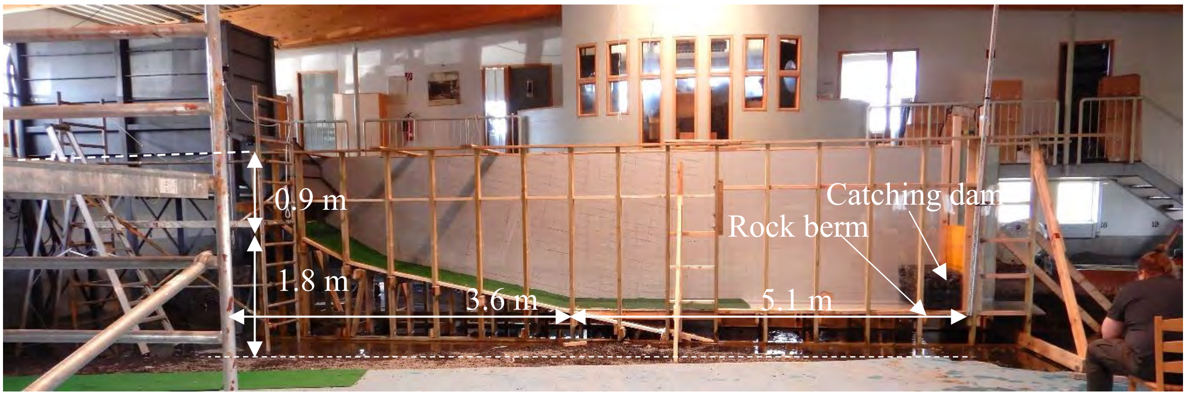

Figure 3 Setup C.6. The experimental chute is 9 m long and 1.2 m wide with a 6 m^3 tank.

3.1 Scaling

The experimental setup was designed based on Froude number scaling of the flow and length scaling of 1:10 (lab.:field), as is common in wave experiments (Bruce et al., 2009) and the following scaling arguments:

Viscous effects: The Reynolds number in these experiments is calculated to be approximately $3{\cdot}10^5$, which is sufficiently high that viscous effects may be neglected.

Froude number: Fr_1 = 3–5, as for large slushflows expected in Patreksfjörður (see section 1).

Flow depth: The flow depth is scaled by a factor of 10.

Dam height: $H_{\mathrm{dam}} / h_2 > 1$, where h_2 is the depth of a stationary hydraulic jump.

Mound height: H_{mound} / h_1 = 2–3, based on experimental results of optimum mound heights in granular flows (Hákonardóttir et al., 2003b; 2003c).

The ratio of the width of the chute to the width covered by obstacles: $B_{mounds}/b_{chute} = 0.5$ and $B_{dam}/b_{chute} = 1$.

Rock size: $D_{\mathrm{field}} = 10\ D_{\mathrm{lab.}}$, where D is the diameter of rocks in the rock dams, to ensure scaling of impact forces vs. weight (horizontal resistance) and void ratio. The rock size scaling is derived from Froude number scaling and the ratio of the force due to dynamic pressure and a resistance force, proportional to the weight of the rocks.

Flow speed: $u_{\mathrm{field.}} = 10^{1/2}\ u_{\mathrm{lab.}}$, derived from the Froude number and flow-depth scaling).

Time: $t_{\mathrm{field.}} = 10^{1/2}\ t_{\mathrm{lab.}}$.

3.2 Dam setup and experimental procedure

In each experiment, the tank is filled up to a depth of 0.9 m and 2.7 m^3 of water released instantaneously onto the chute. The vertical drop from the initial water level onto the horizontal chute section is 2.7 m.

The flow speed on the chute was measured at three locations, upstream of the obstacles as a function of time, using a A-Ott C31 propeller current meter (relative accuracy ±2%). The flow depth was measured visually from video recordings (25 frames/s). Each experiment was repeated three times and captured on video. The volume left on the chute after each experiment was calculated from the depth of the remaining fluid on the chute. The measurements are inaccurate for relatively little overtopping (estimated accuracy ±0.1 m^3).

A catching dam was located at the lower end of the chute. The different dam setups tested are listed in Table 2 and Table 1. Setup A comprises impermeable dams inclined at different angles to the chute (horizontal) between 34° and 100°. Setup C comprises permeable rock dams and/or rock berms. Setup B, entails experiments with mounds upstream of the impermeable dams in setup A.

Table 1 Setup B. Experimental setups of one and two rows of low obstacles (mounds and dams) upstream of an impermeable catching dam.

Setup no.	α_{mounds} (°)	α_{dam} (°)	No. of rows upstream	Description
B.1	90	90	1	One row of mounds + a steep catching dam (A.1)
B.2	90	90	2	Two rows of mounds + a steep catching dam (A.1)
B.3	90	75	1	1 row of mounds + 75° catching dam (A.2)
B.4	90	34	1	1 row of mounds + 34° catching dam (A.4)
B.5	90	90	1	1 low catching dam + vertical dam (A.1)
B.6	90	90	2	2 low catching dams + vertical dam (A.1)

Table 2 Setup A and C. Experimental setups for a single dam at the end of the experimental chute. The dam height is 1 m and $H_{dam}/h_1 = 7–12$. The rock berms and rock dams are 0.5 m thick and span the width of the chute.

Setup no.	α_{dam} (°)	Description
A.1	90	Vertical front face. Control experiment
A.2	75	Typical steep avalanche dam
A.3	60	Steep avalanche dam
A.4	34	Typical soil dam
A.5	95	Overhanging dam, *e.g.* harbour wall
A.6	100	Overhanging dam, *e.g.* harbour wall
C.1	90	1 m high, steep 0.5m thick rock dam, rocks fixed, no back plate (the dam is permeable)
C.2	33 + 90	0.5 m high, 33° berm of fixed rocks on a steep rock dam
C.3	33 + 90	0.5 m high, 33° berm of loose rocks on a steep rock dam
C.4	90	1 m high rock berm on a steep, impermeable dam face (A.1)
C.5	90	0.5 m high, steep rock dam.
C.6	90 + 90	0.5 m high rock berm on a steep, impermeable dam face (A.1)

4. ANALYSIS AND RESULTS

4.1 Chute flow: Experimental setup without obstacles upstream of the dam

The flow on the chute is turbulent and lasts for approximately 9 s. The front is thin, fast flowing and short, see Figure 4. The body of the flow is thicker and slower and remains semi-steady for approximately 1.5 s. The tail of the flow is decelerating and thinning for the remaining 5 to 8 s. The surface of the flow is irregular. The irregularities are characterized by two length scales, a larger scale (order of 1 m) and a smaller scale (order of 0.025 m).

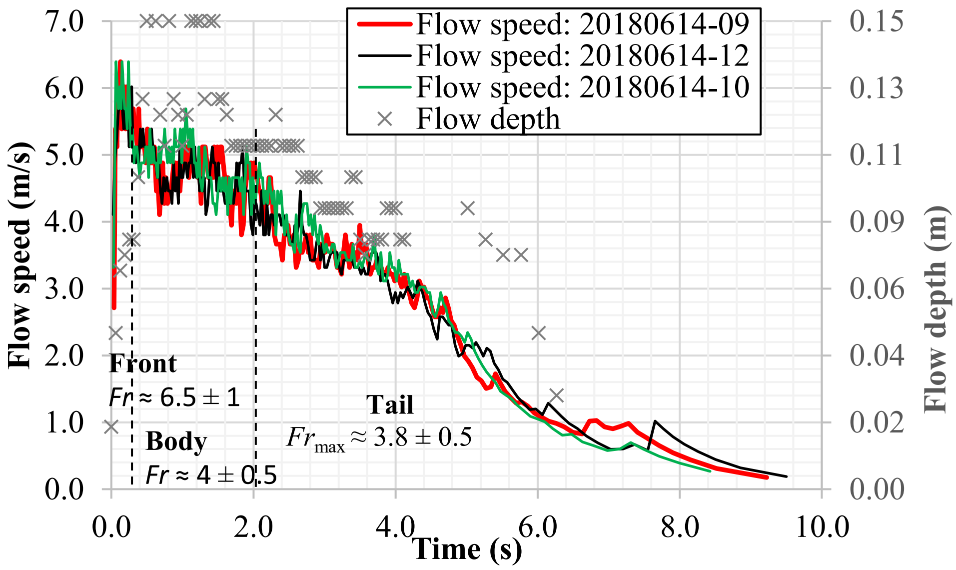

Figure 4 The flow speed and flow depth 0.5 m upstream of the catching dam as a function of time for 2.7 m^3 of water released from the tank and the experimental setup without obstacles upstream of the dam.

4.2 Impact with catching dams: Experimental setups A and C

Photographs of three distinct faces in the impact of the flow with an impermeable dam (setup A.1) and a permeable dam (setup C.1) are shown in Figure 5. Upon impacting the catching dam, the flow splashes high up on the dam face (Figure 5 A). This initial interaction is short lived, typically lasting just 0.06 s, which corresponds to one frame of the video recordings, although the evolution of the splash-up the dam face can be readily followed for 0.7 s. The jet then collapses upon the flow that is moving up the dam face. The run-up is then reduced and a semi-steady fountain that overflows the dam forms and prevails for approximately 1 s (Figure 5 B). These fountains resemble violent wave impacts on ocean walls following the initial splash (see Figure 2). Water continues to pile up at the dam face and the fountain collapses approximately 1.7 s after the initial impact. A hydraulic jump then forms in 0.2 s (Figure 5 C). Splashing over the dam is reduced but is present until the hydraulic jump has propagated approximately 2 m up the chute or over twice its width.

4.2.1 Setup A: Interpretation

The most effective impermeable dam setup in terms of the volume of overflow is setup A.6, with a steeper than vertical dam face. The least effective setup is A.4 with a dam face sloping at 1:1.5 (34° to the horizontal). No difference was observed in the depth of the hydraulic jump for the different setups.

4.2.2 Setup C: Interpretation

The most effective rock dam setup is setup C.1. Setup C.2 with a berm sloping at 34° is least effective and the only rock dam setup with overtopping. The rocks in the berm in setup C.3, become mobilized during the first two flow phases. The rocks had been arranged at the dam face, but were loose, as is common practice for ocean breakwaters. The rock size of 0.1–0.2 m is comparable to rocks of size 1–2 m in the field. Setups C.4 and C.6, with a 1 m and 0.5 m high, respectivly, steep, 0.5 m thick rock layer upstream of a dense, steep catching dam (A.1), yielded similar results as setup C.1.

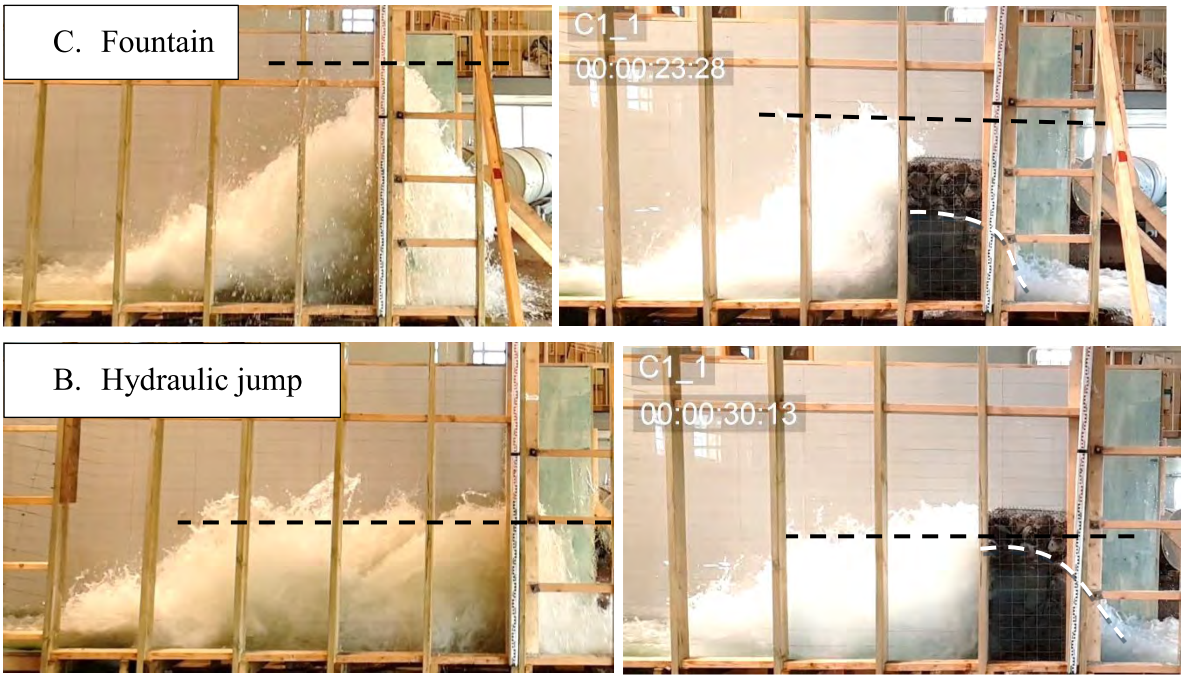

Figure 5 Experimental setup A.1 and C.1. The dashed black lines note the maximum run-up and the dashed white curves enhance the water table in the rockfill. The horizontal grid spacing on the chute is 0.1 m. **A.** Initial splash, approximately 0.6 s from impact. **B.** Fountaining, approximately 1.25 s from initial impact. **C.** Hydraulic jump, approximately 2 s from initial impact.

4.3 Impact with combinations of mounds and catching dams: Experimental setup B

Photographs of three distinct faces in the impact of the flow with two rows of small mounds upstream of an impermeable catching dam (Setup B.2) are shown in Figure 6. A high splash is observed upon the impact with the upper row of mounds. The splash is abrupt, and rises vertically for 0.6 s. The splash collapses over both rows of mounds and also partly upon the upward moving flow and a semi-steady jet is launched over the mounds. The jet lands upstream of the lower row of mounds. A splash is not observed at the lower row of mounds but a jet is formed, smaller than at the upper row. Neither a splash nor fountaining is observed at the face of the catching dam at the end of the chute. Rather a hydraulic jump is formed immediately after the impact.

4.3.1 Interpretation

Setup B.2, with two rows of breaking mounds upstream of the catching dam, is most effective and setup B.4 with a dam corresponding to a construction of loose materials is least effective. Setup B.1, with one row of mounds, is almost as effective as setup B.2 with two rows.

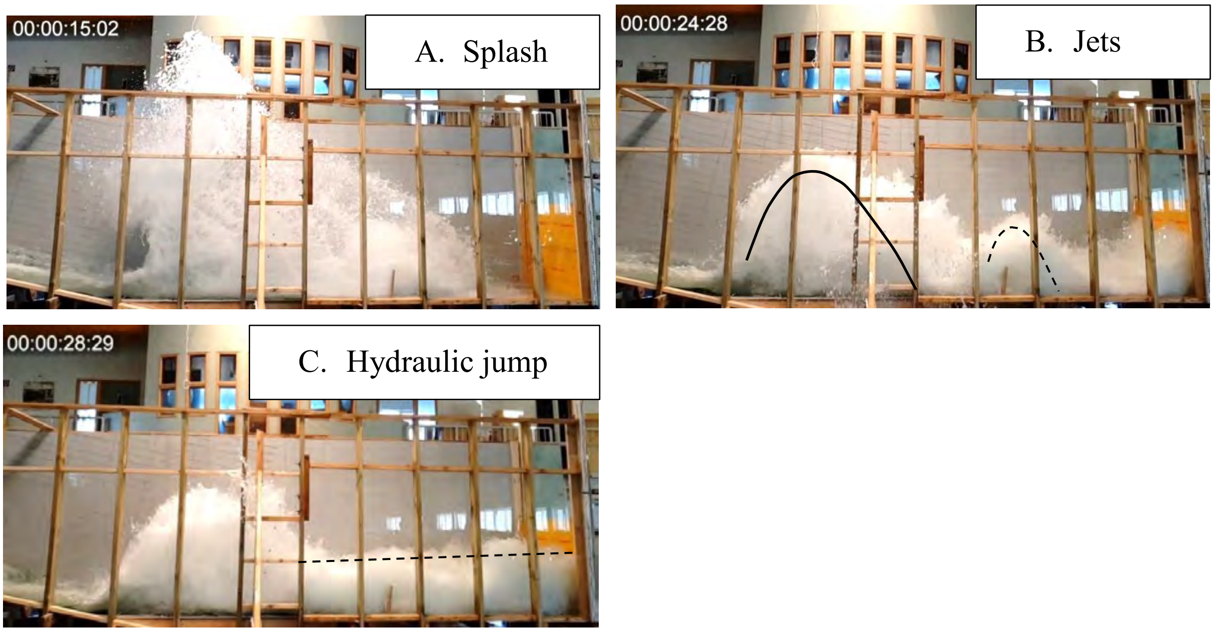

Figure 6 **A.** Initial splash, approximately 0.6 s after the initial impact (left). **B.** Semi-steady flow phase, approximately 2 s after the initial impact. The measured flow speed at the upper row of mounds is $u_1 = 5{,}0 \pm 0{,}25$ m/s. The throw angle, θ is 67° and 71°, at the upper and lower row of mounds, respectively. **C.** Propagation of a hydraulic jump, approximately 2.5 s after the initial impact. The jump has caught up with the lower row of mounds.

5. CONCLUSIONS AND FURTHER STUDIES

The following main results have been observed in the impact of high-Froude number water flow and impermeable catching dams (experimental setup A):

- The initial impact with a dam is violent and a pressure-induced jet shoots up the dam face over twice as high as energy conservation would suggest. This phenomenon is also observed in violent wave impacts with harbour walls.
- The splash collapses after the initial impact and fountaining is observed prior to the onset of a hydraulic jump, approximately 2 s after the initial impact, or 6 s at the natural scale. Overtopping of the dam occurs during this period. The fountain height is comparable with the energy height if no energy is dissipated in the impact with the dam.
- Overtopping decreases with a steeper dam face and is eliminated in the case of a 100° dam face.
- Overtopping may also be reduced or eliminated by reducing the initial splash height at the dam face, with:
  - A row of steep mounds upstream of the dam.
  - A permeable steep rock dam or a steep rock berm at the upstream face of an impermeable dam.

- Impact forces are high enough to move 0.1–0.2 m wide rocks or 1–2 m boulders at the natural scale.

Many questions about the effective design of catching dams to contain slushflows remain unanswered and we raise a few of them here:

- Debris may pile up upstream of dams and mounds in an impact of a slushflow with such defence structures. If a second slushflow is released shortly after, the effectiveness of the protection measures may be reduced. The debris may form a ramp for a secondary release to shoot up.
- Wave-like instabilities or surges and roll waves have been observed in slushflows with Fr close to 1. Those may reduce the effectiveness of dams because of secondary impacts.
- The damping effect of a rock berm may depend on the width of the rock layer that water is ejected through. The width of the rock layer in the experiments was 0.50 m or (2.5–5) D, where D is the diameter of rocks.
- If the voids in a rock dam or a rock berm have filled with ice and snow over the winter, the rock dam will not dampen the initial impact. The slushflow may also fill the voids and reduce the damping effect.
- The observed mobilization of rocks in the berm in experiment C.3 indicates that erosion of mounds built from loose materials by rapidly moving slushflows may quickly reduce or eliminate their effect on the flow, even for large rock sizes. Erosion protection may be an important aspect of the design of slush flow protection measures of this type.

Previous laboratory studies on the impact of granular flows with obstacles, conducted at small length scales (1:100), show granular jumps upstream of catching dams, with a depth readily predicted from shallow-water theory. A substantial difference between granular flows and water flows is, however, observed in the first two impact phases (splash and fountaining):

- A granular splash is hardly observable.
- Fountaining is not observed.
- The transition from the initial impact to a granular jump happens almost instantly, or much more quickly than in water flows.

This difference is ascribed to a dilute flow front of the granular flows that is able to compress considerably, whereas water is incompressible (Hákonardóttir and Hogg, 2005). A difference is also observed regarding energy dissipation in the impact with mounds. In granular impacts, a considerable dissipation of energy occurs at the mound face (Hákonardóttir et al., 2003b, 2003c), which is not observed in water impacts. The mixing of streams from individual mounds and the turbulence during the landing on the chute may account for the dissipation of the energy in the water flows. Air drag may add further to the dissipation at larger scales (Jóhannesson et al., 2009).

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A simple evaluation of dry-snow avalanche hazard using meteorological data

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ABSTRACT

For planning mitigation measures against snow avalanches, the size and frequency of avalanches should be evaluated in a certain region. However, avalanche hazard is not easy to evaluate directly using observed data of avalanche occurrences because long-term data on avalanches is rare. We analyzed snowfall events associated with dry-snow avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of avalanches by approximation of the events to an exponential distribution.

1. INTRODUCTION

The frequency of phenomena that cause natural hazards is an important factor to consider for prevention and protection measures against the phenomena. Current methods for evaluating the frequency of avalanches are as follows: methods directly using long-term data on avalanche occurrences (e.g., Laternser and Schneebeli, 2002; Sinickas et al., 2016), methods of detecting avalanche years from damage and changes remaining in tree-rings (e.g., Decaulne et al., 2012; Corona et al., 2012), methods of estimating the potential conditions for avalanche releases using meteorological data (Jóhannesson and Jónsson, 1996), and methods using the relationship between the total amount of precipitation and the probability of avalanche occurrence (Bakkehøi, 1986). We propose to easily evaluate the frequency of avalanches using meteorological data in a region where long-term data on avalanche occurrences does not exist.

In the frequency analysis, probability distributions of extreme values, such as the annual maximum, are commonly used to ascertain the return period, but complex procedures, such as parameter setting, are necessary for fitting the data to the probability distribution. On the other hand, all values exceeding a certain threshold are sometimes used to evaluate the frequency of phenomena in peaks over threshold (POT) analysis (e.g., Blanchet et al., 2009). In addition, it has been known for a long time that the relationship between the frequency and the magnitude of natural phenomena exceeding a certain threshold could be simply approximated to exponential and/or power-law distributions (e.g., Gutenberg and Richter, 1944). The suitability of exponential and/or power-law distributions for the frequencies of rain events (e.g., Peters et al., 2010) and snow avalanches (Birkeland and Landry, 2002) also has been examined by much previous research. If the approximation could be applied to snowfall events associated with avalanche release conditions, the frequency required to plan prevention measures against avalanches could be easily evaluated using the meteorological data. We analysed the snowfall events associated with the avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of the avalanches by approximation of the events to exponential distribution.

2. METHODS

2.1 Meteorological conditions associated with avalanche releases

For attempting the frequency analysis of snow avalanches using meteorological data, we focused on dry-snow avalanches during heavy snowfall. In particular, avalanche release in forests is one of the characteristic phenomena that occur during heavy snowfall. A typical heavy snowfall event that caused many avalanches occurred in the Kanto-Koshin district on February 14-15, 2014, as shown in Fig. 1a (Izumi et al., 2014). Figure 1b indicates a meteorological condition associated with dry-snow surface avalanche releases in forests as well as other avalanches that occurred during the heavy snowfall (Matsushita and Ishida, 2016). The avalanche releases in forests shown as "●" in Fig.1b occurred in conditions with relative low air temperature and large snowfall amount in a short period of 12 hours compared with other avalanches shown as "×" in Fig. 1b. In addition, conditions associated with avalanche releases in forests, including the results of examination for vegetable and terrain conditions (Matsushita et al., 2018), are summarized as follows:

(1) Snowfall amount S_{12}: During 12 hours, exceeding 45 cm on a slope with inclination of 45° or exceeding 50 cm on a slope with inclination of 30°.

(2) Air temperature T_{12}: mean value during the 12 hours is below -4 °C.

(3) Snow depth SD_{b12}: larger than 50 cm one hour before a period of 12 hours.

We focused on conditions (1)-(3) of dry-snow surface avalanche releases in forests during heavy snowfall and examined the frequency analysis of avalanches using meteorological data.

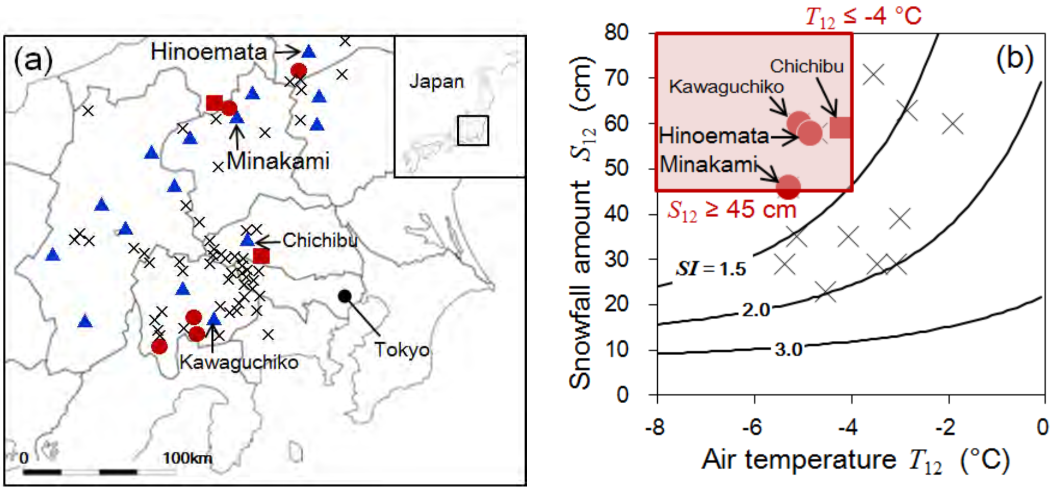

Figure 1 (a) Locations of avalanche releases in forests (●; Matsushita and Ishida, 2016) as well as other avalanches (×; Izumi et al., 2014) during extreme heavy snowfall on 14-15 February 2014. Locations of snow sliding through nets and fences for preventing falling rocks (■) and meteorological observatories of the Japan Meteorological Agency (▲) are also shown. (b) Conditions associated with avalanche releases during the heavy snowfall expressed with maximum snowfall amount S_{12} and mean air temperature T_{12} during 12 hours within snowfall period. Classical stability index *SI* were estimated using S_{12} and T_{12} (Matsushita and Ishida, 2016).

2.2 Selecting the snowfall events associated with avalanche release conditions

To examine the frequency of snowfall events associated with dry-snow avalanche release conditions based on the exponential approximation, we used hourly snow depth and air temperature observed at Minakami (36° 48.0' N, 138° 59.5' E, 531 m a.s.l.) and Hinoemata (37° 00.6' N, 139° 22.5' E, 973 m a.s.l.) where avalanches were released in forests during the heavy snowfall on 2014 (Fig. 1). The data were observed during the periods of 28 winters from November 1989 to April 2017 at Minakami and of 35 winters from November 1982 to April 2017 at Hinoemata by the Japan Meteorological Agency.

First of all, snowfall amount S (cm) was defined as the cumulative value of the positive difference in snow depth each hour. Each snowfall event was regarded as ending when the snowfall ceased (i.e., the hourly difference in snow depth ≤ 0 cm) for more than 5 hours. The numbers of snowfall events n with snowfall amounts S at intervals of 5 cm were counted regarding the cases of snowfall amounts S greater than 30 cm. Dividing the number of events n by the years of observation period provides the frequency of snowfall events $F(S)$ (number of events / year) with snowfall amounts S. In this paper, we used the frequency $F(S\leq)$ based on the cumulative number of snowfall events N from classes of large snowfall amounts at intervals of 5 cm. The frequency $F(S\leq)$ means the occurrence number N of snowfall events per year with snowfall amounts exceeding S cm.

Next, the maximum snowfall amount S_{12} during 12 hours within the period of each snowfall event was calculated and mean air temperature T_{12} during the 12 hours was obtained from hourly data. For evaluating the frequency of snowfall events associated with conditions of dry-snow avalanche releases in forests shown Section 2.1, the events with mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm were discriminated from the snowfall events. Frequencies $F(S_{12}\leq)$ of the discriminated events were calculated in the same manner as that of the snowfall events mentioned above. The frequency $F(S_{12}\leq)$ means the occurrence number N of snowfall events per year with snowfall amounts exceeding S_{12} cm.

3. RESULTS

3.1 Frequency of snowfall events

Figure 2 shows the numbers n and the frequencies $F(S\leq)$ of snowfall events with snowfall amounts S at intervals of 5 cm. The frequencies of snowfall events with snowfall amounts exceeding 50 cm and 100 cm are 2.96 (three times per year) and 0.25 (once per four years) at Minakami, and 4.31 (about four times per year) and 0.74 (once per 1.4 years) at Hinoemata.

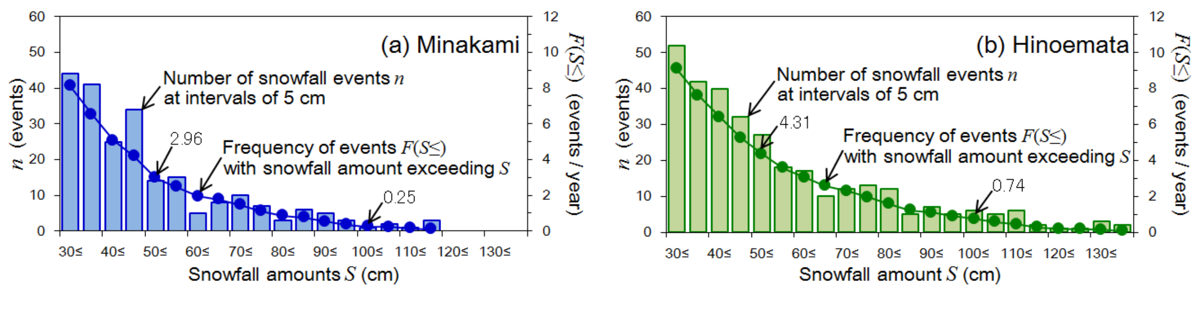

Figure 2 Numbers of snowfall events n (histograms) and frequencies of events $F(S\leq)$ with snowfall amounts exceeding S (solid lines with closed circles) at intervals of 5 cm.

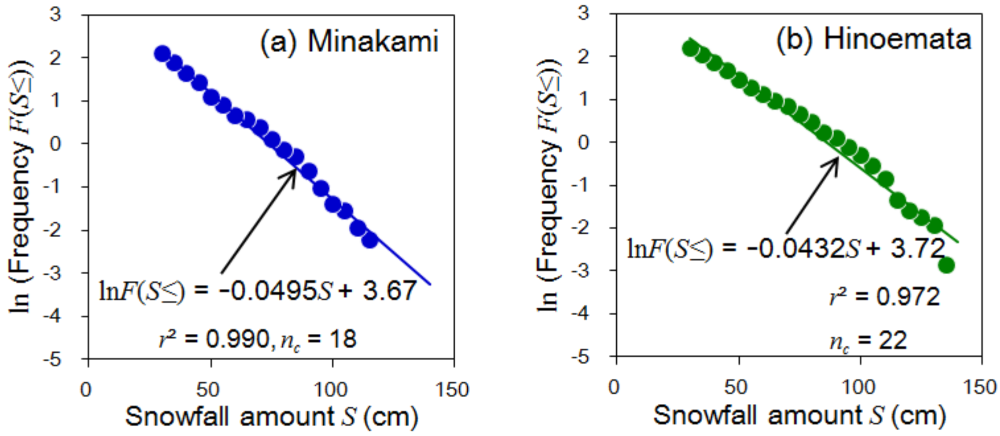

Figure 3 Snowfall amounts S versus the logarithms of frequencies $F(S\leq)$ of snowfall events. The vertical axes are expressed in natural logarithmic scale. Solid lines represent regression lines with coefficients of determination r^2 and number of classes n_c.

Figure 3 represents the relationship between the snowfall amount S and the logarithm of the frequency of snowfall events $F(S\leq)$ with snowfall amounts exceeding S at intervals of 5 cm. The vertical axis of this figure is expressed in natural logarithmic scale shown as "ln". The solid line is a regression line with coefficient of determination r^2 between the snowfall amount S and the logarithm of frequency $F(S\leq)$. The regression analysis indicates a strong linear correlation between the snowfall amount and the logarithm of frequency at a statistically significant level. The frequencies of snowfall events with snowfall amounts exceeding 50 cm and 100 cm that are estimated from the regression equations are 3.30 and 0.28 at Minakami, and 4.76 and 0.55 at Hinoemata. These estimated values agree with the observed values. Therefore, the simple regression analysis with exponential function can be used for evaluating the frequency of snowfall events with snowfall amounts exceeding a certain value.

3.2 Frequency of snowfall events associated with avalanche release conditions

The numbers of snowfall events with mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm are 56 at Minakami and 205 at Hinoemata (Fig. 4). The frequencies of

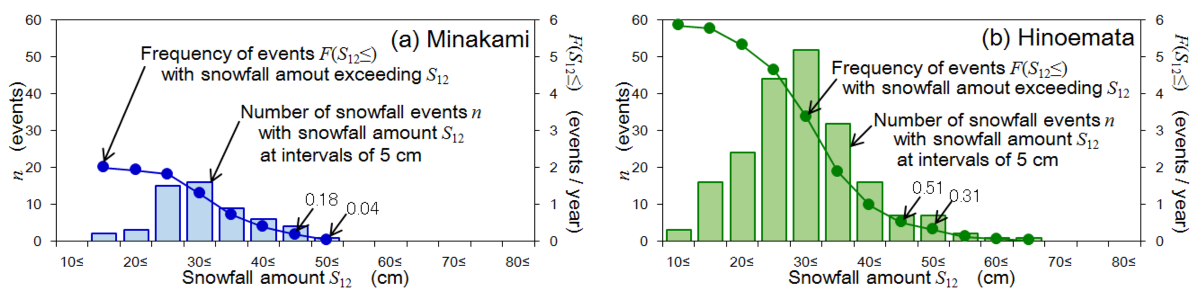

Figure 4 Numbers of events n with the maximum snowfall amount S_{12} (histograms) and frequencies of events $F(S_{12}\leq)$ (solid lines with closed circles) at intervals of 5 cm. The events were selected from the snowfall events shown in Fig. 2 as cases of mean air temperature T_{12} below -4 °C and snow depth SD_{b12} over 50 cm.

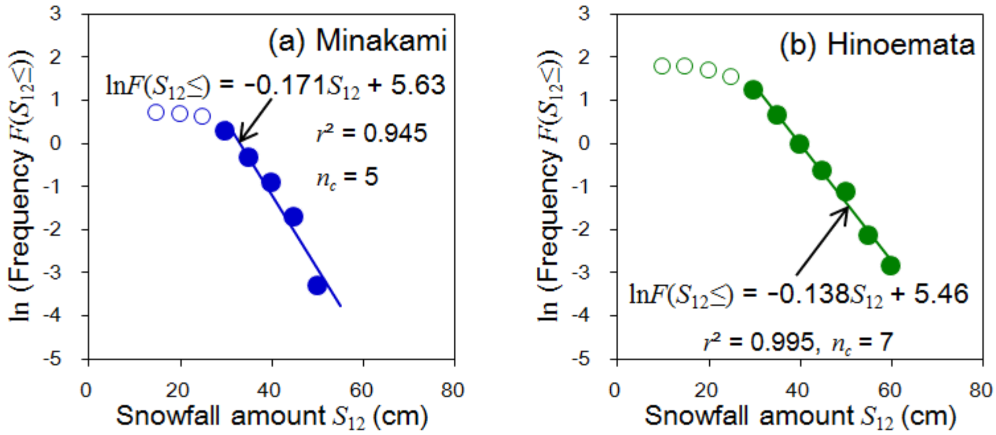

Figure 5 Relationship between the snowfall amounts S_{12} and the logarithms of frequencies $F(S_{12}\leq)$ of snowfall events shown in Fig. 4. Regression equations represented as solid lines were obtained except the events with snowfall amounts S_{12} less than 30 cm (shown as open circles). n_c is the number of classes used in regression analyses.

the snowfall events $F(S_{12}\leq)$ with snowfall amounts S_{12} exceeding 45 cm and 50 cm, which are associated with conditions of dry-snow avalanche releases in forests, are 0.18 (once per 5.5 years) and 0.04 (once per 25 years) at Minakami, and 0.51 (once per two year) and 0.31 (once per three years) at Hinoemata.

Figure 5 represents the relationship between the snowfall amount S_{12} and the logarithm of the frequency of snowfall events $F(S_{12}\leq)$ with snowfall amounts exceeding S_{12} at intervals of 5 cm. Regression lines shown in Fig. 5 were obtained, except the snowfall events with snowfall amounts S_{12} less than 30 cm shown as open circles in the figure. The frequencies of snowfall events with snowfall amounts S_{12} exceeding 45 cm and 50 cm that were estimated from the regression equations are 0.13 and 0.05 at Minakami, and 0.47 and 0.24 at Hinoemata. These estimated values agree closely with the observed values. Therefore, the simple regression analysis with exponential function can be used also for evaluating the frequency of the snowfall events associated with the conditions of dry-snow avalanche releases in forests.

4. CONCLUSIONS

We analysed the snowfall events associated with the avalanche release conditions using meteorological data covering a few decades and evaluated the frequency of the avalanches by approximation of the events to an exponential distribution. Simple regression analysis using the exponential function revealed a strong correlation between the frequency and snowfall amount (i.e., size) of snowfall events at a statistically significant level. Consequently, the exponential approximation can be used in frequency analyses for snowfall events associated with avalanche release conditions. However, avalanche release conditions using meteorological data should be defined to evaluate the frequency of the avalanches in this method.

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Everyday work of an avalanche engineer – Calculation of avalanche loads and protection of small objects in avalanche paths like ropeway towers

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ABSTRACT
The complexity of avalanches especially the interaction with objects like masts or buildings are not sufficiently described in the current guidelines. Therefore, engineers need to utilize scientific approaches or to develop individual solutions. This paper discusses the current Standards for avalanche loads and demonstrates a design of a general avalanche load profile. Furthermore, a special solution of a wedged ropeway tower is shown and approaches towards an improvement for avalanche protection measures for ropeway towers are discussed.

1. INTRODUCTION
Ropeways usually make high alpine terrain accessible and are, thus, frequently built in avalanche prone areas. The towers act as narrow obstacles for the avalanche. The avalanche engineer has to investigate the avalanche hazard and to design a realistic avalanche load profile. The structural engineer has to consider the loads in his calculation in order to make the towers safe against avalanches. However, the complexity of avalanches, especially the interaction of an avalanche with objects like masts or buildings is not sufficiently described in current national guidelines which leads to individual approaches. The main challenge is to find the optimal tower shape which provides a minimum contact area and a maximum cost-effectiveness. One of the major steps in this working process is to draw an avalanche load profile that is as realistic as possible. Furthermore, we developed an optimized tower shape against the avalanche impact.

In this paper, we present our approach resulting from practical experience in a number of ski resorts and daily discussions with other avalanche experts.

2. STANDARDS FOR AVALANCHE LOADS
The Austrian standards for the calculation of avalanche loads on obstacles (ONR 24805) and the Swiss guidelines for the consideration of snow loads and avalanche loads on ropeways (Margreth et al. 2015) are used do distinguish between loads of the gliding snow mass, the dense flow part, the fluidized part and the powder part. The interaction of these different load types and the temporal occurrence are not defined in these standards and must therefore be defined by the avalanche expert.

3. APPROACH TO THE PROTECTION OF ROPEWAY TOWERS AGAINST AVALANCHES/ AVALANCHE LOADS

3.1 Design of a "Realistic" avalanche load profile

Avalanches are dynamic processes with a complex flow behaviour that cannot be described in a simple way. Structural engineers need concrete load specifications of avalanche impacts for the dimensioning of endangered objects. The challenge for avalanche engineers is the transmission of the complex avalanche impact in a realistic, comprehensive and understandable way.

The loads on masts and buildings can be split into the creeping or gliding snowpack, the dense flow part, the fluidized layer and the powder part. Each of these loads is subdivided into different load types (e.g. the dense flow part is divided into the dynamic flow pressure along the flow depth and the flow pressure along the climbing height that decreases linearly). We assume that loads of the gliding snow mass, the dense flow, the fluidized layer and the powder part appear at the same time. Overlapping loads are not added, but the highest load value on each point along the tower is selected (the thick black dashed line in figure 1). With this approach we can provide an avalanche load profile that corresponds to all appearing load types and is applicable for narrow objects like masts as well as for wall-like structures (e.g. buildings). The figure 1 shows the load profile considering all load types.

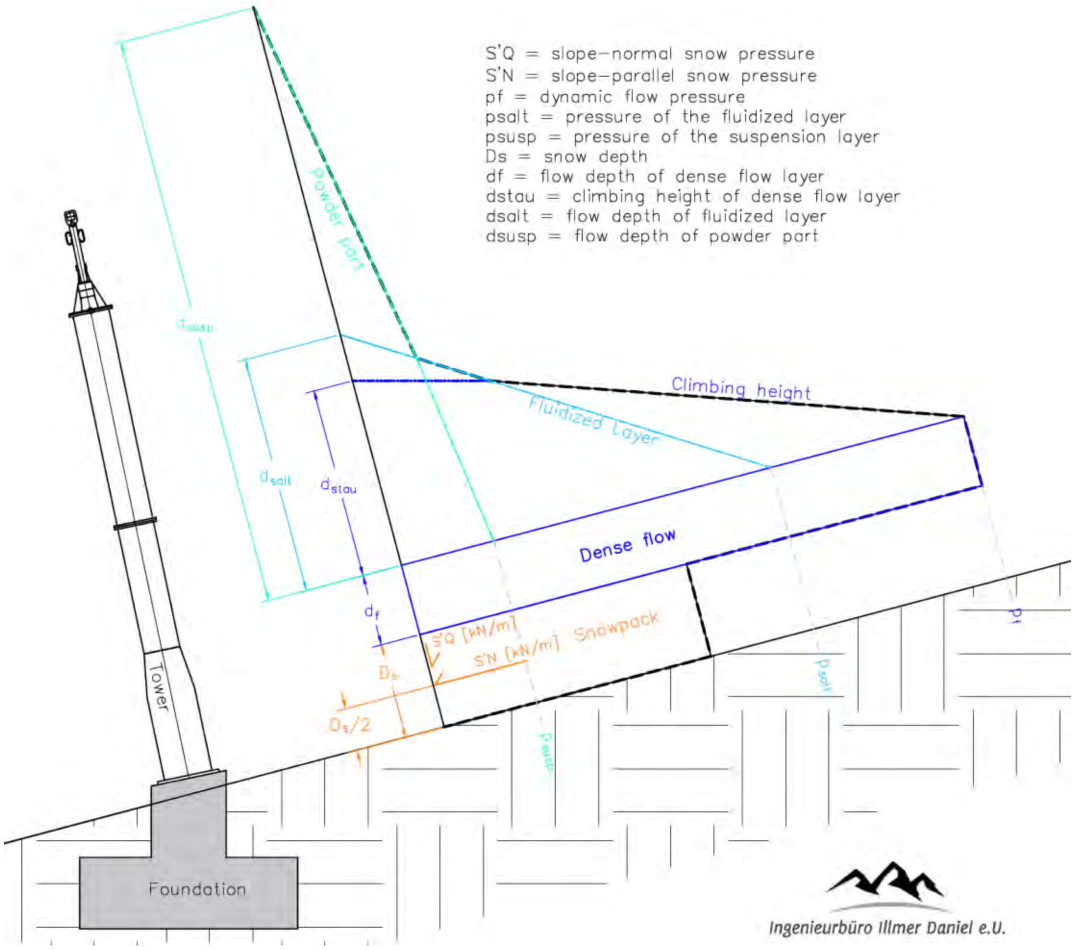

Figure 1 Avalanche load profile on a tower considering all load types (snowpack, dense flow, fluidized layer and powder part)

3.2 Effect of circular cylinder and splitting wedge on avalanche dynamic

The first focus is on the calculation of the climbing height hdyn of the dense flow part on towers that cannot be described realistic with the equations used in practice. The equations in ONR 24805 (2010) for the dynamic flow pressure p_f as for the climbing height of the dense flow part h_{dyn} are the same for circular cylinders and for wedged obstacles.

$$p_f = c_d \frac{\rho_f \cdot v_f^2}{2} \qquad (1)$$

$$h_{dyn} = \frac{v_f^2}{2 \cdot g \cdot \lambda} \cdot f_{b/d_f} \qquad (2)$$

The drag coefficient cd is the same for circular cylinders as well as for wedged objects (cd = 1.5 for the dense flow regime according the recommendations in Jóhannesson et al. (2009) and ONR 24805 (2010)). Equation 2 in ONR 24805 (2010) for the calculation of the climbing height hdyn does not contain any value for the shape of the obstacle and considers just the avalanche type by the variable λ and the obstacle width. Also the slope inclination has not been considered in the equations.

We suppose that the obstacle shape has a crucial influence on the resulting pressure and especially on the climbing height of the avalanche. Equation 2 (climbing height hdyn) results in unrealistic high values for the climbing height in case of high flow velocities. For example a fast avalanche (v_f=25m/s, d_f=1m, cd=1.5) and a narrow obstacle (b=1m) lead to a climbing height of 15m. This seems not to be realistic. Practical observations support our theory that obstacle shape does influence climbing height with lower heights in wedged-shaped object compared to cylindrical objects probably due to a “splitting effect” on the avalanche (figure 2 and 3).

Figure 2 Avalanche impact on a circular cylinder tower. Photo by NGI

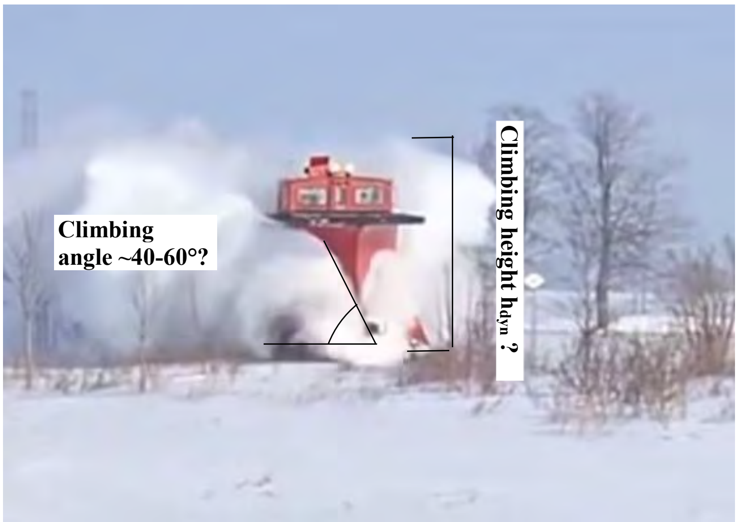

Figure 3 Train with a snow plow in action. TNT Channel – YouTube (2016)

3.3 Optimized design of ropeway towers – "wreath construction"

Ropeway towers usually need to be built in steep terrain in avalanche-prone areas. Our solution for an optimized avalanche protection measure for a ropeway tower is to raise a wedge-like wall around the avalanche exposed side as shown in Figure 4 ("Wreath" construction). The construction material can be concrete, steel or a steel-wood-combination. Such constructions have already be implemented in ski areas.

3.4 Approach for a design of a tower construction based on the shape of the snow plow of the train in figure 3

Figure 5 shows a more complex wedged tower protection which is integrated in the foundation, similar to the form of the snow plow in figure 3. The construction includes a wedge-shaped concrete-shaft with a concrete or steel plate on top. It can be assumed that the avalanche is split by the wedge and climbs up to the level of the energy height. The level of the energy height is reached after the tower. The steel mast of the tower is not reached by the dense flow part of the avalanche. The shaft height above ground must overtop the snow surface, the dense flow height and a safety supplement.

To realize the described approach in 3.3 and 3.4 it is very important that the flow direction is clear, otherwise the wedge acts like a rectangular obstacle.

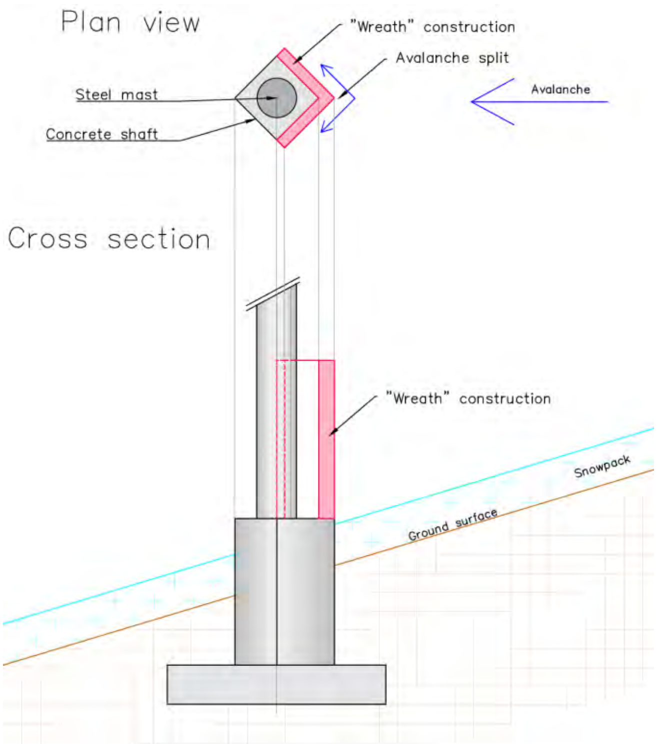

Figure 4 Wedged structure around the avalanche exposed side ("Wreath" construction) on a ropeway tower.

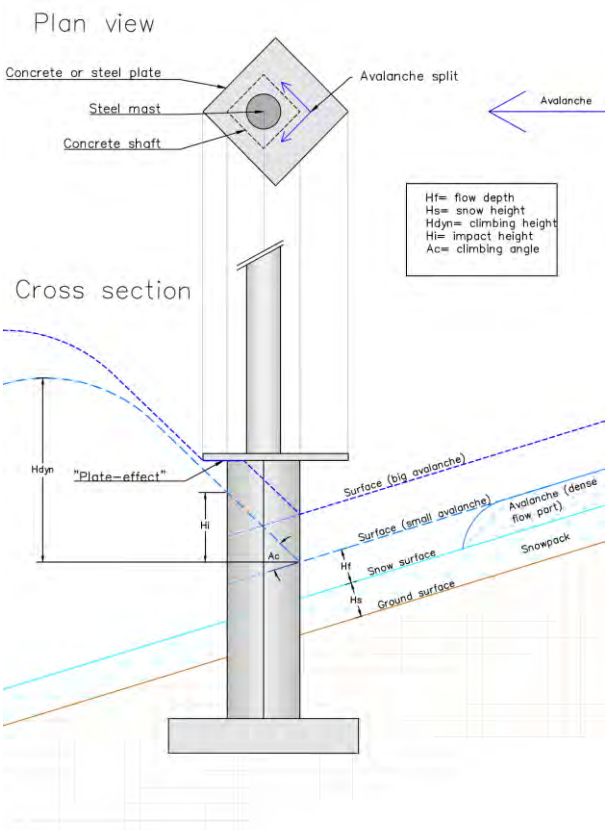

Figure 5 Approach of an improved ropeway tower

4. CONCLUSION

Loads of avalanches can be huge and the interaction with obstacles complex.

Our observations and experiences show that the behaviour of the dense flow part of the avalanche is not the same for circular cylinder as for wedged obstacles. The Austrian and the Swiss guidelines do not distinguish between these obstacle shapes regarding the dense flow regime.

For small objects in avalanche paths like ropeway towers and for high flow velocities we recommend to design the objects as wedged structures and the surface of the wedge as smooth as possible. However, one of the most important requirements to realize wedged structures is a clear flow direction of the avalanche.

The theoretic results and approaches of this paper should be proved with field tests or laboratory experiments. Heil (2017) researched the flow behaviour of snow in a rotating drum. The experiment setting could be adopted by inserting obstacles in the rotating drum. The pressure and the climbing height for different obstacle shapes could be measured.

Field tests could as well be performed on snow-covered lakes. A construction at the front of a snowmobile should constitute obstacles in different shapes: circular cylinder, rectangular and wedge as "narrow obstacles" and walls (straight and inclined) to represent the effect of catching dams and deflecting dams.

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Avalanche warning services as an integrated part of winter road operations in Norway

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ABSTRACT

The Norwegian Public Roads Administration (NPRA) has been one of the partners in the Norwegian Avalanche Warning Service (NAWS) since the service was launched in 2013. NPRA's contributions include both financial support, field observations, scientific review, weather stations, traffic data and near real-time data from instrumented avalanche paths. The strategy for these contributions is the idea that well-executed and documented decision-making at all levels in the organisation, is much more beneficial for safety, accessibility and predictability than just being a passive recipient of a perfect written bulletin.

Since the regional avalanche bulletins became a daily product in 2013, NPRA has developed a number of other activities and processes that ensure seamless data flow between relevant entities and organisations. For instance, a mobile app used by NPRA's road contractors, now transfers data from the snowplow driver to the national team of avalanche forecasters. Local warning services also use the same tools and contributes with local data and hazard evaluations shared with forecasters who are concerned with larger NAWS regions. Radars, geophones and infrasound microphones along the roads are used to detect avalanches. These data are used to send warnings and alerts to road users and operators. Some roads even get automatically closed immediately when avalanches are detected in the release area. In addition, these data are also transferred to the NAWS.

This presentation will give an overview over tools and work processes developed over the last five years. We will focus on the elements that ensures better safety, accessibility and predictability for users of roads prone to avalanches.

Experience and evaluation of reinforced soil systems in catching dams in Iceland 1998–2017

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ABSTRACT

Steep, 10 to 23 m high catching dams, for avalanche protection with an almost vertical wall on the upstream side have been constructed with systems of reinforcing strips or grids and frontal units. A variety of materials, metal or synthetic, or a combination of both, are available for this purpose. Several different systems have been utilized for the reinforced part of the barriers for the past 20 years. A brief analysis was made of the overall performance of the different systems. The focal points of the analysis were the upstream faces and the reinforcement systems with respect to observed durability as observed in 2016, cost, installation procedure (how sensitive the system is to quality of installation and the time needed for installation) and final appearance. It is concluded that the single most important factor in obtaining an acceptable final appearance is the quality of the workmanship of the installation and that project supervision is of great importance. The experience in Iceland does not necessarily have to be transferrable to other countries and locations as conditions vary greatly from country to country.

1. INTRODUCTION

Avalanche dams in Iceland are mainly constructed of fill material from excavations of loose soil/scree material or blasted bedrock at the construction site. The first earth-fill barriers that were constructed after the catastrophic accidents in 1995 were in Flateyri, Nortwestern Iceland. The design was based on a new legal framework on hazard assessment and protection measures from 1997 (505/2000). The design entailed two defecting dams, with a catching dam between them. The first catching dam and braking mounds with a reinforced upstream front were constructed in 1999 above the town of Neskaupstaður, Eastern Iceland. The construction was completed in 2002, soon to be followed by similar structures at Bíldudalur, Seyðisfjörður, Siglufjörður, Bolungarvík, Ísafjörður, Patreksfjörður and Fáskrúðsfjörður, see Figure 1. The number of catching dams built of reinforced fill now stands at 20 at these various locations. Several different systems have been utilized for the reinforced part of the barriers. These systems must be easy and simple to erect, have good compatibility with the existing soils, good durability and an end-product that has a safe and trustworthy appearance. The intended lifespan of the structures is 100 years. The reinforced fill used in almost all the projects to date in Iceland is made of crushed rock. The individual particles of the fill are thus quite sharp-edged.

The Icelandic Avalanche fund and the Government Construction Contracting Agency of Iceland, launched a review program on the dam constructions and experience of the different systems. The results were published in 2016 (Efla et al., 2016). This paper summarizes the results by describing the systems that have been used and the experience gained over the past 20 years.

2. SYSTEMS – SHORT DESCRIPTION

These systems usually consist of two major components; the facing units and the soil reinforcement part. Both components can be made either of steel or synthetic material or both. Concrete can also be utilized for facing units, but has only been used for low guiding dams or

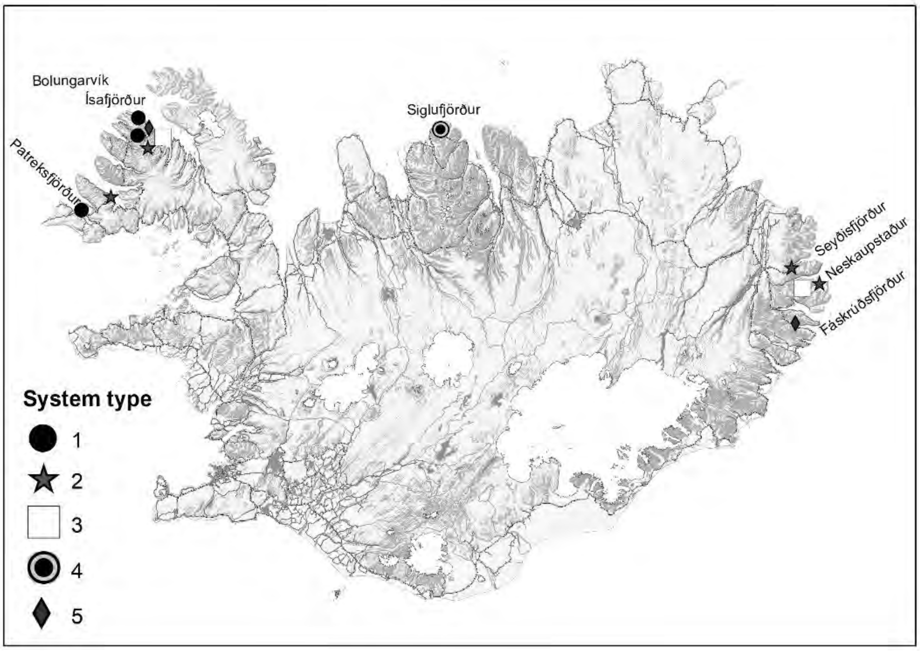

Figure 1 Location of catching dams and braking mounds constructed with steep upstream face in Iceland.

channel walls. Apart from the Siglufjörður barriers, nearly all the dams constructed in Iceland have the similar appearance of a rock wall that is contained by a mesh of heavily galvanized steel. The systems that have been constructed in Iceland are:

1. L-shaped facing units of steel with geosynthetic reinforcements (geogrid) and 0.65 m and 0.8 m high facing units.
2. C-shaped facing units of steel with flat steel strips as reinforcement and 0.5 m high facing units.
3. Flat facing panels of steel with geosynthetic strips as reinforcement and 0.6 to 1.8 m high facing panels.
4. Facing units made of synthetic material with geosynthetic reinforcements (geogrid), with 0.15 m high facing units.
5. Facing units made with wire mesh steel gabions, 1m high, and geogrid reinforcements.

A brief description of each system follows.

2.1 System no. 1

The geosynthetic reinforcement is laid out on a level grade and tensioned, see Figure 2. The L-shaped facing units are placed on top of the geosynthetic reinforcement (geogrid). Guiding rods are placed in front of the panels to secure the placement of the facing units. The stones in the lower half of the front are then placed and subsequently the fill is laid out behind the stones and compacted. A geotextile is placed between the stones behind the facing units and the fill, if needed to fulfil filter criteria. When the reinforced fill has been levelled the upper half of the stones in the front are placed and the next row can commence.

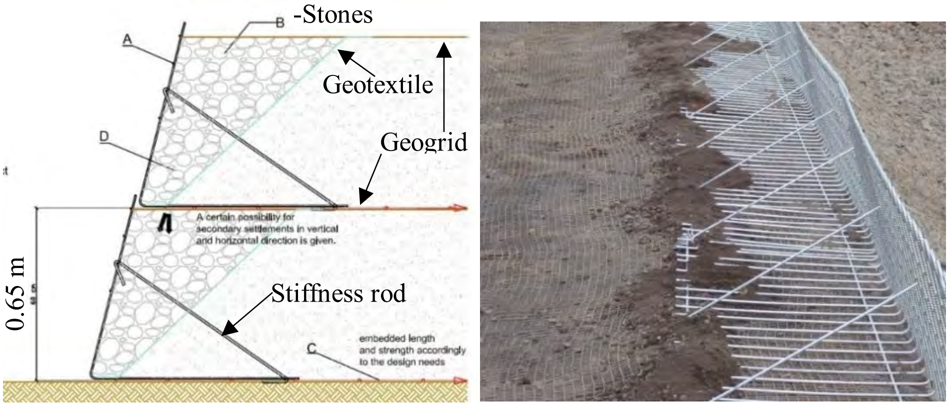

Figure 2 System no. 1: L-shaped facing. A schematic diagram and a photograph during construction in Patreksfjörður

2.2 System no. 2

C-shaped facing units are placed in much the same way as the L-units of system no. 1, on a level grade with guiding rods in front of the units, see Figure 3. Steel strips are then placed on a level grade and connected to the facing units with bolts. The reinforced fill is placed on top of the metal strips extending almost to the front. This stabilizes the system and when the first lift of fill is completed the stones in the front are placed and the next layer can commence. A geotextile is placed between the stones behind the facing units and the fill, if needed to fulfil filter criteria.

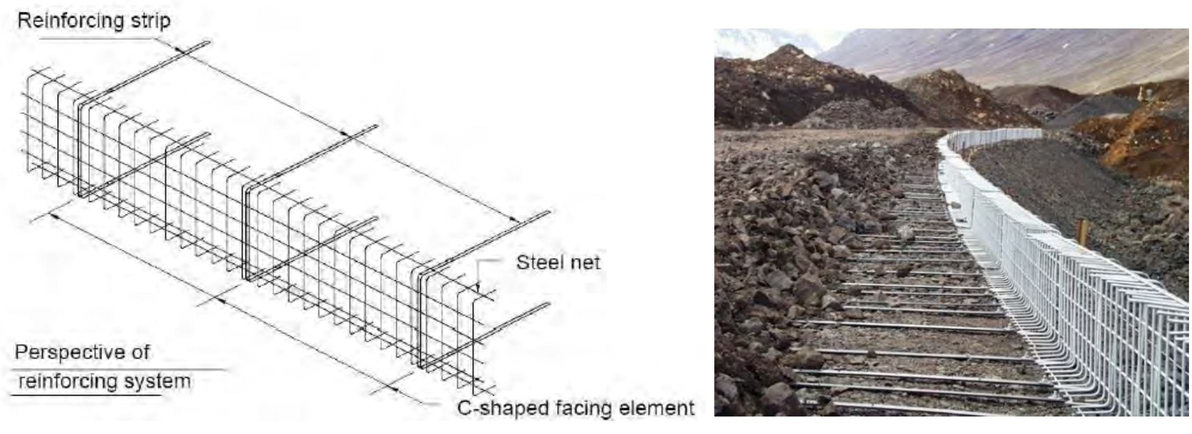

Figure 3 System no. 2: C-shaped facing units. A schematic diagram and a photograph during construction in Neskaupstaður

2.3 System no. 3

Flat facing panels of steel are placed with the aid of a scaffolding system, see Figure 4. Synthetic reinforcement strips are attached to the facing panel utilizing a special metal hook and tensioned. The reinforced fill is placed on top of the straps and the stones subsequently placed at the front. The process is reiterated, and the scaffolding system extended higher up the front face. The flat facing panels are connected using a galvanized metal wire. A geotextile is placed between the stones behind the facing units and the fill, if needed to fulfil filter criteria.

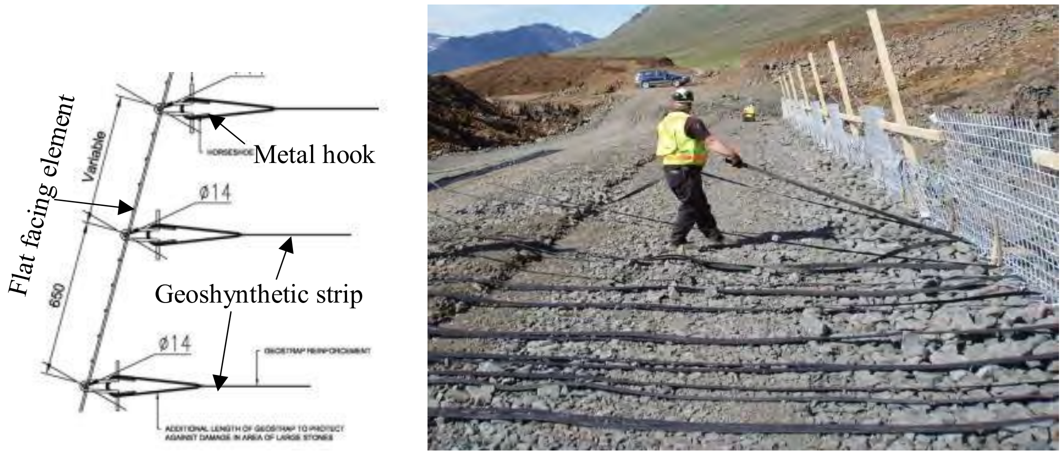

Figure 4 System no. 3: Flat facing panels. A schematic diagram, with units in mm, and a photograph during construction in Neskaupstaður.

2.4 System no. 4

Geosynthetic reinforcement (geogrid) is placed on a level grade and tensioned, see Figure 5. Geosynthetic cells are placed and filled with soil and the reinforced fill placed and compacted behind it up to the level of the cells. This process is then reiterated until the next layer of geosynthetic reinforcement is placed. Mixed fill material with a specified amount of organic material can be used in the front cells to enhance vegetation in these cells. The idea is to cover the steep front face in vegetation by providing favourable conditions for growth.

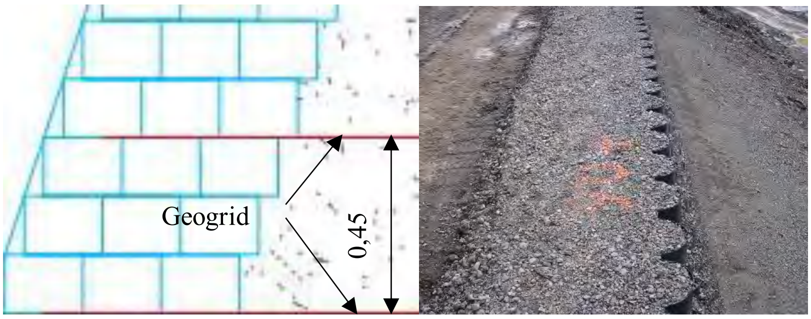

Figure 5 System no. 4: Facing of geosynthetic cells with a vegetated finish. A schematic diagram and a photograph during construction in Siglufjörður.

2.5 System no. 5

Geosynthetic reinforcement is placed on a level grade and the gabion placed on top of it in the front, see Figure 6. The gabion is filled with stones and the reinforced fill placed subsequently on top of the geogrid extending from the back of the gabion. The height of the reinforced fill equals that of the gabion. When the correct height of the fill has been reached the process is reiterated.

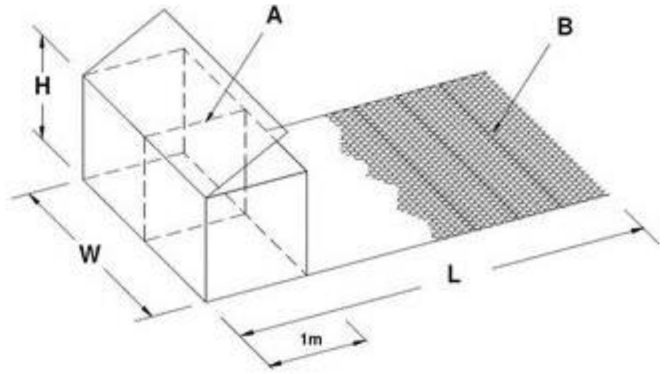

Figure 6 System no. 5: Steel gabions. A schematic diagram.

3. EXPERIENCE IN ICELAND

In total, 20 catching dams have been constructed with steep upstream faces from reinforced earth systems. An overview of the dams constructed with each of the five systems is given in Table 1 and Section 3.1 "Dams constructed with reinforced earth systems" and an analysis of the experience with the different systems at those locations is discussed in section 3.2 "Analysis".

Table 1 An overview of dams constructed from the five earth reinforcement systems.

Village	**Patreksf.**	**Bíldud.**	**Bolungarv**	**Ísaf.**	**Sigluf.**	**Seyðisf.**	**Neskaupst.**	**Fáskrúðsf.**	**Sum**
System no.									
1	1		2[1]	1		2	1[1]	1	**8**
2		1		1			1[1]		**3**
3				4					**4**
4					5				**5**
5				1					**1**
Total	**1**	**1**	**2**	**7**	**5**	**2**	**2**	**1**	**21**

3.1 Dams constructed with reinforced earth systems

[1] catching dam and braking mounds

3.1.1 System no. 1

System no. 1 is shown on Figure 2. It has been utilized at three locations in Western Iceland: Bolungarvík, Ísafjörður and Patreksfjörður and one in Eastern Iceland: Fáskrúðsfjörður, see Figure 1.An example of the final appearance of the system is in Figure 7.

Bolungarvík: The first dam to be constructed was a 22 m high catching dam with 8 pc of 10 m high braking mounds under the Traðarhyrna mountain in the village of Bolungarvík in the Northwestern part of Iceland. System no. 1 was used with 0.8 m high facing units and a wraparound solution for the geogrid reinforcement. Construction commenced in the year 2008. After difficulties at the early stages of the installation the system was redesigned and a third component was introduced. A wire mesh that was placed directly behind the L-shaped facing units that extended longer into the reinforced fill to ensure a secure connection between the facing units and the geogrid reinforcement. The first dam was then followed by a second 12 m high extension using the same solution. Construction of both structures was completed in 2012.

Ísafjörður: A 15–8 m high catching dam below the Kubbi mountain in the village of Ísafjörður some 15 km south of Bolungarvík. Construction work started in 2011 and was completed in 2013. Here, 0.6 m high facing units and the simple solution of the geogrid reinforcement without wraparound was used.

Patreksfjörður: A 12m high catching dam was erected in the village of Patreksfjörður in the southern part of the Westfjords peninsula under the Brellur mountain. Construction started in the spring of 2013 with completion of all work two years later in 2015. The same system as in Kubbi, Ísafjörður, was used.

Fáskrúðsfjörður: A 7.5 m high catching dam was constructed above the town of Fáskrúðsfjördur in the path of Nýjabæjarlækur brook, using the same system as in Bolungarvík. The dam was designed to catch slushflows from the Nýjabæjarlækur ravine and was completed in the year 2014.

Figure 7 System no. 1, on the left, an example of final appearance the Bolungarvík dam. System no. 2, on the right, an example of final appearance of the Fljótsdalur splitter.

3.1.2 System no. 2

System 2 is shown schematically on Figure 3 and an example of the final appearance is on Figure 7. The system has been utilized at three locations in Eastern Iceland: Neskaupstaður, Seyðisfjörður, and in Fljótsdalur and two locations in Western Iceland: Ísafjörður and Bíldudalur.

Neskaupstaður: The first construction completed utilizing this system was the 17 m high catching dam and the 13 pc. of 10 m high braking mounds beneath the Drangagil ravine above the village of Neskaupstaður. This was also the first major construction installed in Iceland using the reinforced earth principle. Construction started in 1999 and was completed in 2002.

Seyðisfjörður: A 20 m high deflecting dam and a 20 m high catching dam were constructed on a plateau at 600 m a.s.l. in the mountain Bjólfur above the village of Seyðisfjördur. Construction started in 2003 and was completed in 2005.

Ísafjörður 14 braking mounds were constructed to supplement a conventionally constructed earth-fill deflecting dam on Seljalandsdalur in Ísafjörður, starting in 2003 and completed in 2005.

Bíldudalur: A deflecting dam was constructed in the year 2005 above the village of Bíldudalur. for protection against slushflows from the Búðargil ravine. The upper half of the dam was steep, constructed with earth reinforcement, while the lower half had the gentle slope of a conventional earth-fill dam (1:1.5; vertical:horizontal).

Fljótsdalur: Additionally, a 11 m high splitter, to protect the transformer station of the Kárahnjúkar HEP from avalanches from the Teigsbjarg mountain, was constructed in the year 2007. This construction was not in the program funded by the Icelandic Avalanche and Landslide Fund.

3.1.3 System no. 3

System no. 3 is shown schematically on Figure 4. It has been utilized at two locations: In Neskaupstaður and in Ísafjörður. An example of the final appearance is on Figure 8.

Neskaupstaður: A 18 m high catching dam and 23 pc. 10 m high braking mounds were constructed under the Tröllagil ravine in Neskaupstaður Construction started in 2010 and was completed in 2013.

Ísafjörður: Four up to 12 m high catching dams were constructed below The Gleiðarhjalli mountain-plateau above Ísafjörður village. Construction started in 2014 and was completed in 2016.

Figure 8 System no. 3 – an example of final appearance in Ísafjörður.

3.1.4 System no. 4

System no. 4 has only been used at one location in Iceland, above the village of Siglufjördur in the northern part of Iceland. The system is shown schematically on Figure 5 and an example of the final appearance is on Figure 9. Five catching dams with a total length of approximately 2.5 km and up to 15 m high were constructed above almost the entire village. The construction project started in the year 2003 and was completed in 2008.

Figure 9 System no. 4, on the left, an example of final appearance in Siglufjörður. System no. 5 on the right, an example of final appearance in Ísafjörður. The fill material is rounded gravel.

3.1.5 System no. 5

System no. 5 is shown schematically on Figure 6. It has only been utilized in one project. It was an 8 m high splitter that was constructed to protect an incineration plant at the outskirts of Ísafjörður village. The splitter was designed for a 50 years lifespan, which is shorter than the expected 100 years lifespan for dam above residential settlements. The construction took place in 2002, see Figure 9.

3.2 Analysis of performance of the reinforcement systems

A brief analysis was made of the overall performance of the different systems and the construction process of the projects that were associated with each solution. The focal points of the analysis were the upstream faces and the reinforcements systems with respect to observed durability as observed in 2016, cost, installation procedure (how sensitive the system is to quality of installation and the time needed for installation) and final appearance.

3.2.1 Final appearance, durability of facing units and installation procedure

The analysis indicates that the final appearance of the steep upstream front is mainly dependent on the quality and thoroughness of the construction work, and also, but to a smaller degree on the height of the facing units and height of the structure but dependency was not linked to the type of fill material used. This underlines the importance of a high quality on site supervison on the installation.

For system no.°2, because of it᾿s stepped nature and the stiffer facing units, bulging is almost non-existent, and all discrepancies are easier to accommodate.

All of the systems may give a satisfactory appearance if craftsmanship during construction is good. System no. 4 stands out for it's welcoming green appearance.

Systems no. 1 and 3, using metal facing units, rely on more flexible units in the front than system no. 2. Therefore, bulging and other discrepancies in the evenness of the upstream face are more prominent. Because of the less stiff nature of the systems these are more dependent on the quality of the installation work. However, in system no. 1 where the wiremesh was also included the final appearance was quite satisfactory, but the durability of the wiremesh remains uncertain and the added installation time is a drawback.

For system no. 1 the surface of each layer has to be levelled carefully in order to properly align the facing units in each layer. To achieve this a thin layer of much finer material must be placed. This requires the introduction of a geotextile between the stones in the front and the much finer adjustment layer. The geotextile has to be placed very carefully and with good workmanship otherwise the outwashing of the finer material can increase deformations and compromise the structural integrity of the front.

3.2.2 Durability and cost of the reinforcement strips or grids

As mentioned above the reinforcement systems being used in Iceland are either steel strips or geosynthetic materials, either geogrids or polyester strips, or a combination of both, with a steel wiremesh and geogrid. The steel has the advantage over the synthetic material in the way that more information has been gathered through the centuries on the behavior of steel under various conditions such as weather, corrosion and icing thus making it easier to design for a given life-span than the more recently innovated geosynthetics. However, the steel is more costly than the synthetic materials.

The synthetic materials are more suitable in aggressive environments, such as saline conditions. The reinforced fill used in almost all the projects to date in Iceland is made of crushed rock. The individual particles of the fill are thus quite sharp-edged. This requires higher safety factors on the synthetic materials. The response of the synthetics to weathering and constant freeze and thaw cycles remains unknown.

It has been noted that the fill material used for reinforced fill in the projects in Iceland is coarser than the systems are designed for. This will influence the synthetic reinforcement in a negative way and can also damage the galvanization on the steel strips.

4. CONCLUSIONS

The experience in Iceland of use of reinforced earth systems for steep high upstream fronts in catching dams and braking mounds for avalanche protection has been briefly described. The systems that have been used are of various nature and have both advantages and disadvantages. It is concluded that the single most important factor in obtaining an acceptable final appearance is the quality of the workmanship of the installation and that project supervision is of great importance. The experience in Iceland does not necessarily have to be transferrable to other countries and locations as conditions vary greatly from country to country.

ACKNOWLEDGEMENT

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Observed changes in hydrology downstream of large earth-fill dams in Iceland. Lessons learned

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ABSTRACT

Most avalanche defence dams in Iceland are built as earth fill dams. The defence structures are constructed from excavations of loose soil/scree material or blasted bedrock upstream of the dams. The excavation areas may extend up to 50 m horizontally upstream of dams and cut 5–15 m into the upstream slope. Their function upstream of catching dams is to create a deceleration area for avalanches and catch avalanche debris stopped by the dam. Upstream of deflecting dams they serve as a run-out area to the side of the protected area and sometimes into the sea. The dams may be up to 25 m high and a 1000 m long, with lee sides stretching down to back yards and plots of the closest residential houses. As a result, natural streams may need to be combined into fewer and larger streams and routed directly to the sea, as the existing infrastructure may not be not able to handle the increased flow. Furthermore, groundwater streams from the hillside above open into the excavation pit, rather than following the loose hillside material or bedrock to the sea. These macroscopic changes in the landscape, upstream from residential areas and towns, have turned out to affect various aspects of the downstream hydrology, such as groundwater levels, discharge in streams that are relocated or combined, discharge in existing streams and response times for runoff into back yards next to steep lee sides of dams. The excavation areas upstream of catching dams can be used for temporal damping of precipitation peaks. However, debris flows, that are a common occurrence during peaks in precipitation, may fill up the storage area upstream of dams and reduce the capacity of culverts through the dams. These issues will be discussed in some detail, examples analysed and recommendations given for future dam design.

Using data from automatic snow sensors for avalanche forecasting in Iceland

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ABSTRACT
Real time data on weather and snow conditions are essential for avalanche forecasting. The timing and size of an avalanche depends on the amount of snow in the starting area, the stability of the snow as well as the triggering factor. Therefore, snow data directly from avalanche starting zones are a useful input to avalanche forecasting.

The avalanche forecasting team at the Icelandic Meteorological Office has relied on snow depth data from different types of snow depth sensors installed in avalanche starting zones for over 20 years. Since 2006, SM4 snowsensors have been tested and used as an important part of the avalanche forecasting system. The SM4 snowsensor was developed by a small innovation company in Ísafjörður, Iceland, POLS Engineering. The idea was to create a simple, robust instrument that could easily be installed within or close to avalanche starting zones. The SM4 consists of a 3 m cable with thermistors mounted at 20 cm interval on a wooden or fiber post and it uses the GSM system to transfer data. The raw output is a temperature profile, and based on that, an algorithm calculates snow depth in real time. The temperature profile within the snowpack is also of value for avalanche forecasting, since the metamorphism of snow crystals depends on the temperature gradient. Steep gradient indicates formation of facets within the snow cover, and facets are a common form of a weak layer in the Icelandic snowpack.

In the presentation, we will introduce the SM4 sensor and explain how the data are used for avalanche forecasting.

Society and environment in the context of changing climate in Arctic regions

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ABSTRACT

Municipalities in the Arctic regions have been facing dramatic changes in the climate over the last 30–40 years. The Barents region including the Svalbard archipelago has experienced the strongest warming of all Arctic communities. Climate models indicate that the warming trend will continue. In addition, in response to predicted increase in middle- and high-latitude annual precipitation, the freshwater availability may increase in the Arctic in the future. Changes in type of precipitation, its seasonal distribution, timing, and rate of snowmelt represent a challenge to municipalities and transportation networks subjected to flooding and droughts and to current industries and future industrial development. A reliable well-distributed water source is essential for all infrastructures, industrial development, and other sectorial uses in the Arctic. Fluctuations in water supply and seasonal precipitation and temperature may represent not only opportunities but also threats to water quantity and quality for Arctic communities and industrial use. The impact of future climate change is varying depending on the geographical area and the current state of infrastructure and industrial development. Longyearbyen in the Svalbard archipelago was struck by two avalanches recently with two fatalities. The authorities are now planning mitigation measures such as supporting structures and barriers. Several challenges are facing authorities and consultants involved in designing new infrastructure, snow avalanche and land slide protection structures under climate warming scenarios. This presentation will discuss the main challenges for Arctic engineers engaged in future infrastructure development.

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Adjusting for uncertainty when combining runout estimates for extreme snow avalanches

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ABSTRACT

Many developments in or near snow avalanche terrain require a high-confidence estimate of dense or powder avalanche runout distance for a specified return period. In Canada, this runout is typically estimated along the centerline of the path using up to four sources: occurrence records, trim lines in vegetation, statistical runout models, and indirectly calibrated dynamic models. The uncertainty in the estimated runout distance and return period for each of these sources can vary. The proposed two-step method is largely a formal version of often undocumented methods traditionally used by some avalanche practitioners. First, each of the runout estimates is adjusted for the specified return period using models or expert knowledge. Second, each adjusted estimate is numerically weighted based on the practitioner's confidence in the estimate. Estimates with greater uncertainty are assigned lower weight according to the practitioner's lower confidence in the estimate. The combined runout estimate is the weighted average. Should substantial uncertainty remain that the runout will be exceeded for the specified return period (e.g. due to fewer runout estimate sources), a safety margin can be added. These steps in obtaining a high-confidence estimate of extreme runout distance can be documented in the report. A worked example is presented.

1. INTRODUCTION

Avalanche hazard and risk maps as well as some infrastructure planning projects require that impact pressure and hence velocity be well estimated in the runout zone of the avalanche path. The velocity in the runout zone is best obtained from an avalanche dynamic model fitted to a high-confidence runout (i.e. the design runout) for the return period required for the project and situation (e.g. $T = 300$ years). This design runout is commonly obtained by combining extreme runout estimates from various sources.

Up to four largely independent sources are available to estimate extreme runout in an avalanche path: occurrence records, trim lines in vegetation, statistical runout models, and indirectly calibrated dynamic models (Canadian Avalanche Association, 2002, p. 13-15; Canadian Avalanche Association, 2016, p. 25-28). Traditionally, some Canadian practitioners calculated the average of the runout estimates from these different sources, excluding the estimates in which they had low confidence. Some reports listed the sources used and then stated the design runout without explaining how it was obtained.

This paper describes a more transparent – and arguably improved – process for combining the runout estimates from different sources based on Jamieson and Campbell (2018). First, the time scale of each source is considered, and the corresponding runout estimate is adjusted to the design return period. Second, each adjusted estimate is numerically weighted based on the practitioner's confidence in the estimate. Adjusted estimates with greater uncertainty are assigned lower weight according to the practitioner's lower confidence in the estimate. The design runout – to which a dynamic model can be fitted – is the weighted average of the adjusted estimates.

Margreth (2014) and likely others have been previously mentioned numerical weighting of runout estimates. Referring to runout estimates from dynamic models, he proposed that for simple hazard situations in Switzerland that are similar to the paths used to calibrate the dynamic model, the weight applied to the estimates could be as high as 0.8. The weight would decrease to zero for complex hazard situations, especially when the model results do not fit observations or expert judgment. In North America, where statistical runout models are often used as a source of runout estimation, the weight applied to the statistical estimates would decrease similarly where the terrain and snow climate differ substantially from the paths used to calibrate the statistical models.

For many avalanche paths in Canada, extreme runouts from vegetation damage obtained from field surveys and air photos are – when available – of low uncertainty (i.e. good confidence), followed by statistical runout estimates for which uncertainty is typically moderate (i.e. fair confidence). Runouts from indirectly calibrated dynamic models are often of high uncertainty (i.e. poor confidence).

2. METHOD

As part of a book chapter, Jamieson and Campbell (2018) described the following two-step process of confidence-based weighting of runout estimates from different sources.

2.1 Step 1: Adjusting the runout estimates from each source to the relevant return period

Extreme runouts for a specific return period are often estimated based on four largely independent sources (e.g. Canadian Avalanche Association, 2002; Bründl and Margreth, 2015):

(1) Written (or sometimes oral) records of long running avalanches. In North America, the farthest recorded runout is typically extrapolated to adjust the runout to the design return period. This approach can be based on a single runout during an observation period that is often substantially shorter than the design return period. Alternatively, the runout for the design return period can be estimated by linearly regressing binned runouts on ln T, as described in Jamieson and Gould (2018). In this method, many runouts influence the regression and hence the predicted runout for the design return period.

(2) Vegetation damage identified in historical air photos, satellite imagery and field studies. Where avalanche runouts extend into forests in Canada, the trim line farthest down the path typically represents the runout of a dense-flow avalanche within the previous 50+ years. While the extent of the runout (trim line) is often measurable with low uncertainty, extrapolation of a single runout with a short time scale (e.g. 50 years) to a substantially longer return period (e.g. 300 years) may be required.

(3) Statistical models of extreme runout based on paths in the same mountain range (e.g. Lied and Bakkehøi, 1980; McClung and Mears, 1991). The return period for the paths used to calibrate the models is often 30 to 100 years. If the return period for the project is longer (e.g. 300 years), the runout estimate can be increased based on expert

judgement. Alternatively, where the return period can be estimated at a reference point in the runout zone, the runout for the design return period can be estimated using McClung's (2000) Space-Time model, which has been validated by Sinickas and Jamieson (2016).

(4) Indirectly calibrated dynamic models of extreme avalanches. Some of the older 1-dimensional models such as PCM (Perla et al., 1980) and PLK (Perla et al., 1984) yield runout estimates for a nominal return period of ~100 years. The runout can be adjusted with expert judgement for other return periods relevant to the project. Some of the input parameters for models such as AVAL-1D and RAMMS (Christen et al., 2002, 2010) have been published for specific return periods (WSL-SLF, 2005, 2017); if these are used, the predicted runout will not require adjustment.

2.2 Step 2: Combining the runout estimates based on the practitioner's confidence in each estimate

In this step, each adjusted runout is numerically weighted based on the uncertainty in the estimate, which depends on the situation, time scale of the runout estimate, and estimation method (e.g. vegetation damage, statistical model). Estimates with greater uncertainty are assigned lower weight wt_i according to the practitioner's lower confidence in the estimate. These are then combined to yield the confidence-weighted average runout (i.e. design runout) ro*:

$$\mathrm{ro}^* = \sum_i \mathrm{wt}_i \mathrm{ro}_i \,/\, \sum_i \mathrm{wt}_i \qquad [1]$$

When there are limited sources of runout estimates or all of the runout estimates lack good confidence, an "uncertainty buffer", often of 20 or more meters can be added to ro* based on expert judgment. Alternatively, a dimensionless uncertainty factor, say 1.1 could be applied to increase ro* past the reference point by 10%.

The uncertainty in the runout estimates from indirectly calibrated dynamic models warrants explanation. These models are considered indirectly calibrated because they are not fitted to an extreme runout in the path under consideration. The runouts predicted by such models depend strongly on input parameters, specifically on friction coefficients and for some models, on the release mass (or average release depth). These input parameters strongly influence runout but there has been little calibration of input parameters in Canada (Buhler et al., 2018). In western European countries such as Switzerland, some of the important input parameters have been calibrated by region and return period for the 1-dimensional model AVAL-1D (Christen et al., 2002; WSL-SLF, 2005). Also, for the 2-dimensional RAMMS model (Christen et al., 2010), the friction coefficients have been calibrated based on elevation, slope angle, slope curvature, flow volume and return period (WSL-SLF, 2017).

3. WORKED EXAMPLE OF ESTIMATING DENSE-FLOW RUNOUT

This section outlines a worked example for the dense-flow runout along the center-flow of hypothetical Path A for a 300-year return period.

It is helpful to select a reference point for the runouts along the centerline of the runout zone. In this example, the reference point is the β point where the slope angle decreases to 10° (Lied and Bakkehøi, 1980), so ro is the horizontal distance of the runout past the β point. When the runout estimate is towards the start zone from the reference point, ro is negative.

For Path A, horizontal runout estimates for various sources are shown in Fig. 1.

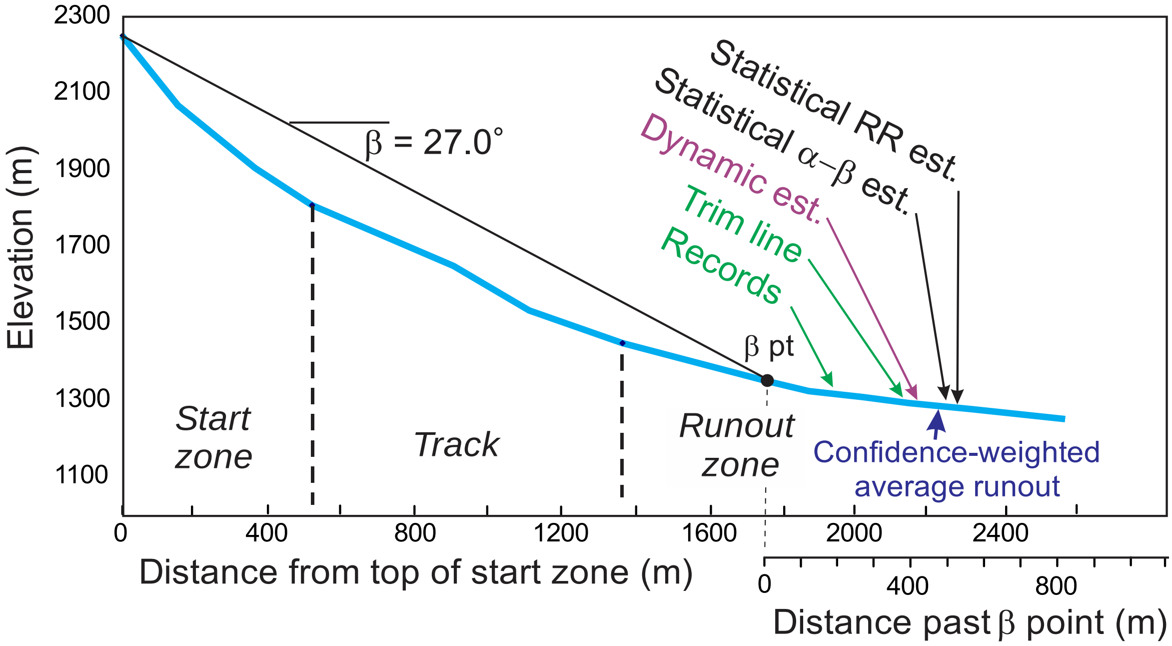

Figure 1 Hypothetical example of unadjusted dense-flow runout estimates from different sources along the centerline of an avalanche path (blue line): longest recorded runout (records), farthest vegetation damage (trim line), indirectly calibrated dynamic model and statistical models (α–β and Runout Ratio (RR)). These estimates are combined to determine the confidence-weighted average runout from a dense-flow avalanche ro* for the design return period.

The runout estimates from Fig. 1 are also given in Table 1 column 2 along with the associated time scale (column 3), which is either the return period for model estimates, or the elapsed years for the written or vegetation records. The ordinal ratings of confidence for each runout are shown in column 4. The numerical weights, wt_i, in column 5 are assigned by the practitioner based on the ordinal ratings of confidence in column 4. In this example, the weights range from 1 to 10 but other ranges of nonnegative numbers are acceptable since Eq. 1 is normalized by the sum of the weights.

In the written records of occurrences observed over 25 years, the longest runout is 200 m past the β point. The practitioner estimates that the 300-year runout would be 150 m farther, which is of poor confidence (wt = 1) since the observation interval is only 25 years long.

The forest damage (trim line) farthest along the path is 390 m past the β point. The trees just upslope of this are about 65 years old. The estimated 300-year runout is 70 m farther, which is of good confidence (wt = 10).

The α−β (Lied and Bakkehøi, 1980) and Runout Ratio (McClung and Mears, 1991) statistical methods yield runout estimates 490 and 515 m past the β point. The estimated 300-year runouts are 40 m past the runouts predicted by each of the two models. These are of fair confidence and each is assigned a weight of 3, giving these runout estimates less combined weight as the farthest forest damage and more weight than the dynamic model or the limited occurrence records.

Table 1 Dense-flow runout estimates along centerline of Path A and confidence levels for runout estimates and associated time scale. The column numbers are cited in the description of the weighting process in the text.

Column number					
1	**2**	**3**	**4**	**5**	**6**
Source of runout estimate	**Horizontal distance past β point (m)**	**Time scale: return period or elapsed time (years)**	**Confidence in runout for design return period**	**Weight wt_i**	**Horizontal distance past β point (m) ro_i (T ~300 year)**
Written records	200	25	Poor	1	350
Farthest forest damage from field survey and air photos	390	~65	Good	10	460
Statistical α–β model [a]	490	30 to 100	Fair	3	530
Statistical Runout Ratio model [a]	515	30 to 100	Fair	3	555
Dynamic model for dense-flow with friction coefficients	410	~100	Poor	1	440
Confidence-weighted average 300-year dense-flow runout					480

[a] To be conservative, especially for paths expected to run relatively longer than the paths used to calibrate the model parameters, a non-exceedance probability > 0.5 can be applied.

The indirectly calibrated dynamic model with a nominal return period of 100 years predicts a runout 410 m past the β point. The estimated 300-year runout is 30 m farther along the runout zone. Confidence is poor (wt = 1) because these models are sensitive to the inputs including the friction coefficients and release mass (or average release depth).

Using Eq. 1, the weighted average 300-year runout for dense-flow avalanches ro* is calculated to be 480 m past the β point. This can be used to *directly calibrate* a dense-flow dynamics model, which will yield a high-confidence estimate of velocity at any point in the runout zone.

Sections like this one can be included in reports to increase transparency.

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Interaction of granular avalanches with obstacles and topography

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ABSTRACT

Snow avalanches are strongly influenced by the basal topography that they flow over. In particular, localized bumps or obstacles can generate rapid changes in the flow thickness and velocity (shock waves) that dissipate significant amounts of energy. Understanding how avalanches flow over or around obstacles is therefore very important for the design of catching or deflecting dams. Even the flow over a smooth bump is not as simple as one might expect. At steady state the flow can detach from the obstacle and form an airborne jet, or it can stay attached to the bump by forming an upstream shock. Multiple steady states also form in the oblique flow past a wedge, with either a weak, strong or detached shock forming dependent on the upstream Froude number and the wedge deflection angle. Flows past cylinders generate bow shocks and grain free regions on the lee side, while blunt bodies form an upstream detached shock and a dead zone adjacent to the obstacle. Depth-averaged avalanche models are able to solve for most of these configurations although they are not able to model the airborne jet where the particles follow ballistic trajectories.

1. INTRODUCTION

The first shallow-water-like snow avalanche models were developed in Russia (see e.g. Grigorian et al. 1967) and were motivated by the close analogy between the flow of a shallow layer of snow and a shallow layer of fluid. Savage and Hutter (1989) provided the first formal derivation of a depth-averaged model appropriate for snow avalanches and the theory used in this paper is a generalization of that early work and is a synthesis of the two-dimensional models of Gray, Wieland and Hutter (1999) and Gray, Tai and Noelle (2003). The model is formulated in an orthogonal curvilinear coordinate system $Oxyz$ in which the downslope coordinate x is defined by a curvilinear reference surface that follows the terrain and is inclined at an angle $\zeta(x)$ to the horizontal, the y-axis points across the slope and the z-axis is the upward pointing normal. In these coordinates the depth-averaged mass and momentum balances for the avalanche thickness $h(x,y,t)$ and the depth-averaged velocity $\overline{u}(x,y,t)$ are

$$\frac{\partial h}{\partial t} + \mathrm{div}(h\bar{\boldsymbol{u}}) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(h\bar{\boldsymbol{u}}) + \mathrm{div}(h\bar{\boldsymbol{u}} \otimes \bar{\boldsymbol{u}}) + \mathrm{grad}\left(\frac{1}{2}gh^2\cos\zeta\right) = h\boldsymbol{S} - hg\cos\zeta\,\mathrm{grad}\,b, \tag{2}$$

where g is the constant of gravitational acceleration, the operators div, grad and dyadic product $\otimes$ are defined in the (x,y)-surface and z=$b(x,y)$ defines the height of any superposed topography above the curvilinear reference surface. The source term on the right hand side of (2) is due to the component of gravity acting in the downslope direction $\boldsymbol{i}$ and a Coulomb friction μ that opposes the direction of motion

$$\boldsymbol{S} = g \sin\zeta\, \boldsymbol{i} - \mu(g\cos\zeta + \kappa\bar{u}^2)\frac{\bar{\boldsymbol{u}}}{|\bar{\boldsymbol{u}}|}, \tag{3}$$

where $\kappa = -\partial\zeta/\partial x$ is curvature of the terrain-following coordinate and which provides a correction to the hydrostatic pressure. The system is hyperbolic and it is therefore useful to define the Froude number $\mathrm{Fr} = |\bar{\boldsymbol{u}}|/\sqrt{g\ h\ \ \cos\zeta}$, which is the ratio of the flow speed to the gravity wave speed. In particular, the flow is subcritical if $\mathrm{Fr} < 1$, critical if $\mathrm{Fr} = 1$ and supercritical if $\mathrm{Fr} > 1$ in which case shocks (or discontinuities) in the solution are anticipated. In this situation equations (1-2) are no longer valid, because they assume smoothness. Instead it is possible to derive jump conditions (see e.g. Chadwick 1974) for the depth-averaged mass and momentum that apply across the discontinuity

$$[\![h(\bar{\boldsymbol{u}}\cdot\boldsymbol{n} - v_n)]\!] \quad = \quad 0, \tag{4}$$

$$[\![h\bar{\boldsymbol{u}}(\bar{\boldsymbol{u}}\cdot\boldsymbol{n} - v_n)]\!] + [\![\tfrac{1}{2}gh^2\cos\zeta]\!]\boldsymbol{n} \quad = \quad 0, \tag{5}$$

where the jump bracket notation is the difference of the enclosed quantity on either side of the shock, $\boldsymbol{n}$ is the normal to the shock and v_n is the shock speed in the normal direction.

2. MULTIPLE STEADY STATES FOR THE FLOW OVER A SMOOTH BUMP

Fig. 1(a,b) shows two different flows over a smooth bump arising from identical upstream conditions (Viroulet et al. 2017). In Fig. 1(a) the avalanche flows rapidly over the bump and forms an airborne jet, while in Fig. 1(b) the avalanche first impacts and then mobilizes a static layer of grains in front of the bump. This allows a normal shock wave to propagate upslope until it finds a stable location. The subsequent oncoming flow is dramatically slowed by the upstream shock and forms a subcritical flow that transitions back to supercritical as it flows over the bump. Importantly, however, the flow does not detach from the obstacle.

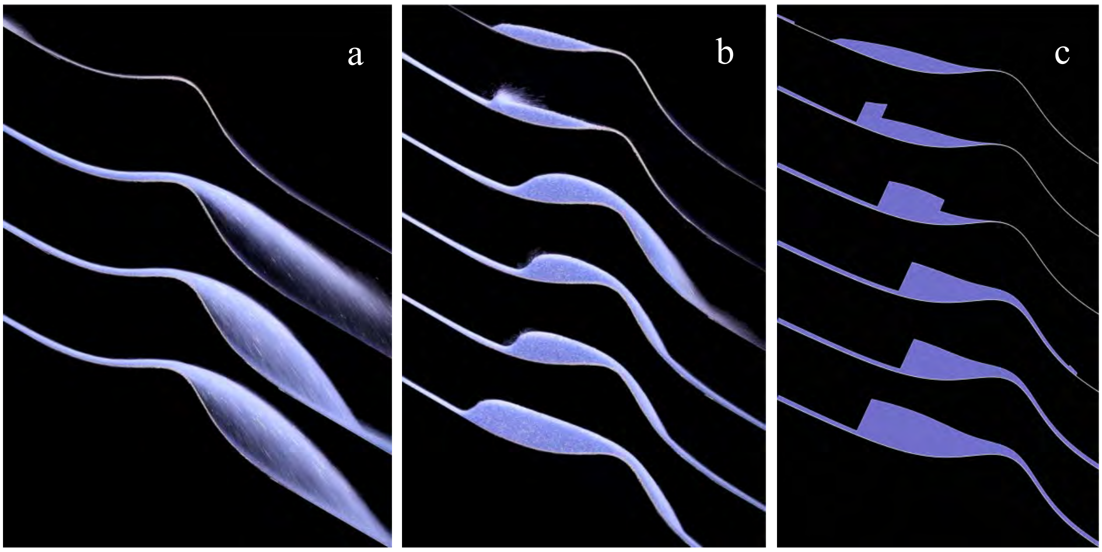

Figure 1 An experimental avalanche flowing over a smooth bump (a,b) for the same upstream Froude number $\mathrm{Fr} = 7.6$. A numerical simulation (c) for the case when there are static grains upstream and a normal shock forms (Viroulet et al. 2017).

The jet and the upstream shock solutions represent two steady states of the system. It is possible to flip between the two, by either momentarily blocking the jet or by scraping away some of the subcritical material. The terrain-following avalanche theory (1-3) is able to predict when the normal traction is equal to zero and hence when the avalanche takes off. The flying grains can then be treated as an inviscid jet (Hákonardóttir et al. 2003; Johnson et al. 2011) or by following the ballistic trajectories of the grains (Viroulet et al. 2017).

It is also possible to derive an exact solution, for the case when a normal shock forms upstream of the bump, using both the terrain-following theory and a more conventional avalanche model in which the height of the topography is prescribed by $z = b(x)$ above an inclined plane at an angle ζ to the horizontal. The critical point ($\mathrm{Fr} = 1$) plays a crucial role in determining a unique position for the steady-state shock in both cases. Unlike some conventional avalanche models the terrain-following theory is able to match the experimental shock position for a wide range of inclination angles, using the same frictional parameters, making this problem a sensitive test case. Using shock-capturing numerical methods (Kurganov and Tadmor, 2000) it is possible to simulate the evolution towards the steady state (Fig. 1c) including the impact with, and mobilization of, the static grains in front of the bump.

3. WEAK, STRONG AND DETACHED OBLIQUE SHOCKS

There are also multiple steady states for the flow of an avalanche past a deflecting wedge as shown in Fig. 2(a,b). For a sufficiently high upstream Froude number Fr_1 and low wedge deflection angle θ (see Fig. 2c) the jump conditions (4-5) imply that the shock deflection angle β can either be small, which is known as weak shock, or large, which is known as a strong shock (Rouse 1938, Ippen 1949, Gray et al. 2003, Hákonardóttir, K. M., Hogg, 2005, Gray and Cui 2007, Vreman et al. 2007, Akers et al. 2008). Weak shocks tend to form naturally if there is no downstream resistance to motion, but strong shocks can be triggered by temporarily blocking the flow or if the constriction is sufficiently small. Strong shocks are potentially very interesting for the design of avalanche protection structures, because the decreases in velocity and the increase in thickness across them is much greater than for weak shocks, so they dissipate a lot of energy. When the incoming Froude number Fr_1 is too low or the wedge angle is too high then there are no steady-state solutions that are attached to the wedge tip and a detached oblique shock forms upstream instead.

4. BOW SHOCKS AND GRAIN FREE REGIONS

For flows around cylinders (Fig. 3) the shock always detaches from the obstacle and forms a bow shock upstream of it. There is a stagnation point on the cylinder, where the velocity is zero, which implies there is a rapid deceleration as the grains as they pass through the shock and the subcritical region upstream of the cylinder. As the grains move around the obstacle the flow becomes supercritical again and expands on the lee side. The internal pressure is not sufficient to immediately push the grains around the lee side of the cylinder and a void opens up that is completely grain free. The lateral pressure gradients pushing in from either side slowly close the void with increasing downstream distance as shown in Fig. 3(a,b). Shock-capturing numerical simulations (Cui and Gray 2013) using the avalanche equations (1-3) on an inclined plane, with a no penetration condition on the cylinder walls, are able to capture the time-dependent development of the flow around the obstacle, as well as the downstream closure of the grain-free region, and closely match the steady-state solution (Fig 3c) .

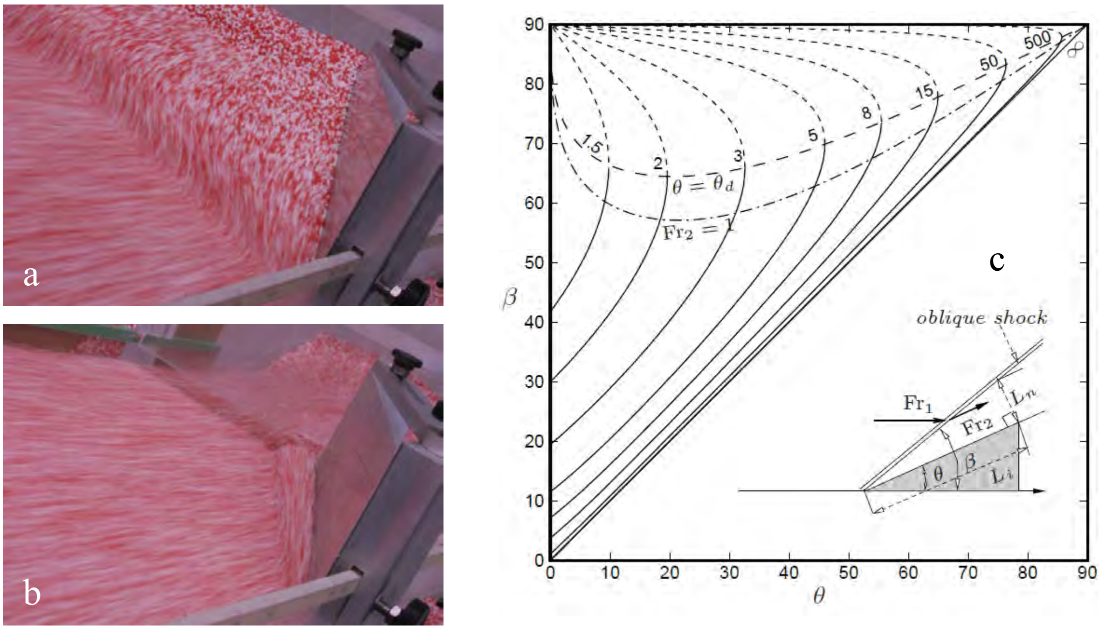

Figure 2 Oblique views of (a) a strong shock and (b) a weak shock for a flow at $Fr_1 = 5$ that is deflected by wedge at an angle $\theta = 20^o$ (Gray and Cui 2007). Provided Fr_1 (indicated by the numbers in c) is sufficiently high and the wedge angle θ is low enough, there is either a weak (solid lines) or a strong (dashed lines) solution for the shock deflection angle β. If the incoming Froude number is too low then the shock detaches (Gray and Cui 2007, Cui, Gray and Johannesson 2007*)*.

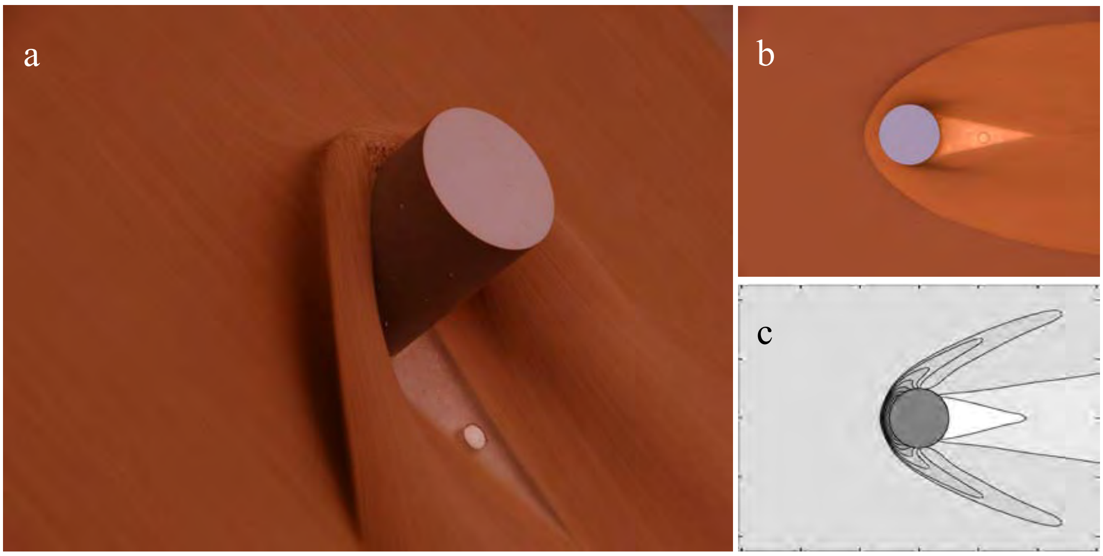

Figure 3 (a) Oblique and (b) overhead views of a supercritical flow of dry sand past a cylinder for $\zeta = 36^o$ and $\mathrm{Fr} = 6$. A bow shock forms upstream of the cylinder and a grain free (vacuum) region forms on the lee side. (c) Computed contours of the avalanche thickness using a depth-averaged avalanche model. The vacuum region is shown in white (Cui and Gray 2013).

5. BLUNT OBSTACLES AND THE FORMATION OF STATIC DEAD ZONES

When the obstacle has a blunt face, the avalanche can spontaneously form a dead zone adjacent to the obstacle, in which there is no flow, as shown experimentally for the pyramidal obstacle in Fig. 4(a,b). As a result the incoming flow is deflected by the dead zone, rather than the obstacle itself, and a detached bow shock then forms upstream. Shock capturing numerical simulations that define the topography in terms of its height $z = b(x, y)$ above the inclined plane are able to quantitatively capture both the formation of the dead zone and bow shock, as well as the fact that most of the grains in the dead zone are left on the upstream face of the pyramid when the flow ceases. The small airborne region of grains flowing over the pyramid faces (Fig. 4a) is not captured by the theory (Fig.4 c), but the predictions for both the flow and the grain free region on the lee side are not adversely affected.

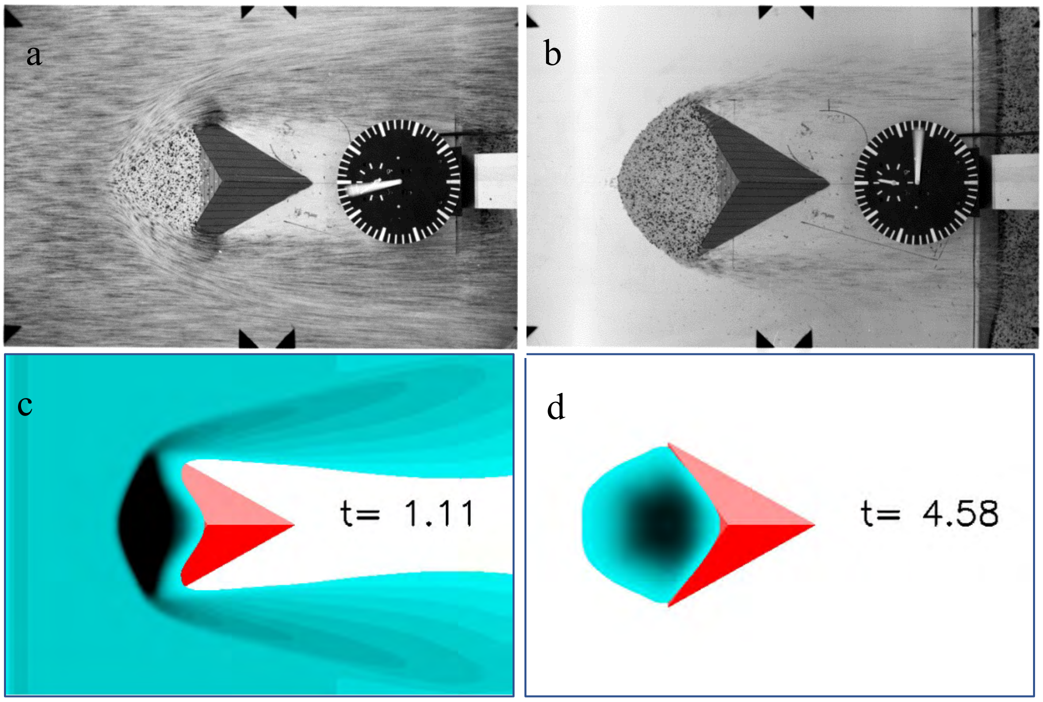

Figure 4 The formation of a shock and a static dead zone (Gray, Tai and Noelle 2003) upstream of the pyramidal obstacle in experiment (a,b) and simulation (c,d). The downslope direction is from left to right.

6. CONCLUSIONS

The depth-averaged terrain-following avalanche equations (1-3) provide a useful framework for computing the flow around many types of obstacle (Gray et al. 1999, 2003, Viroulet et al. 2017). The model is able to realistically capture key phenomena of rapid avalanches, such as multiple steady states and the formation of normal, oblique and detached shocks, grain-free regions as well as static dead zones. The theory can also solve for the point at which a flow will detach from the ground. An inviscid fluid (Hákonardóttir et al. 2003) or ballistic model (Viroulet et al 2017) can be used to solve for the trajectory of the jet. However, there is still much that is not understood about the dissipation that occurs when the jet lands (Johnson and Gray 2011) and forms an avalanche downstream of the obstacle.

ACKNOWLEDGEMENT
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Snow avalanches hitting deflecting and catching dams in Iceland 1997–2018

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ABSTRACT
More than forty snow avalanches have hit deflecting and catching dams in Iceland since the start of a government programme to build protection measures for Icelandic settlements around the turn of the century. The avalanches that have hit deflecting dams have reached up to 13 m vertical run-up and an avalanche overran a 20-m high catching dam in one case without anyone coming to harm. The outlines and other observations of the avalanches provide interesting insight into the dynamics of snow avalanches that hit obstructions. The avalanches on the deflecting dams have in some cases been observed to form a narrow stream along the dam side that is interpreted as an indication of the formation of an oblique shock in the interaction with the dam as predicted theoretically by depth-averaged granular-material dynamics. The avalanche dams have greatly improved the safety of several settlements threatened by snow avalanches. The engineering principles on which the dam design is based are primitive and the improvement in safety provided by the dams can, therefore, not be quantitatively assessed. It is clear that the dams have stopped or deflected several avalanches that would otherwise have come very close to or even entered the respective settlements.

1. INTRODUCTION

A programme for the construction of protection measures for settlements endangered by snow avalanches and landslides was initiated in Iceland after two catastrophic avalanches in 1995 claimed 34 lives at Súðavík and Flateyri in the Westfjords, NW-Iceland. Ten deflecting dams and sixteen catching dams for the protection of settlements, with height in the range 10–22 m, have been built until now. Several of them have already been hit by snow avalanches, some of them up to nine times.

The observations of avalanches that have hit the recently constructed dams can be interpreted to consider (1) the prioritization that was used to decide which settlements were first protected with dams after 1995 out of the many settlements in need for protection, (2) the hazard zoning, in particular the assumptions about the frequency of avalanches, on which the dam design was based, and (3) the performance of the dams and the realism of the employed design assumptions. Continuous reassessment of these three key questions is an integral part of the risk management for settlements threatened by snow avalanches and landslides in Iceland and an essential part of the justification for the large investments that are made in the programme to improve the safety of these settlements.

This paper summarises the lessons learnt from observations of avalanches that have hit the deflecting and catching dams in Iceland in the last two decades and describes observations at four of the locations in some detail.

2. SNOW AVALANCHES HITTING DAMS

Table 1 summarises key information about protection dams hit by snow avalanches in Iceland since 1997. In total, more than 40 avalanches have hit seven deflecting dams, one deflecting wedge and seven catching dams/mounds in six towns and villages. Since the landscaping of the excavation area is an important aspect of the design of avalanche dams, avalanches, that enter the excavation area, are counted in the table in addition to avalanches that hit the dams themselves.

Table 1 Deflecting and catching dams in Iceland that have been hit by snow avalanches in the period 1997–2018, construction year (T_c), the type of the dam ("D" for deflecting dam, "C" for catching dam, "W" for a deflecting wedge, "l" for an upper dam side of loose materials, "s" for a reinforced, steep upper dam side, "s-l" for a steep upper dam sides sitting on top of a base with less steep slope, "l-s" upper side mostly constructed from loose materials but with some steeper parts), vertical dam height (H_D, m), crown length (L, m), fill volume (V_f, thousands of m^3), deflecting angle (φ, degrees, only for deflecting dams), and number of avalanches that have hit the dam or entered the excavation area (N) are specified for each dam.

Location/path	T_c	Type	H_D	L	V_f	N	φ	Comment
Bíldudalur, NW-Iceland								
Búðargil	2008–2010	D/s-l	22	300	75	1	22	Lower end of loose materials
Flateyri, NW-Iceland								
Skollahvilft	1996–1998	D/l	15–20	600	375	9	18–20	
Innra-Bæjargil	1996–1998	D/l	15–20	600	375	5	18–25	
Bolungarvík, NW-Iceland								
Ytragil/Gil	2008–2012	D/s-l	22	720	380	1	–	
Ísafjörður, NW-Iceland								
Seljalandsmúli	2003–2004	D/l-s	13.5–16	700	370	2	45–50	
Funi	1999–2002	W/s-l	10	2x50	30	6	30	Lower ends of loose materials
Siglufjörður, N-Iceland								
Ytra-Strengsgil/ Jörundarskál	1998–1999	D/l	15–18	700	400	6/5	15–18	The dam information applies to the Ytra-Strengsgil dam. The number of avalanches includes five avalanches on a small dam below Jörundarskál
Hafnarfjall	2003–2008	C/s-l	up to 15	2500	440	>5	–	Many avalanches that hit five dams in total
Bakkahverfi	2003–2008	D/l	9	200	9	1	~30	Defl. dam north of the village
Seyðisfjörður, E-Iceland								
Brún in Bjólfur	2003–2004	C/s-l	20	450	150	3	–	

Three locations stand out with an exceptionally large number of avalanches, the two deflecting dams at Flateyri, a deflecting wedge protecting a single, industrial building at Funi in Ísafjörður and the deflecting dams that protect the southern part of the town of Siglufjörður. Between six and nine avalanches have hit dams at each of these locations since the construction of the dams around the year 2000 as described in more detail in separate subsections below.

2.1 Deflecting dams at Flateyri

Figure 1 shows the outlines of avalanches from the paths Innra-Bæjargil and Skollahvilft in Eyrarfjall mountain above the village of Flateyri, NW-Iceland, since two deflecting dams and a catching dam were built above the village in 1997 (VST and NGI, 1996), only two years after the catastrophic avalanche in 1995 that claimed 20 lives. The avalanches have terminated along the entire Skollahvilft dam east of the village with the longest one on 21.2.1999 running ca. 150 m beyond the end of the dam and with a maximum vertical run-up of 13 m on the dam side. Avalanches since 1997 have also terminated along the entire dam below Innra-Bæjargil with the longest one on 28.2.2000 terminating in the ocean. It had a maximum vertical run-up of 11–12 m on the dam side. The maximum run-up on both dams was ca. 5 m short of the top of the dam.

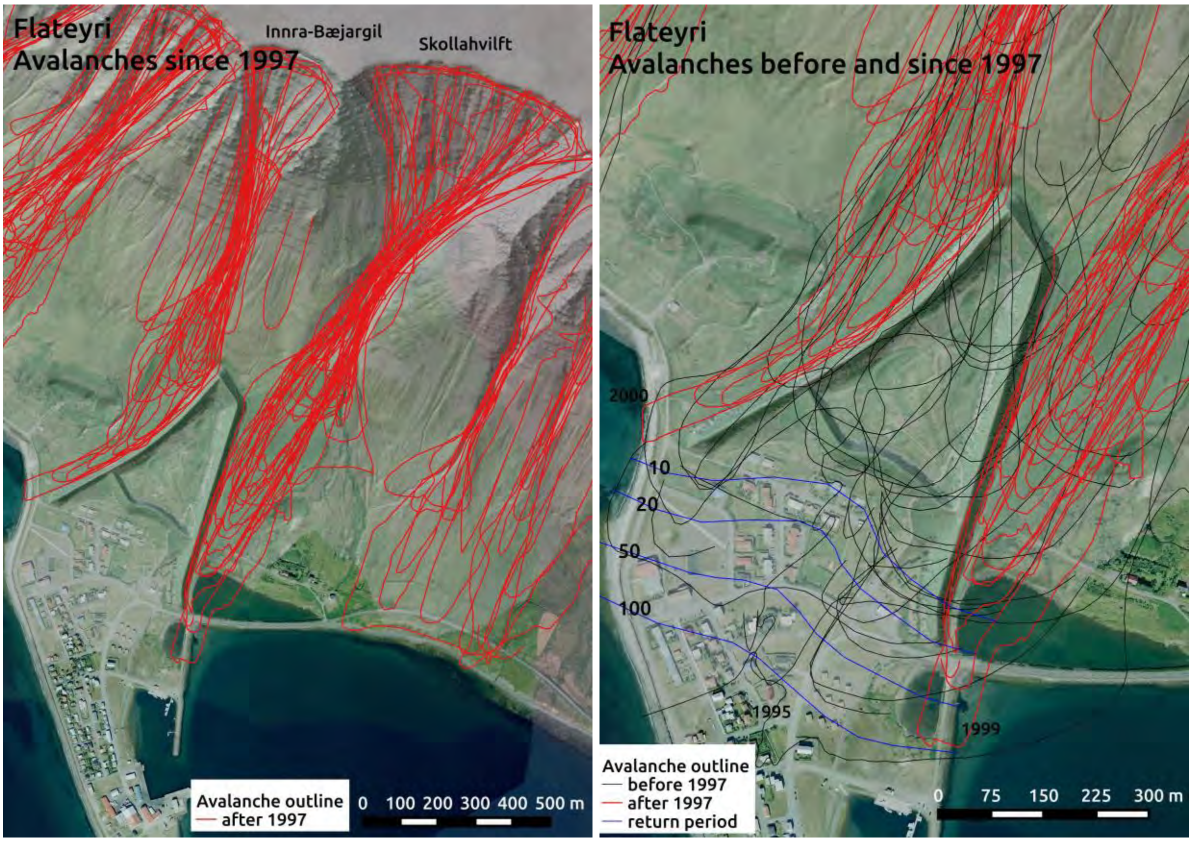

Figure 1 Outlines of snow avalanches at Flateyri, NW-Iceland since the construction of deflecting dams above the village in 1997. The background is a transparent shading of a lidar DEM from 2009 superimposed on an orthophoto from Loftmyndir ehf (©). The figure to the right shows a zoom-in of the dams and an estimate of the return period of snow avalanches in the settlement before the construction of the dams (Arnalds and others, 2004; Jóhannesson, 1998). Symbols show the location of FMCW radars installed on the eastern dam in 2004 to measure the velocity of the avalanches.

An FMCW radar that measures the velocity of the avalanches has been operated on the Skollahvilft dam since 2004, measuring velocities of up to 50–60 m/s for an avalanche on 30.3.2009, presumably several hundred meters upstream from the dam, and 25–40 m/s for the bulk of the avalanche as it flowed against and along the dam.

Figure 1 also shows an estimate of the return period of snow avalanches at Flateyri before the construction of the dams (Arnalds and others, 2004; Jóhannesson, 1998; a rough estimate for the shorter return periods was added here). The run-out length of the avalanches along the dams may be expected to be longer than it would have been without channelling effect the dams, for example the longest avalanche in 1999 has been estimated to have reached ca. 100 m longer than it otherwise would because of the interaction with the dam. When the longer run-out due to the dam is taken into consideration, the large number of avalanches that have reached the dams in only two decades seems more-or-less consistent with the estimated return period.

2.2 Deflecting dam at Seljalandsmúli, Ísafjörður, NW-Iceland

Two avalanches in 2004 and 2005 have reached the excavation area of a deflecting dam below Seljalandsmúli in Ísafjörður, NW-Iceland (Hnit and NGI, 1996). One of them left some marks on the dam side but run-up distance and run-up height were hard to determine because of heavy snowfall and snowdrift. The other reached two rows of braking mounds that are located upstream of the dam.

2.3 Catching dam and braking mounds at Bolungarvík, NW-Iceland

One avalanche in 2012 reached the row of braking mounds upstream from the 22 m high catching dam at Bolungarvík, NW-Iceland. The avalanche was stopped at the mounds and did not reach the dam.

2.4 Wedge at Funi, Innri-Kirkjubólshlíð, Ísafjörður, NW-Iceland

The Funi industrial building in Ísafjörður, NW-Iceland, may be the building, with substantial presence of people, that is most heavily threatened by snow avalanches in Iceland. Figure 2 shows the outlines of avalanches before and after the construction of a protective wedge in 2000 (VST & NGI, 1996). The building was severely damaged by a snow avalanche in October 1995 which is depicted on the map with an outline that surrounds the building on three sides.

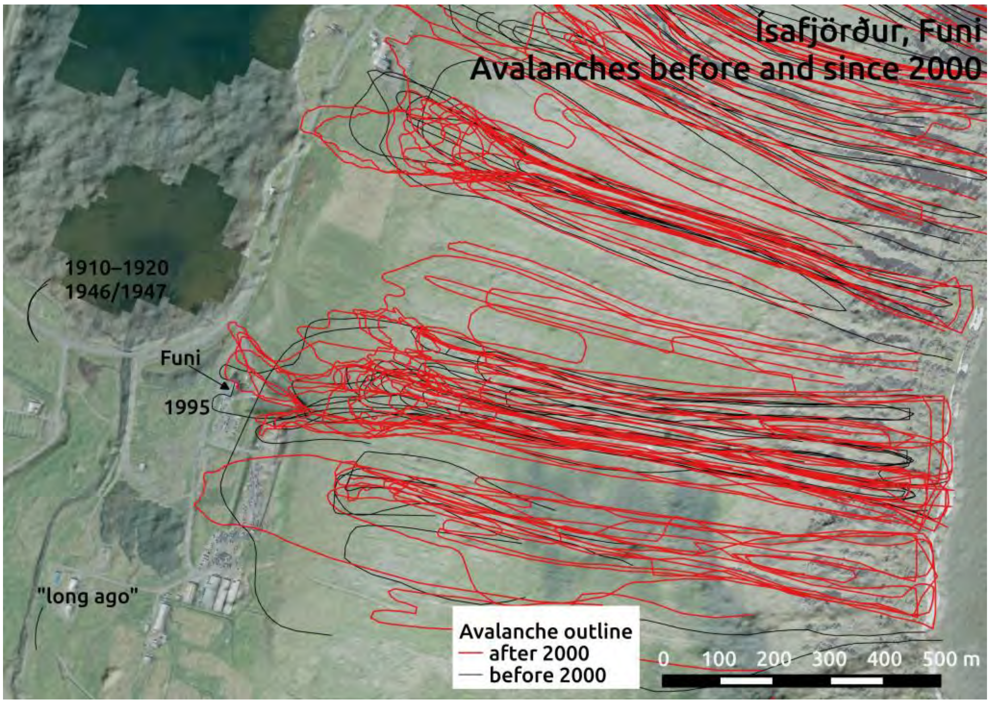

Figure 2 Outlines of snow avalanches at the Funi industrial building below the Innri-Kirkjubólshlíð mountainside in Ísafjörður, NW-Iceland, since the construction of a deflecting wedge above the building in 2000 (red curves), as well as all recorded avalanches before this time (black curves). The background is a transparent shading from the ArcticDEM superimposed on an orthophoto from Loftmyndir ehf (©).

The wedge has been hit by snow avalanches six times since 2000 and it is likely to have saved the industrial building it is intended to protect from damage several times. In some of the cases, the avalanches seem to have hit the wedge with an explosion-like impact that threw snow clods ballistically over the dam, leaving an up to 0.5-m-thick layer of snow clods on the back side of the dam and in the area between the wings of the wedge. The return period estimate of the hazard zoning (Arnalds and others, 2007) and the recent avalanche history indicate that the return period of avalanches at the location of the building before the construction of the wedge may be ~5 years or even shorter which is a remarkable situation for an industrial building with regular presence of employees. Two reported avalanche tongues from the early and middle 20th century (in 1910–1920 and 1946/1947) at the bottom of the fjord in the middle of the valley, far below Funi as shown on Figure 2, are another indication of the extreme avalanche danger in this area.

2.5 Deflecting and catching dams at Siglufjörður, N-Iceland

Figure 3 shows the outlines of avalanches from the paths Ytra-Strengsgil and Jörundarskál in Hafnarfjall mountain above the village of Siglufjörður, N-Iceland, since two deflecting dams were built above southern part of the village in 1998 (VS, 1997). The two dams have been hit by eleven avalanches in the two decades since their construction, some of which seem likely to have come very close to or even entered the settlement if the dams had not deflected them away from the village. This is largely consistent with the estimated return period of ca. 10 years for avalanches that reach near the top of the settlement (Arnalds and others, 2001; a rough estimate for the shorter return periods was added here).

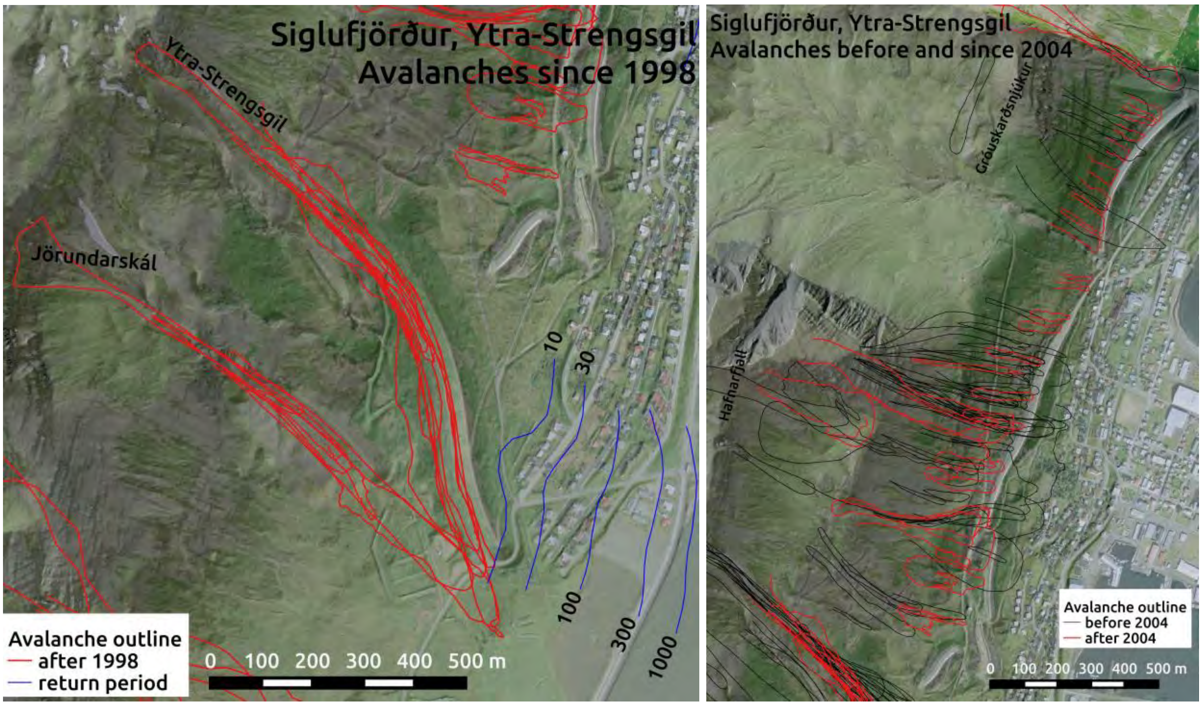

Figure 3 Left: Outlines of snow avalanches from the Ytra-Strengsgil and Jörundarskál avalanche paths at the southern end of the town of Siglufjörður, N-Iceland, since the construction of deflecting dams above the settlement in 1998 (red curves), as well as an estimate of the return period of snow avalanches in the area (Arnalds and others, 2001) (blue curves). The background is a transparent shading from a lidar DEM from 2009 superimposed on an orthophoto from Loftmyndir ehf (©). Right: Outlines of avalanches before (red curves) and after (black curves) the construction of five catching dams and a deflecting dam above the main settlement in 2004.

Good measurements of the run-up on the dam side have been hard to make for these avalanches because the tongues of the largest avalanche have been covered with new snow and snowdrift before measurements could be made. The maximum run-up may have been close to or a little more than half the dam height. Overall, the Ytra-Strengsgil and Jörundarskál dams and the adjacent excavation areas seem to have deflected avalanches smoothly away from the settlement in a manner consistent with the design assumptions for the dams.

Several avalanches have hit the row of five catching dams above the entire settlement of Siglufjörður north of Ytra-Strengsgil (VS, 2002) (Figure 3). The avalanche debris has reached almost to the top of the steep upper dam sides in two cases, underlining the importance of supporting structures to provide improved safety for the main settlement in Siglufjörður. Approximately 4.5 km of supporting structures have been installed in the mountainside of Hafnarfjall and Gróuskarðshnjúkur since 2004.

2.6 Catching dam at Seyðisfjörður, E-Iceland

Figure 4 shows the outlines of avalanches that have hit a 20-m high catching dam that was built on a shelf at 650 m a.s.l. in the mountain Bjólfur above the town of Seyðisfjörður, E-Iceland, in 2003–2004 (VA and NGI, 2003). The largest avalanche, in 2006, presumably a fast-moving, dry-snow avalanche, partly overran the dam without leaving much of a snow deposit above the dam. The tongue that overran the dam was composed of snow clods that appeared to have been thrown ballistically over the dam after the impact with the steep upper dam side.

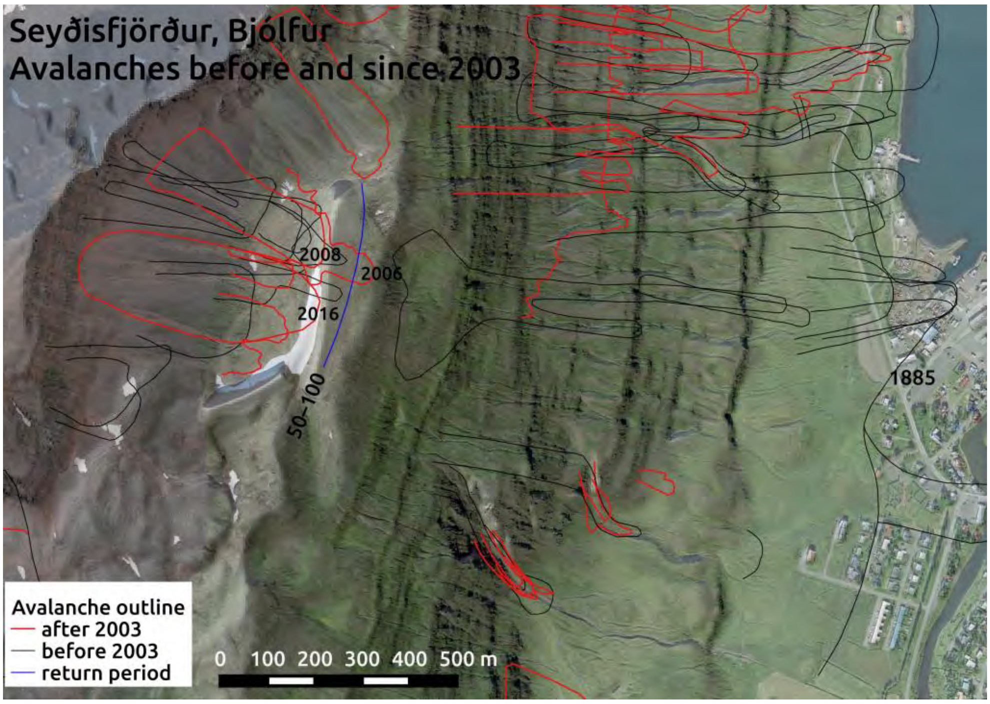

Figure 4 Outlines of snow avalanches from the Bjólfur mountain above the town of Seyðisfjörður, E-Iceland, since the construction of 20-m high catching dam and a deflecting dam on the shelf Brún at 650 m a.s.l. in the mountainside in the year 2003 (red curves), as well as all recorded avalanches before this time (black curves), and an estimate of the return period of snow avalanches that reach the edge of the shelf (Arnalds and others, 2002). The background is a transparent shading of a lidar DEM from 2011 superimposed on an orthophoto from Loftmyndir ehf (©).

3. DISCUSSION AND CONCLUSIONS

The very high frequency of avalanches at Flateyri, Funi and at Strengsgil/Jörundarskál in Siglufjörður in the last two decades is consistent with the frequency assessment of the hazard zoning at these locations and confirms the great hazard in the respective settlements before the construction of protection dams. This recent avalanche history, thereby, also confirms the prioritization developed in the aftermath of the catastrophic avalanches in 1995 (e.g. Jóhannesson and others, 1996), which led to the construction of protection measures for these locations in the first phase of the buildup of protection measures for settlements in Iceland. This prioritization was based on the recorded avalanche history before 1995 as summarized by many workers, in particular Jónsson et al. (1992), Grímsdóttir and Sæmundsson (2001), Haraldsdóttir (2002) and Ágústsson (2002) for the areas discussed in this paper.

The avalanches that have hit deflecting dams have in all cases been successfully deflected and the outlines and other observations of the avalanches provide interesting insight into the dynamics of snow avalanches that hit obstructions. The avalanches on the deflecting dams have in some cases been observed to form a narrow stream along the dam side that is interpreted as an indication of the formation of an oblique shock in the interaction with the dam as predicted theoretically by depth-averaged granular-material dynamics (Cui and others, 2007). One avalanche partly overran the 20-m high catching dam at Brún in Bjólfur in Seyðisfjörður without anyone coming to harm, demonstrating the ability of snow avalanches to scale even the highest catching dams. The avalanche dams have greatly improved the safety of several settlements in Iceland threatened by snow avalanches. The engineering principles on which the dam design is based are primitive and the improvement in safety provided by the dams can, therefore, not be quantitatively assessed, particularly for the catching dams. It is clear that the dams have stopped or deflected several avalanches that would otherwise have come very close to or even entered the respective settlements. The performance of the dams, especially the catching dams, for much greater avalanches is nevertheless not certain. Improved models to simulate avalanche flow against dams are, therefore, urgently needed. Observations of real avalanches that have hit dams, such as the avalanched discussed in this paper, will be essential for the development of such models.

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Planning for highways in avalanche-prone areas in Troms County, Northern Norway

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ABSTRACT

The Norwegian Public Roads Administration (NPRA) is challenged by nature during planning of new roads or renovation of existing roads. Steep mountain sides and limited suitable land for roads force the NPRA to plan for roads in areas prone to natural hazard processes. In the last years, the NPRA has been planning for new roads at several locations in Troms County, Northern Norway. Two of them are on E8 in Ramfjord and Lavangsdalen, 20 km respective 40 km from Tromsø. Dry-snow avalanches are the main concern for these new roads. A new Norwegian method for calculating acceptable risk on roads was applied to these road sections and it proved to be a challenge to reach desired risk level at several locations. A simple cost-benefit analysis was carried out for necessary mitigation measures. Lavangsdalen proved to be the most challenging location. It is known for long dry avalanche runouts and roughly every winter road travellers are hit by avalanches. Mitigation measures for the desired safety level proved to extremely costly and therefor mitigation measures for two other and lower safety levels were also worked out. It will be up to the NPRA to decide which safety level they go for in the final stages of this work.

1. INTRODUCTION

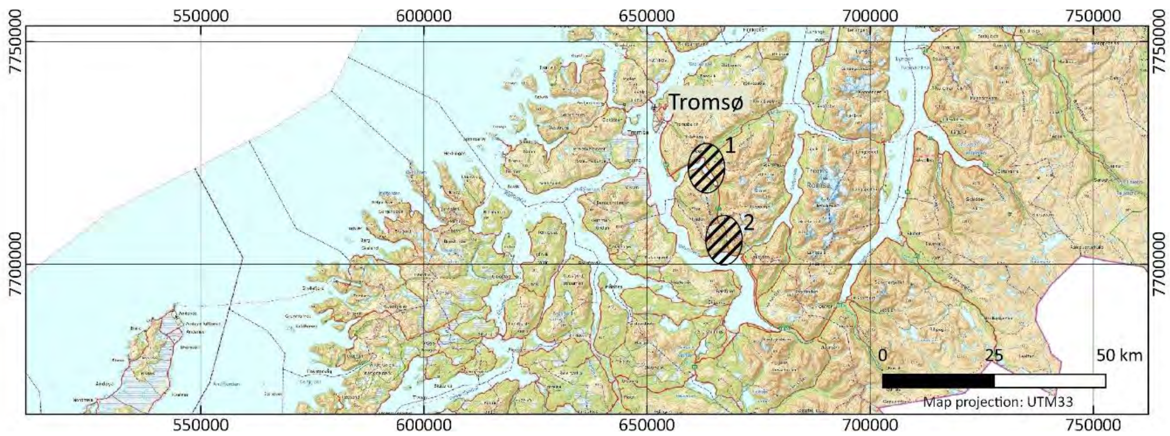

Figure 1. Overview over Troms county Norway. The road sections are shown as hatched areas. Area 1 shows the road section in Ramfjord, area 2 shows road section in Lavangsdalen. Background map: norgeskart.no.

The Norwegian Public Roads Administration (NPRA) is actively working on improvements of the road and highway network in Norway. The work on renovation of the E8 road section from

Tromsø to Balsfjorden southeast of Tromsø (areas 1 and 2 in Figure 1) has been going on for a while. The E8 is the main road and important transport route to the city from Finland. In 2015 the NPRA decided to work out a preliminary plan for mitigation measures against snow avalanches for road sections 1 and 2. These road sections are mainly threatened by snow avalanches, but slush flows may also occur. This work is described in (Norges Geotekniske Institutt NGI, 2017a, 2017b).

2. CRITERIA

2.1 Ramfjorden – Indre Laukslett/Nordbotn

2.1.1 Criteria

In 2014 NPRA presented at guidelines for acceptable risk on highways in Norway (SVV, 2014). These guidelines are the main criteria for preliminary design presented in this work.

In the work presented here NPRA has planned for annual average daily traffic in twenty years (AADT20) to be between 4000 and 8000 vehicles/day; 8000 vehicles/day was set as the design value. According to Figure 2 in the guideline this traffic volume would according to probability class VI or probability of closure f be between 1/100 and 1/1000 pr. unit length of road (1000 m in the guidelines).

Two avalanche simulation models are used for this road section, Voellmy MoT (from NGI) for Indre Laukslett area and RAMMS (Christen et al., 2010) for the Nordbotn area. Data from RAMMS simulation were already available for the Nordbotn area when this work started, and it benefitted from it.

2.1.2 Hazard assessment and mitigation measures

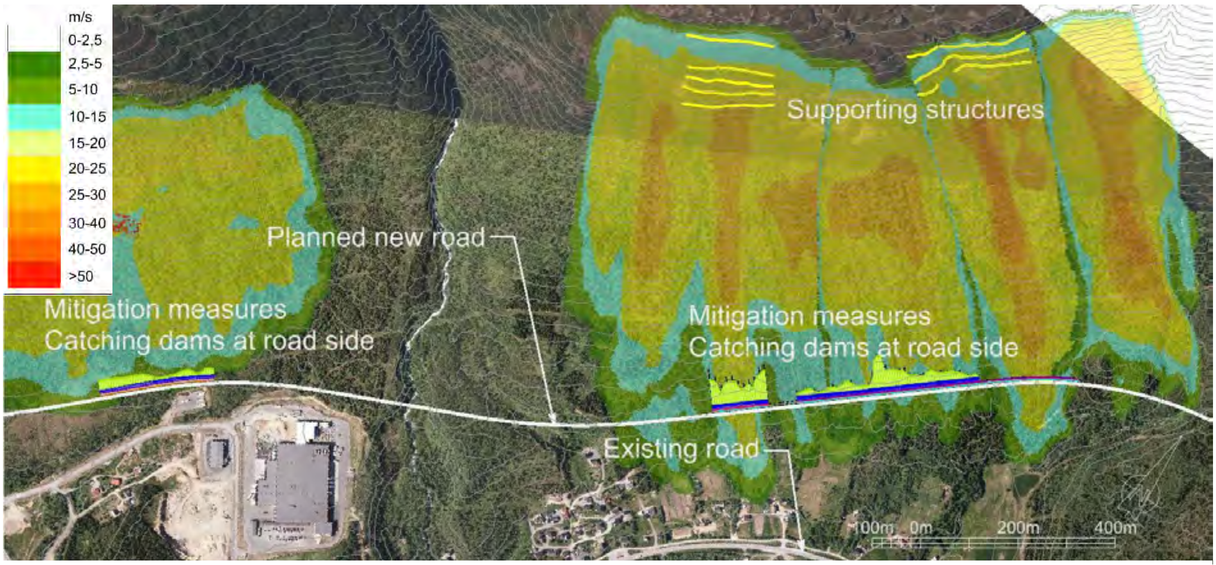

Figure 2 The figure shows the location of new planned road E8 at Indre Laukslett (to the left) and Nordbotn (to the right) in Ramfjorden. Proposed supporting structures are shown with yellow lines and the colored areas are avalanche simulations from Voellmy MoT to the left and RAMMS to the right. The simulations shown are without any mitigation measures. The distance between the light gray contour lines is 10 m. Aerial photo: Norgeskart.no.

The avalanche site to the left in Figure 2 does not have any registered avalanches to the planned road but tree damages at the starting zone indicate some activities and the topography indicates the possibility that avalanches can reach the road. There are several registered avalanches at the avalanche site to the right some of them stopping just above the residential area.

The planned relocation of the road E8 at the residential area at Indre Laukslett and Nordbotn in Ramfjorden has the aim to improve the road geometry and move the traffic from the residential and coastal area further away. However, this relocation comes with a cost as the avalanche hazard must be mitigated for parts of the road.

The avalanche risk at planned road at Indre Laukslett area (to left in Figure 2) is little and only small, approx. 6.5 m high catching dam above the planned road is needed to mitigate the risk to an acceptable level. The catching dam geometry is similar to the one shown in Figure 3.

At Nordbotn the planned road is in steep terrain where mitigation measures are needed, and only limited space is available for large catching dams. By combining small catching dams and supporting structures in the starting zone the risk for the road traffic is mitigated to an acceptable level. Figure 3 shows a typical cross section in planned road and a catching dam at Nordbotn.

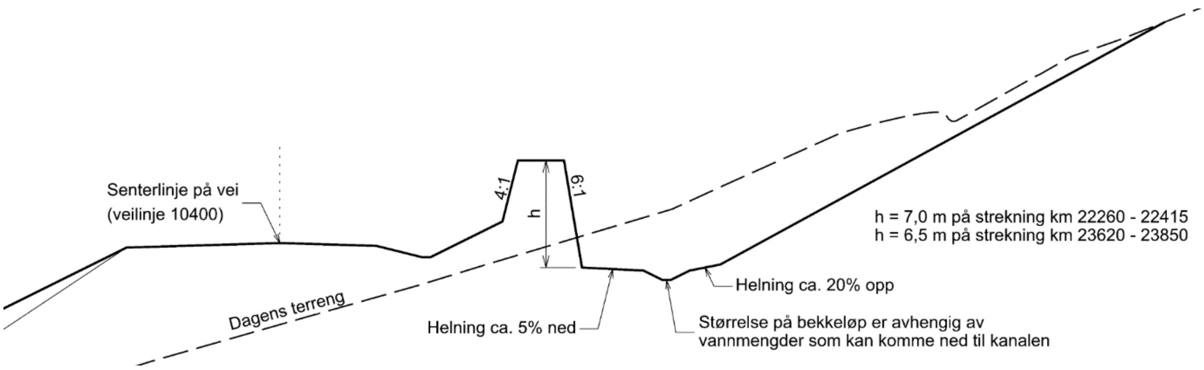

Figure 3. Typical cross section in planned road and a catching dam in Nordbotn.

2.2 Ramfjorden-Sørbotn

2.2.1 Criteria

AADT20 and safety level is the same as in chapter 2.1.1.

RAMMS avalanche simulation model was used for this road section as most of the simulation had already been done when planning the mitigation measures started.

2.2.2 Hazard assessment and mitigation measures

Hazard assessment for this road section was done by NPRA in 2014 (Larsen, 2014) and in 2015 NGI worked out hazard assessment for large area of Troms county where Sørbotn was part of the work (Norges Geotekniske Institutt NGI, 2015).

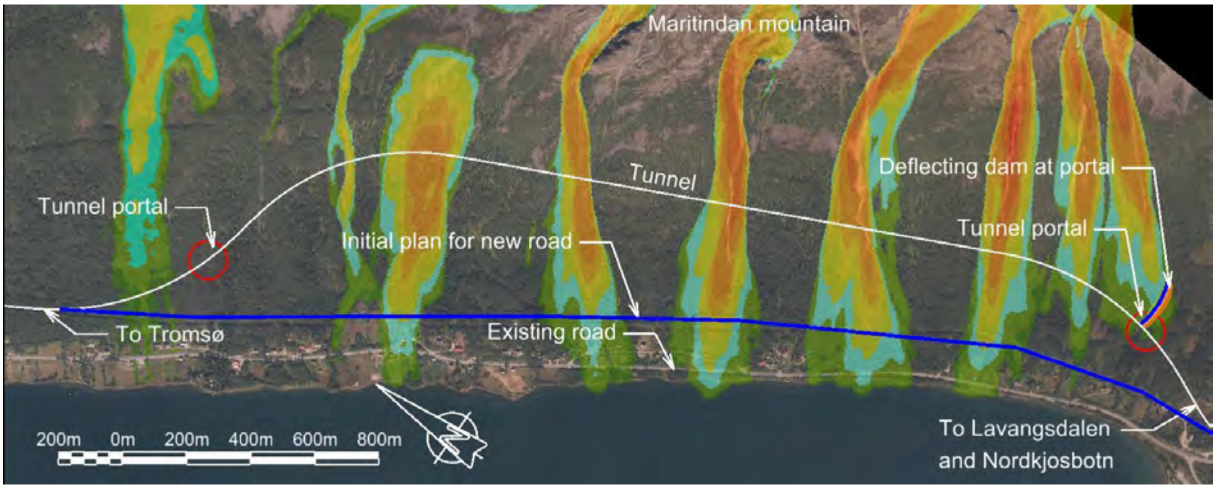

Figure 4. The figure shows avalanches from Maritindan mountain in Sørbotn, Ramfjorden. Blue line shows initial road alignment, white line shows the new planned road E8 in a tunnel and red circles show the tunnel portals. The main avalanche tracks are shown with colored areas (RAMMS simulation), avalanche velocity scale is shown in Figure 2.

Avalanches from Maritindan mountain are well known but they have not reached the settlement in recent years. The initial plan for new road alignment is shown in Figure 4 as a blue line just above the settlement along the coast line. Passing the avalanche paths was a huge challenge as all changes in existing terrain might contribute to unforeseen consequences for the settlement below. Galleries were considered but they would have been costly and might have increased the avalanche runout distance. Steep terrain is not favorable for large catching dams of earthen material and they were not really an alternative here. Tunnel was the only option left but there was a problem to find a suitable location for the portals due to excess of loose material and bad rock. The white alignment in Figure 4 shows the proposed location today. A short deflecting dam above the east portal is proposed as avalanches might hit the portal and cause closures. The height is set to approx. 5 m, but it has to be reconsidered in the detail design phase as snow drift might reduce the effective height.

2.3 Lavangsdalen

2.3.1 Criteria

The traffic volume AADT20 is the same as for previously mentioned sections and in the beginning the probability of closure f was between 1/100 and 1/1000 pr. unit length of road. As work progressed NPRA wanted also to check the magnitude of mitigation measures for probability of closure f 1/50 - 1/100 and 1/20 - 1/50.

Vollemy MoT avalanche simulation model from NGI was used for this road section.

2.3.2 Hazard assessment and mitigation measures

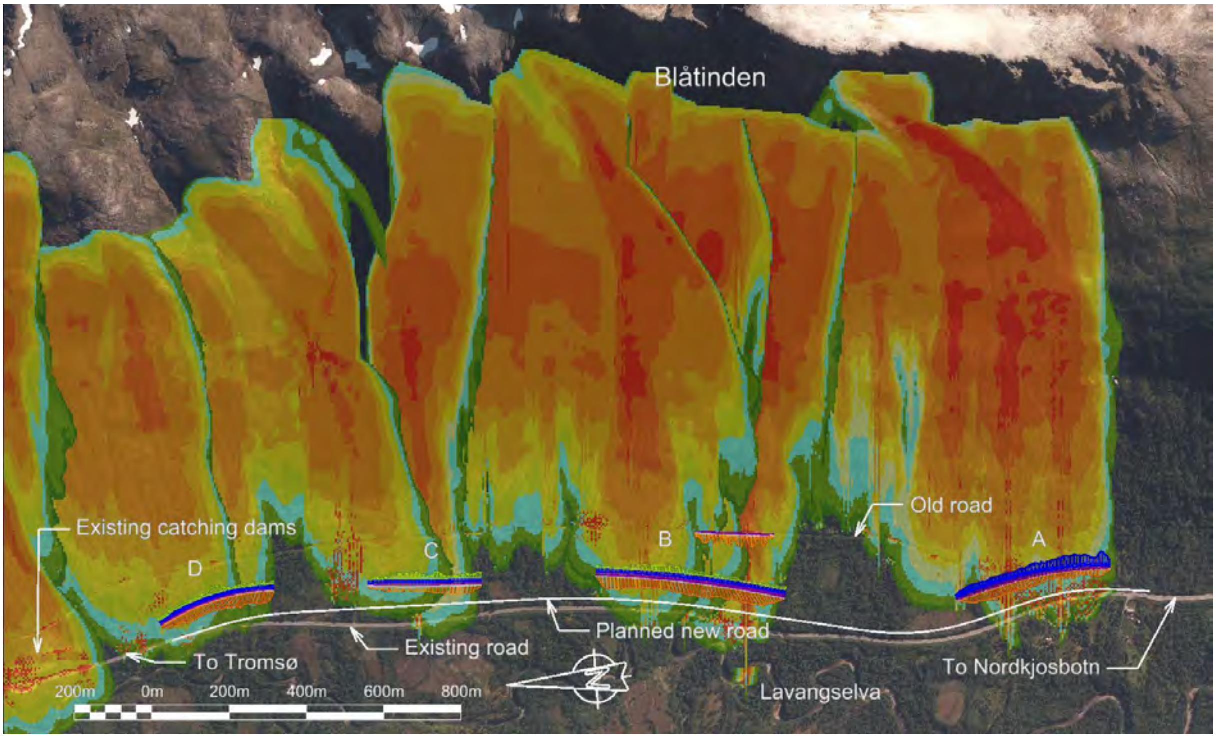

Figure 5. The avalanche site in Lavangsdalen. Planned new road E8 is shown with white line, proposed catching dams are shown with orange and blue colors, and avalanche paths and simulated avalanche velocities (with Voellmy MoT) are shown as the colored areas. Velocity scale is shown in Figure 2.

No hazard assessment was available for this area prior to this work. The aim of this work was not to make hazard maps but to assess the hazard and plan for mitigation measures.

Lavangsdalen is known for its avalanche problems during winter time. In recent times avalanches have hit vehicles in the northern part of the valley but fortunately without any fatalities. As NPRA is planning to relocate approx. 3 km of existing road E8 at the southern part of Lavangsdalen (Figure 5) an assessment of the avalanche danger was worked out for the new location. Several scenarios of simulated avalanches were checked, Figure 5 shows the case for probability of closure 1/50 - 1/100. The other simulation scenarios 1/100-1/1000 shows longer runouts and larger volumes, and 1/20-1/50 shows shorter runouts and less volumes.

To mitigate the avalanche hazard supporting structures were considered in the starting zone as well as catching dams just above the planned road. A large volume of supporting structures, approx. 20000 m to 40000 m, were considered to fulfill the initial safety criteria or 1/100 to 1/1000, but the estimated cost proved to be enormous and therefore not a realistic alternative and was put aside.

Figure 5 shows the avalanche simulation for probability of closure 1/50-1/100. Four main areas A-D in Figure 5 are identified where avalanches can hit the road. Of those four area B has the largest volume and highest avalanche velocity. It was necessary to add one line of approx. 8 m high mounds some 80-100 m uphill to reduce the velocity at catching dam enough to be able to build a catching dam.

Ground investigations revealed that catching dam B was located on a quick clay area and the geotechnical stability could not be secured without extensive ground/base stabilization. Also, one of the criteria for stability is to excavate as little as possible above the dam as the upslope stability would be threatened.

The proposed height of catching dam B is 15 m with the mound's upslope, other catching dams at areas A, C and D are between 8 and 13 m high. The geotechnical engineer's advice for the other catching dams is also to reduce excavation upslope due to possible stability problems. Almost all building material must be transported to the site.

The proposed cost of these catching dams is high and therefore NPRA asked for further study of mitigation measures with reduced level of safety or 1/20 to 1/50. Avalanche simulation for this level reveals that only area B will need a catching dam to meet acceptable safety level. The proposed dam height in this case is 13 m and the length are approximately 280 m.

3. EPILOG

The renovation and relocation of highway E8 in Ramfjord and Lavangsdalen is as of today still in a planning phase. It is unclear when NPRA will be able to fund the construction of these road sections and it is also unclear which safety level they will accept for the road sections.

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Longyearbyen Svalbard – Mitigation Measures for Sukkertoppen and Vannledningsdalen

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ABSTRACT

After a deadly avalanche in December 2015 and material damages due to an avalanche in February 2017 the national and local authorities in Norway have initiated mitigation work in Longyearbyen, Svalbard. Snow fences were built in the mountain side above the town in February 2018 and supporting structures and a drainage canal are near completion late fall 2018. Further work on planning of mitigation measures below the Sukkertoppen mountain and Vannledningsdalen valley is in progress and a plan for construction start is set at the beginning of the summer 2019.

The ongoing work on the mitigation is focusing on two main areas: the area just above the town centre and the area on and around the delta below Vannledningsdalen valley. Vannledningsdalen, a nearly 2 km long valley, has a history of slush flows, some of them fatal. For mitigation here, two main concepts are being studied: deflecting walls along the stream to the main river Longyearelva and a curved up to 15 m high deflecting wall which directs the slush flow out of the main stream to an open area below Sukkertoppen. For the centre area supporting structures are being studied in combination with a small catching dam for debris flows, or a row of braking mounds in combination with approx. 13 m high catching dam. The effect of expected climate change is uncertain but plays a large role in the final choice of the mitigation concept. Permafrost and solifluction are one of the greatest concerns for these structures, as it is unclear if the permafrost ground can carry the weight of these large dams. Ground- and surface water is also a big issue as the permafrost limits the drainage possibilities.

1. INTRODUCTION

The avalanche danger in Longyearbyen (Figure 1) has been known for a long time and has been described by Erik Hestnes and others in several NGI reports such as (Norges Geotekniske Institutt NGI, 2001). In December 2015 and February 2017 avalanches hit residential buildings at the root of the Sukkertoppen mountain (location Lia) killing two persons in the December incidence and caused considerable material damages in both incidences. The 2015 incidence has been described in (DSB, 2016), (Issler et al., 2016), (Jaedicke et al., 2016), (Hestnes et al., 2016), (Brattlien et al., 2016), and the 2017 incidence and mitigation work in (NVE, 2017), (Jonsson and Jaedicke, 2017) and (Jonsson et al., 2018b).

Svalbard archipelago lies in the permafrost belt north of 64°. The mean year temperature has increased by approx. 3°C since 1900 but there have been large variations between years and between decades (Isaksen et al., 2017). From 1970 the temperature increase on Svalbard is amongst highest registered on earth. In the period 1971–2000 the mean year temperature was

Figure 1. Overview over the habitation below Sukkertoppen mountain and on the delta below Vannledningsdalen. Black polygon boundary depicts the area that poses threat to the people and buildings in the runout zone. Blue dotted polygon to the left of Sukkertoppen depicts the area protected in 2018.

–5.9°C but in 2016 the mean year temperature was –0.1°C (Isaksen et al., 2017). The report also predicts for the "best" scenario an increase in temperature of 3.6°C by the end of the 21st century and the "worst" which is 9.2°C. Further details on this worst case scenario are given in (I. Hanssen-Bauer et al., 2019).

All changes in climate in these arctic regions will affect the permafrost and thus existing and new/future infrastructures including mitigation measures for natural hazards such as snow avalanches, slush- and debris flows. As an example of this change the permafrost temperature has increased at rates between 0.06°C and 0.15°C at 10 m depth from 2009 and at Adventdalen and Janssonhaugen the active layer depth has increased by 0.6 cm to 1.6 cm per year (I. Hanssen-Bauer et al., 2019).

This project describes an ongoing mitigation work for the area below Sukkertoppen mountain Longyearbyen, see Figure 1. The client is The Norwegian Water Resources and Energy Directorate (NVE) on behalf of Longyearbyen lokalstyre (LL) and the main work is carried out by HNIT consulting Iceland, Skred AS Norway and the geotechnical consultant Rambøll Norge AS. Information in this article is based on a report from the first phase of the hazard assessment and the preliminary phase of the mitigation work (Jónsson et al., 2018a).

2. HAZARD ASSESSMENT

Prior to 2015 various hazard assessments had been worked out by NGI, (Norges Geotekniske Institutt NGI, 2015a) for various residential sites in Longyearbyen. In the wake of the fatal accident in December 2015 NVE initiated a new and complete hazard assessment for Longyearbyen and surroundings (Multiconsult AS, 2016) but after the avalanche accident in February 2017 the reliability of the report and hazard zoning has been questioned. A new workgroup was formed by NVE in 2017, the group consisted of three consultants i.e. Skred AS, Norwegian Geotechnical Institute (NGI) and UNIS in Svalbard, and it included also one representative from NVE. The workgroup delivered a new hazard map for the area below Sukkertoppen mountain early 2018 (Figure 2). Hazard assessment for the delta area below Vannledningsdalen (Haugen residential area) had been prepared by NGI in 2015 (Norges Geotekniske Institutt NGI, 2015b) and Multiconsult AS in 2016 (Multiconsult AS, 2016). The

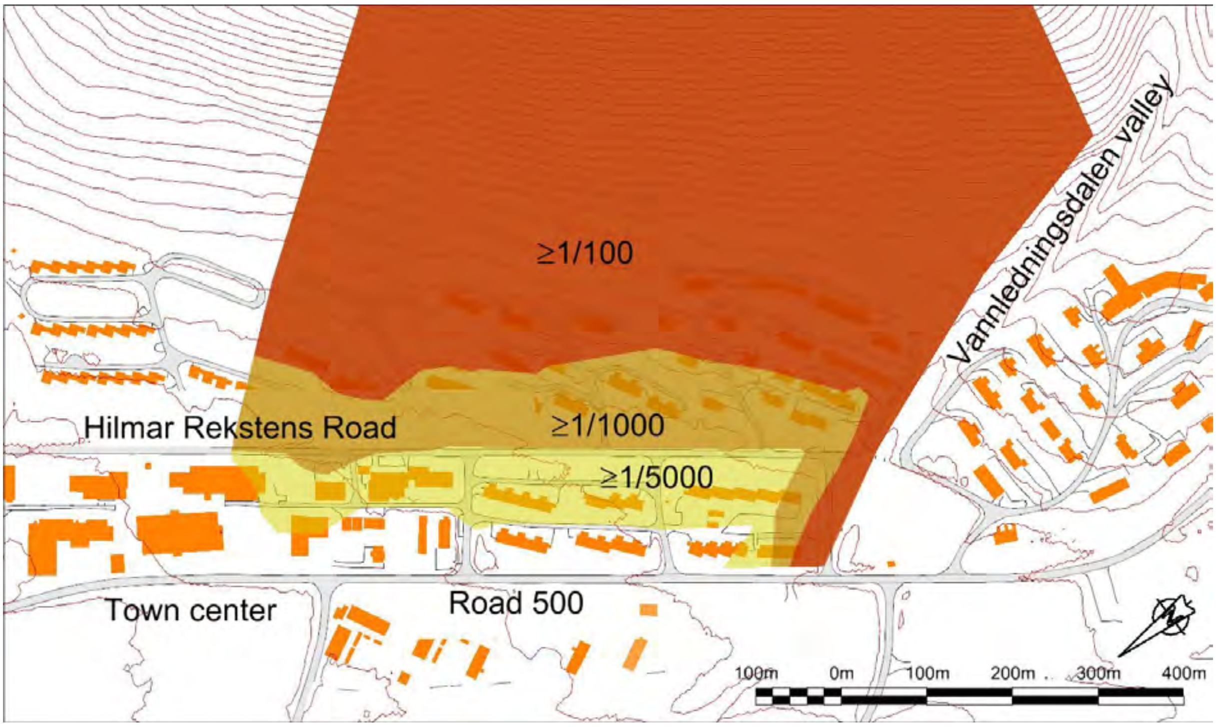

Figure 2. Hazard zoning for the Sukkertoppen area in Longyearbyen. Vannledningsdalen and the area on Haugen is not included in this hazard zoning.

criteria of these assessments have been questioned and it was therefore important to work on new criteria and hazard assessment for the ongoing mitigation work.

3. PLANNING FOR MITIGATION MEASURES

Through the years the discussion on mitigation measures in Longyearbyen has first and foremost been around Vannledningsdalen (slush flows) and Lia above town centre (dry snow avalanches) (Norges Geotekniske Institutt NGI, 2013, 1992, 1991). After the fatal accident in December 2015 the authorities initiated a hazard assessment work (Multiconsult AS, 2016) and at the same time a work on mitigation measures in arctic areas was introduced (Larsen, 2016). Mitigation work started in 2018 when the first phase of mitigation measures (snow fences, drainage canal and supporting structures) were built for the town centre (Jonsson et al., 2018b).

The second phase of the mitigation work was initiated in 2018 when NVE engaged consultants to work out a plan for mitigation measures for the area from town centre to Vannledningsdalen, see Figure 1. A preliminary report with various mitigation combinations and hazard zoning was delivered in December 2018 (Jonsson et al., 2018a).

3.1 Design criteria

One of the main challenges in this work was the lack of information on snow height in Sukkertoppen mountainside and Vannledningsdalen. This is information affects both hazard assessment and mitigation work. Two measurements, five cross sections from one “normal” winter are available from Vannledningsdalen and provide us an indication on the snow height. Observed annual precipitation at Svalbard airport is only 196 mm for the reference period 1971-2000 (Isaksen et al., 2017) and it is expected to increase with several tens of percent’s by the

Figure 3. The avalanche site during rescue operation in December 2015. This photo is one of the best information on snow conditions in Lia. The fracture line to the left is approx. 3 m and approx. 1 m to the right with estimated average height of 2 m and volume of approx. 15000 m³. Photo: Svalbardposten.no.

end of the 21st century. However, this scant observed annual precipitation does not say much about possible 24h precipitation in winter. The December 2015 event (Figure 3) is probably one of those cases where intense precipitation in combination with strong winds brings in a lot of snow due to a long fetch behind the slope and forms unstable snow cover. The snow height was roughly estimated to be in the range of 5-6 m on northern part of Lia (Norges Geotekniske Institutt NGI, 2018) but the height of accumulated snow on the northern shoulder of Sukkertoppen mountain is unknown. The release height of the avalanche in Feb. 2017 was measured to be approx. one meter at the fracture at top but neither the snow height nor the snow distribution elsewhere in the mountainside are known. However, there are several photos available from “normal” winters that show the distribution in the mountain side and that indicates large quantities at the shoulder and little snow in the middle of the mountain side.

The area to be protected can be divided into three locations, 1) the town centre, 2) Vannledningsdalen and Haugen area and 3) the area between those two areas, the “middle area”. In the ongoing work, areas 1) and 2) had the highest priority.

3.2 Mitigation alternatives

In (Larsen, 2016) protection of the residential area below Sukkertoppen mountain is discussed briefly and earlier NGI has proposed mitigation measures for the same area. In early 2017 NVE initiated a mitigation work for the 2015 avalanche accident area (Lia), shortly described in (Jonsson et al., 2018b). The second phase of the mitigation work was initiated in 2018 and a preliminary report on proposed mitigation measures was delivered in December 2018.

The initial work was a delivery of nine sketches or combinations of which five where chosen to be worked on further. For the town center two main concepts were studied, i) supporting structures in the starting zone and ii) a catching dam with or without braking mounds. For the

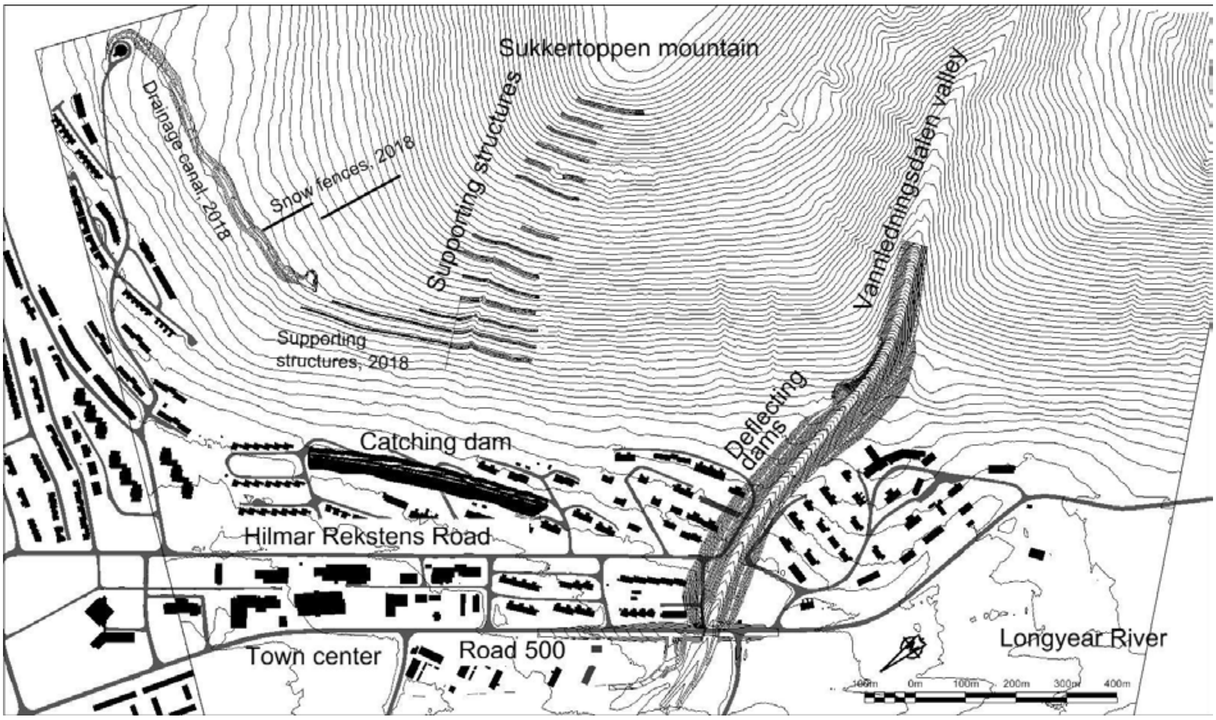

Figure 4. The figure shows Sukkertoppen mountain, Vannledningsdalen, town center and the residential area. Supporting structures, catching dam and deflecting dams are the chosen alternatives for Longyearbyen municipality. Mitigation measures built in 2018 are shown on the left side of the figure. The area between the catching dam and deflecting dams is according to cost/benefit analysis not feasible to protect and the buildings and other infrastructure will most likely be sanitated. Contour lines equidistance is 5 m.

Vannledningsdalen two concepts were studied, i) a curved deflecting dam (called "swing dam") that starts as deflecting dams but gradually diverts the flow out of the stream to an open space north of the valley, and ii) deflecting dams on both sides of the stream from Vannledningsdalen.

The chosen alternatives (Figure 4) shows approx. 1500 m of supporting structures with Dk height varying from 3.5 m to 5.0 m. The catching dam below the supporting structures is approx. 5.5 m high and its purpose is to stop small flows such as small avalanches, slush flow and debris flow from entering the town center. The impact side of the dam is supposed to be steep and of reinforced facing material. Total length of the catching dam is approx. 360 m.

The deflecting dams and canal between them is approx. 600 m long. The maximum height of the dams is approx. 14 m but most of the length above Road 500 it is 12 m. Below Road 500 the height is max. 7 m. The cross section of the dams is for the gentlest slope like 1:2 but it is necessary to build steeper walls to cope with the slush flow undulation. Fine tuning is still not finished.

It will be necessary to cut off Hilmar Rekstens road at the dams/canal but the bridge on the main Road 500 must be rebuilt to let most of the slush flow under. The crossing of the road and canal/dams will be challenging as the flow must pass the road with as little as possible of the flow masses flowing in direction of buildings. At the same time an aesthetic as well as wind and drifting snow must be considered for a dam which is 10+ m high at the road shoulder. In normal summer the river water never reaches Road 500 as surface water it is infiltrated higher up in the riverbed and it seems as part of it sinks out at the residential buildings near Road 500. To stop this infiltration can be a difficult task.

The permafrost conditions are a challenge here for all mentioned structures, especially when changes in climate are considered. Snow fence built in the winter and spring 2018 on northern side of Sukkertoppen mountain indicates a movement (solifluction) of 3–5 cm/y in slope inclination of 15–20°. The solifluction will affect the foundation of the supporting structures as well as the frost jacking which is considerable. The weight of the dams is of great concern as (Isaksen et al., 2017) and (I. Hanssen-Bauer et al., 2019) estimate that the permafrost will have disappeared in Longyearbyen by the year 2100. The consequences for the dams are uncertain but it might cause some settling of the dams and failure in the foundations.

3.3 Landscaping

Landscaping is an important part of this mitigation work specially the design of dams just above town center and the deflecting dams along the stream Vannledningselva. As of today, the involvement of landscaping architect has been minimal as the work until now has been conceptual rather than on details. Hints have though been given on some of the important and most visual part of these constructions. The landscaping work will be in close cooperation with the local authorities.

3.4 Hazard zoning

To make possible a cost/benefit analysis of the different mitigation concepts, hazard zones were made for each concept. These hazard zones were then used to evaluate which buildings could be left in the area after the measures were implemented, and which have to be removed.

4. EPILOG

The client NVE and LL decide to go for supporting structures as a mitigation measures for the town centre and deflecting dams along both sides of the stream from Vannledningsdalen.

When this article was written the work on the technical design and tender documents for supporting structures has just started.

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Wind simulation for Longyearbyen mitigation measures

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ABSTRACT
The national and local authorities in Norway have initiated the second phase of mitigation work in Longyearbyen Svalbard archipelago. The work is a continuation of earlier work carried out in 2017–2018 and the aim is to protect infrastructure, mainly houses and hotels, from processes as snow avalanches, slush flows and debris flows. The planned mitigation is a combination of physical structures and removal/relocation of buildings. Wind is not directly one of the processes leaving the infrastructure at risk but plays an important role in the snow distribution in this open and bare landscape. Any physical measures located near buildings will affect the local wind flows and it can cause unwanted snow accumulation or wind fields that can cause problems for the traffic.

The authors have earlier used wind simulation (CFD model) on a small-scale surface model to study wind fields around planned roads and highways, and mounds for snow avalanches. The aim of this work is to find out if planned deflecting dams made for slush flows along the river “Vannledningselva” will cause unfavourable wind fields for roads and buildings. Three wind directions were modelled with boundary windspeeds of 15, 20 and 25 m/s at three elevations 2, 5, 10 m height over the surface model.

1. INTRODUCTION

The aim of the second phase of mitigation work in Longyearbyen is to protect the residential area for dry snow avalanches from Sukkertoppen mountain and from slush flows from Vannledningsdalen valley. A preliminary study of mitigation measures for The Norwegian Water Resources and Energy Directorate (NVE) and the local authorities, Longyearbyen lokalstyre (LL) was carried out early winter 2018/2019 (Jonsson et al., 2018). The findings show that supporting structures in part of Sukkertoppen mountain together with a small catching dam in the runout zone will protect the centre of the town, and two deflecting dams alongside the Vannledningselva will protect the residential area below Hilmar Rekstens road and at Haugen area.

These two deflecting dams will start at the apex of the river/debris flow fan above the residential area at Haugen (Figure 1) and reach the main river, Longyear river, in the middle of the Longyear valley. The total length is approx. 600 m. The proposed measures have to cross the main road between Nybyen residential area and the town centre. The crossing is challenging in many ways such as how to divert the slush flow when it crosses/passes the road (where a new bridge will be built) and how to form the dam ends at the road side. Another problem the dams

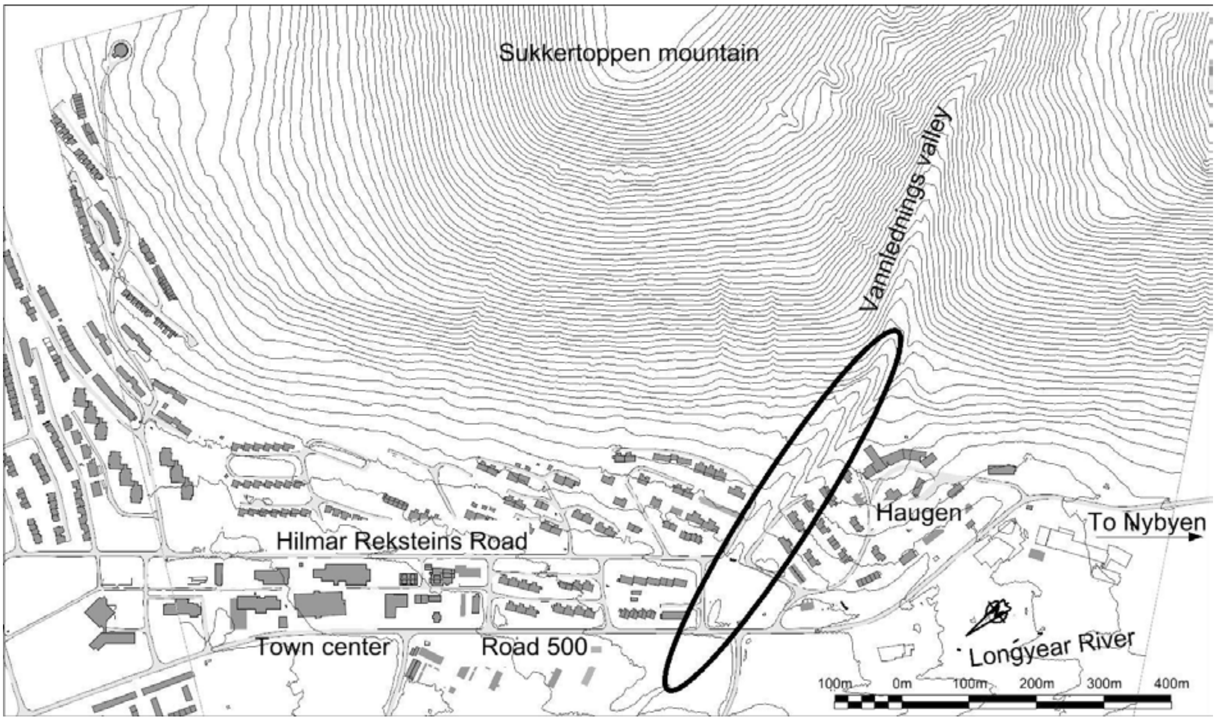

Figure 1 Overview over Longyearbyen and Vannlednings valley. The planned location of the deflection dams along the Vannledningselva is inside the ellipse.

will cause are wind currents and/or turbulences at the main road. Three main wind directions are thought to affect the road at the crossing. Wind is also the main contributor to relocation of snow and snow drifts can have unwanted effects on the roads and housing when the deflecting dams are in place.

Wind simulation for snow avalanche mitigation measures has previously been described in (Jónsson and Þórðarson, 2003) where wind fields and possible snow accumulation around mounds was studied and in (Þórðarson and Jónsson, 2005) where CFD simulation was used to try to understand snow drifts in an area with planned supporting structures in Hafnarhyrna mountain Siglufjordur Iceland.

One of the main concerns about the deflecting dams and planned new bridge is how much drifting snow will accumulate in the canal between the deflection dams during winter time and if the drifts will cause problems for slush flows to flow under the planned bridge in a slush flow incidence. Too much snow might require removal of it in order to maintain the function of the canal and bridge. Concerns are also raised about snow drifts around buildings and reduced visibility and drifts at Road 500.

The main purpose of the wind simulation is to map the wind fields around the deflecting dams at micro scale and to interpret how snow will accumulate.

2. WINDSIMULATION METHOD

There is a broad variety of CFD models on the market that can simulate wind, but fewer models simulate drifting snow. The authors have some experience of wind simulation and interpretation of the wind fields but much less experience with these particle CFD models. Neither the budget nor the time frame allowed for the study of particle CFD models.

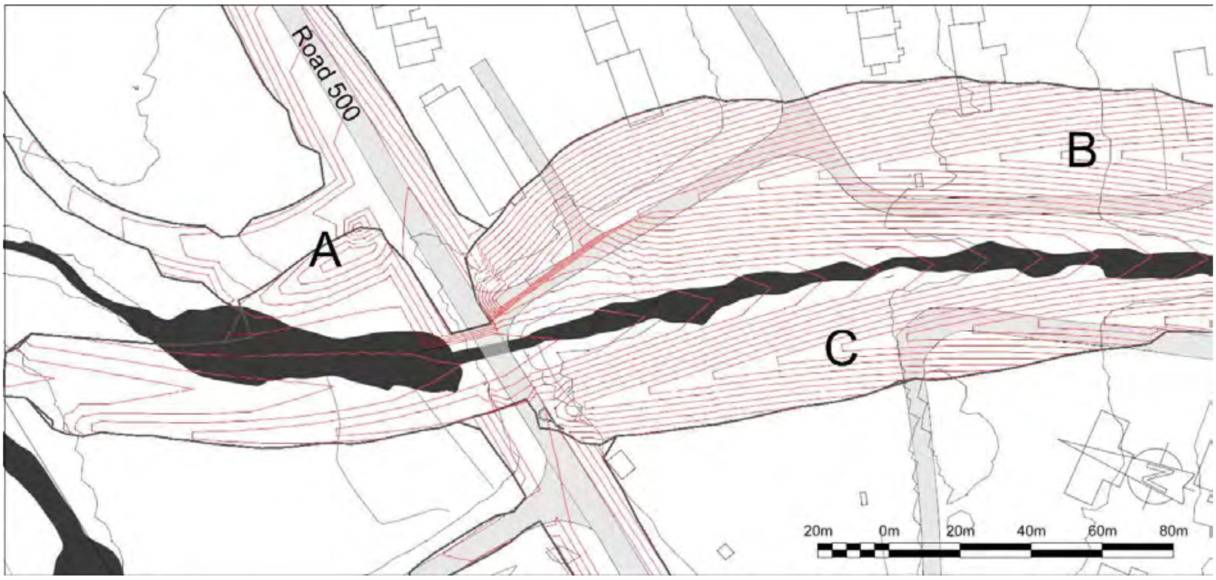

Figure 2 The figure shows Vannledningselva (dark shapes), Road 500 and the planned deflecting dams on both sides of Road 500 (red contours). Letters A-C depict top of dams. The distance between contour lines at the dam is 1 m. This digital elevation model of the deflecting dams was used in the wind simulation in early stage, but the final design will be somewhat different at Road 500, but it is expected that the main principles will be the same. The model shows the cut through road 500 for the river.

The wind flow was simulated using the WindSim software which is a specialized tool for wind simulation in complex terrain. The engine of WindSim is a PHOENICS solver which is a general-purpose CFD software package widely used in different industrial and research communities.

The digital surface model (DSM) for the area is based on a high-resolution point cloud model were existing buildings were part of the model. The deflecting dams were merged onto the DSM with grid resolution of 2 m. In addition, Aster Gdem v2[1] Worldwide Elevation Data was used for the outer domain. Roughness is based on GLC30[2] and roughness contours manually captured from Google Earth imagery. The size of the DSM was 2,4x2,65 km and the total simulation domain is a box with dimension of 2,4x2,65x4,7 km. The total number of cells was approx. 2,9 million (WindSim AS, 2018).

The inlet wind directions were: 40°, 220° and 340° and wind speed 10 m/s, 20 m/s and 25 m/s. In total 9 simulations were performed to have 3D wind field for ±15° around the inlet directions. Wind velocity plots are shown at 2 m, 5 m and 10 m above ground for the wind direction of 40°, 220° and 340°. The wind directions 40° and 220° are in and out Longyear valley and 340° is along Vannlednings valley. The wind directions 40° and 220° are used in the further work as they represent wind approx. perpendicular to the dams.

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[1] https://asterweb.jpl.nasa.gov/gdem.asp
[2] Global Land Cover with 30 m resolution.

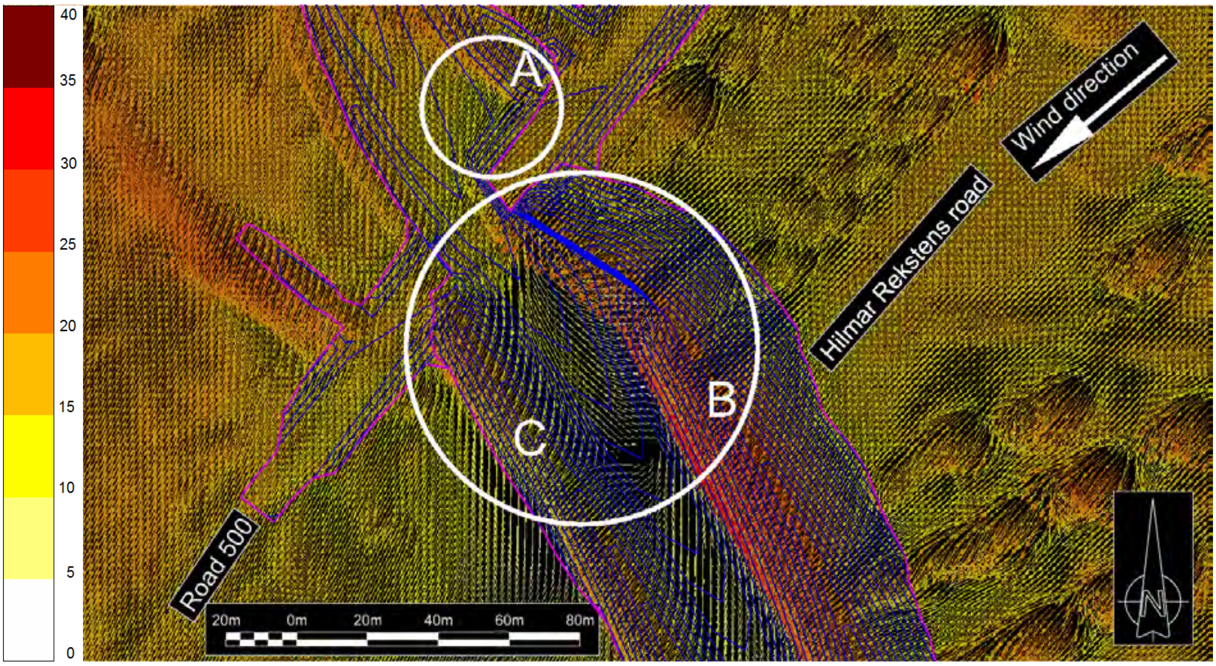

Figure 3 The figure shows wind speeds as colored vectors. Wind speeds in m/s are shown on the scale to the left. The deflecting dams and Road 500 (blue contour lines) are shown as blue contour lines in the background. Boundary wind direction (40°) is shown at the upper right corner and boundary wind speed is 20 m/s for wind 2 m over surface. Letters A-C shows the location of the dams.

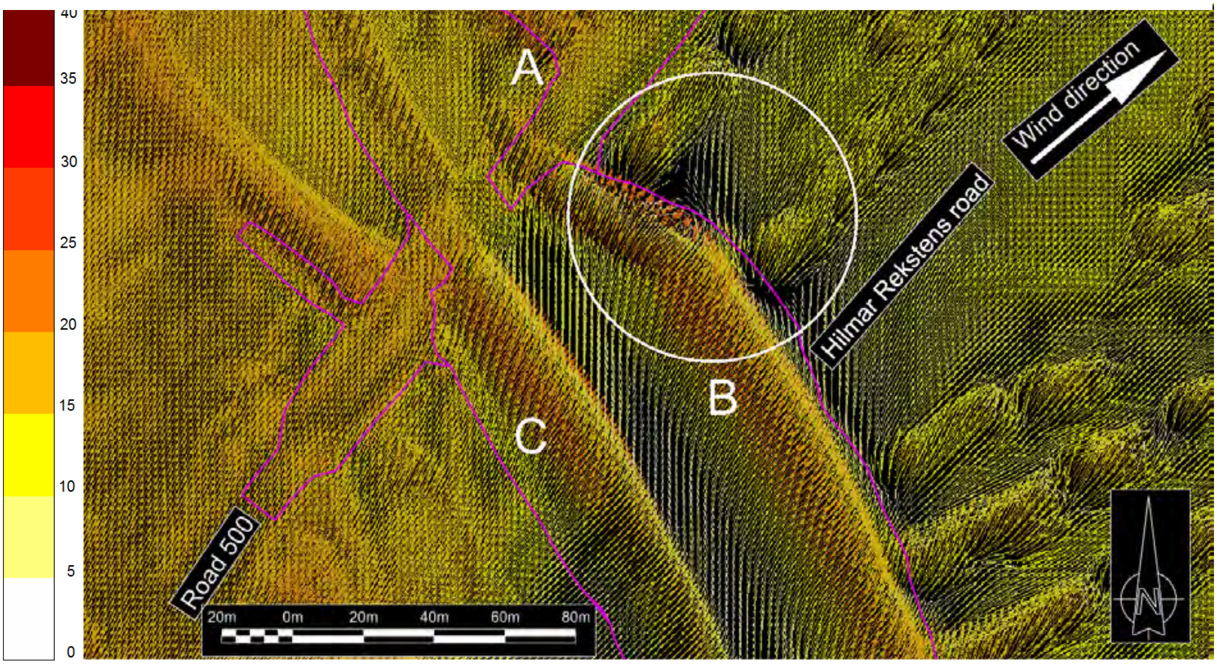

Figure 4 Wind speeds are shown here as colored vectors. Wind speeds in m/s are shown on the scale to the left. The deflecting dams and Road 500 (purple outlines) are shown in the background. Boundary wind direction (220°) is shown at the upper right corner and boundary wind speed is 25 m/s for wind 2 m over surface. Letters A-C shows the location of the dams.

3. RESULTS

The results from the high-resolution wind simulation at the crossing of Road 500 and the deflecting dams are shown in Figure 3 and Figure 4. No wind simulation has been done for the existing terrain/surface and infrastructure and therefore we do not know if wind from 40° or 220° will cause increase in wind and snow drift accumulation due to the dams.

Figure 3 show relative strong wind flow along the Road 500 past dams A and B (see also numbering in Figure 2). A small "lee" zone can be seen below the Road 500 and dam A. The most important and interesting area is between dams B and C and Road 500. The wind simulation indicates a large lee zone up to 100 m from Road 500. At the same stretch the dam height is changing from 8 m near the road to 12 m further up. The vector lines show the wind blows around the dam end at the road and then turns up the canal; part follows the steep dam face at northern deflecting dam and a bit stronger wind turns to the south and passes the southern deflecting dam (C). The wind blows also over the dam top and it is quite strong. A combination of these wind fields seems to cause a vortex starting at Road 500 and fading out approximately at line between B and C on Figure 3 (the black spot in the canal). A contributor to all this might also be the wind around the buildings along Hilmar Rekstens road which also hits the dam just about where the dam has reached its highest part. Snow drifts can expect from the road and upward in the canal. It is also interesting to see how the buildings below and above Hilmar Rekstens road contributes to lower wind speed at the dam compared to the open space at Hilmar Rekstens road.

Further up the dam one can expect cornices at lee side of dam top on both deflecting dams. The wind simulation shows the wind blowing up the canal for some 40-70 m before the it turns to south and over the south deflecting dam C.

As mentioned earlier the wind simulation indicates increase in wind on Road 500 at the dam crossing for wind blowing in the valley (40°). Prior to the wind simulation work snow drifts were expected to form at the end of the dams at the road but the simulation does not indicate this in the same extend.

For wind direction out the Longyear valley (220°) the wind simulation indicates much less force in the wind at the deflecting dams than for the opposite wind direction (Figure 4); here wind speed is 25 m/s to make coloured vectors more visible. The residential area on Haugen contributes to relatively large lee area from the buildings to dam C. Interesting is the lee side just above Road 500 north of dam B. Wind that passes the dam hits the roof tops with little lower wind speed but between the buildings and the dam appears to be a vortex that might contribute to snow accumulation at planed pathway and buildings at the north side of the dam.

Above the residential area, at the apex of the fan, the simulated wind flows partly down Vannlednings valley between the dams and large cornices are not expected but further down cornices are expected.

A similar condition to the upper part of the dams at Vannledningselva are the catching dams in Bolungarvik Iceland, Figure 5. Wind did blow along the dams and none or only small cornices were formed at dam top. Further to the left (outside the figure) a curvature in the dam geometry caused a lee area outside the dam where snow accumulated. The opening between the dams canalize the wind and that might help clearing the dam slopes of snow.

Figure 5 Snow drifts around houses and catching dams in Bolungarvík Iceland after a storm period; wind was blowing from upper right corner to the left, see yellow arrow. Source: Google.com/Maps.

4. CONCLUSIONS

The deflecting dams discussed in this work have not yet been built and therefore we cannot verify the findings discussed in this article. The wind simulation results are interpreted and correlated to the authors knowledge from other works and observations from real dams and residential areas. The authors claim that wind simulation software like in our case WindSim are useful tools for studying small scale wind fields around mitigation measures like dams. From the wind fields the snow accumulation areas can be predicted by studying the gradient and lee areas but the limitation is that the volume of snow cannot be predicted.

It will be interesting to follow up this work when the deflecting dams have been built, maybe around 2024-2025, and some experience has been gained from winter conditions.

ACKNOWLEDGEMENT

The authors would like to thank NVE and LL for giving access to wind simulation data from the mitigation work (Jonsson et al., 2018).

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Avalanche hazard mapping and mitigation for settlements in Iceland – an overview

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ABSTRACT

After two catastrophic avalanches in 1995, that killed 34 people in their homes, laws and regulations regarding avalanche hazard in Iceland were changed and the hazard management responsibilities of the involved governmental agencies and institutes were clarified. Since then, hazard zoning has been carried out for 23 towns and villages in Iceland where there is some avalanche hazard. Local governments are required to take actions to mitigate the risk for settlement with some residential houses in red zones according to the hazard maps. Most of the houses in the worst areas have been protected. The Icelandic Meteorological Office is responsible for avalanche monitoring for settlements and evacuation of houses during avalanche cycles. Without avalanche protection, the areas with the greatest hazard would often be evacuated. The protection measures that have been built both improve safety and reduce the discomfort associated with avalanche cycles for the inhabitants. They also make the daily avalanche monitoring for settlements easier by reducing number of areas that need monitoring during "normal" avalanche cycles. Avalanche hazard assessment has also been carried out for a great number of farms and recreational buildings in rural areas where the new regulations require hazard assessments for all new buildings.

1. INTRODUCTION

After two catastrophic avalanches in 1995, that killed 34 people in their homes, laws and regulations regarding avalanche hazard in Iceland were changed and the hazard management responsibilities of the involved governmental agencies and institutes were clarified. The Icelandic Meteorological Office became responsible for hazard zoning, avalanche monitoring, evacuation of endangered areas in collaboration with civil defence authorities and technical advice to the government regarding avalanche protection measures.

2. HAZARD MAPPING

According to laws and regulations about avalanche safety, the Icelandic Meteorological Office (IMO) is responsible for hazard zoning in Iceland. It has been decided to use annual probability of an individual being killed in an avalanche as a measure of avalanche risk (Jónasson and others, 1999). The acceptable risk according to the regulation is 0.2 of 10.000 per year (local risk of 0.3 of 10.000 per year if continuous presence in the endangered area is assumed) and areas with unacceptable risk are divided into three hazard zones (A, B and C, also denoted with the colours yellow, blue and red) with increasing level of risk with the C-zones having the highest risk.

After the regulation change, following the avalanche accidents in 1995, hazard zoning has been carried out for 23 towns and villages where some avalanche hazard was considered likely. Hazard zoning has, furthermore, been carried out for two ski areas. Avalanche hazard assessments have also been carried out for a great number of farms, recreational buildings, hotels and other constructions in rural areas where the new regulations require hazard assessments for all new buildings. This type of hazard assessment has become more important in recent years with increased tourism in Iceland. Hazard assessments have now been made for over 130 such locations in rural areas, see Figure 1. Hazard management related to thawing permafrost and landslides on downwasting glaciers due to warming climate has also come up as an urgent task in recent years.

Figure 1 Areas where hazard due to snow avalanches and landslides has been assessed in Iceland since 1995. The black points show settlements and ski areas. The white points denote locations in rural areas where hazard assessments have been made.

3. AVALANCHE PROTECTION

Local governments are required to act to mitigate the risk for settlements with some residential houses located in C-zones according to hazard maps. Many houses in the worst areas have been protected with avalanche defence structures but several areas with some residential houses in red zones remain to be protected. The avalanche hazard zoning of protected areas is updated to take into account the improved safety provided by the protection measures.

4. EVACUATIONS

The IMO is responsible for monitoring of avalanche danger for settlements and evacuation of houses during avalanche cycles in collaboration with civil defence authorities. There is a high uncertainty in avalanche monitoring. Those involved try to be on the safe side and expect to evacuate houses many times without the houses being hit by an avalanche. Without avalanche protection measures, the areas with the greatest avalanche hazard would often need to be evacuated, in some cases many times in the same winter.

The settlement of Bolungarvík, for example, had the most frequent evacuations of all settlements in Iceland before it was protected by two catching dams and a row of braking mounds, built between 2008 and 2012. Figure 2 shows the number of houses evacuated in the settlement as a function of time. For comparison, evacuations of an industrial area in the neighbouring town of Ísafjörður is also shown in the figure. The area in Ísafjörður is unprotected and is thus still regularly evacuated. There are roughly 10 km between the areas and the mountains above have similar aspect. When both areas were unprotected, houses were always evacuated in Bolungarvík when an evacuation was ordered in Ísafjörður and in some additional cases in Bolungarvík. It cannot be stated that this pattern would have continued but it is clear that without the protection measures, the buildings in the affected area in Bolungarvík would have been evacuated several times since the dams were built. The protection measures that have been built since 1995 have greatly improved the hazard situation in many settlements in Iceland. They both provide safety and reduce the discomfort associated with avalanche cycles for the inhabitants. They also make the daily avalanche monitoring for settlements easier by reducing number of areas that need monitoring during “normal” avalanche cycles because protected areas such as in Bolungarvík are not of regular concern.

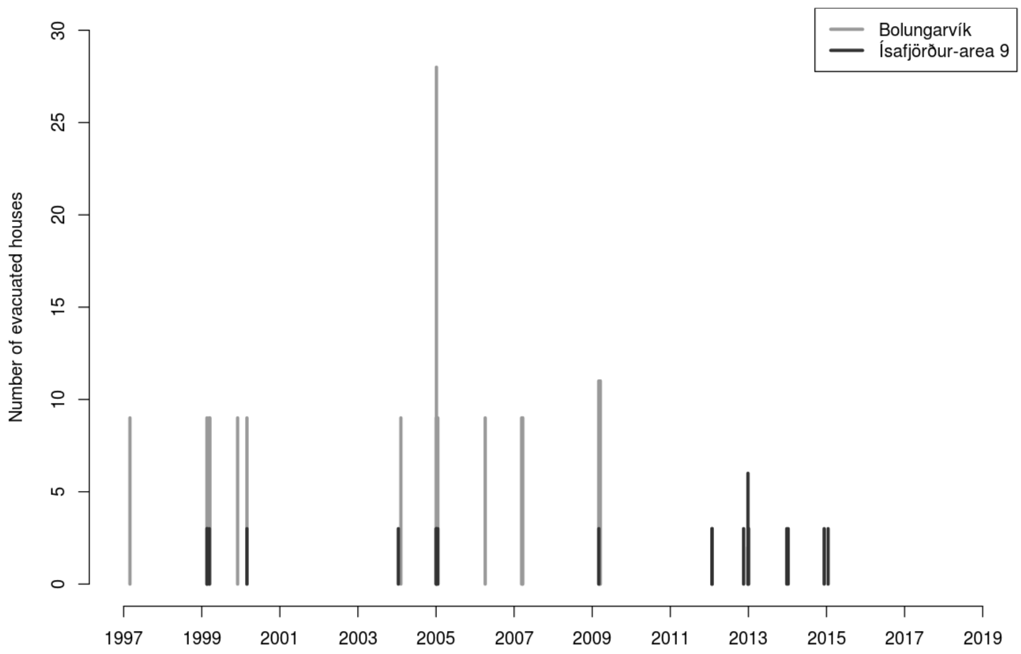

Figure 2 The number of evacuation of houses in Bolungarvík and the most exposed evacuation area in the neighbouring town of Ísafjörður. The settlement in Bolungarvík has been protected with two catching dams and a row of braking mounds built, between 2008 and 2012.

5. CONCLUSIONS

The presentation will give an overview of the status of hazard zoning in Iceland with a focus on changes in hazard management after a substantial number of settlements have been protected with permanent structures, and on future tasks and challenges. The protection measures that have been built, following hazard zoning where residential houses have been judged to be located in C-zones, both provide safety and reduce the discomfort associated with avalanche cycles for the inhabitants. They also make the daily avalanche monitoring for settlements easier by reducing number of areas that need monitoring during “normal” avalanche cycles. An increasing number of requests for hazard zoning have been received in recent years in connection with buildings in rural areas, in particular recreational buildings and buildings associated with tourism. It is foreseen that future hazard assessment work in Iceland will mainly deal with avalanche hazard in ski areas, rural areas and reassessment of hazard where protection measures have been constructed as hazard assessments have now been made for all threatened towns and villages. Hazards due to landslides from thawing permafrost and steep slopes above downwasting glaciers are also of growing concern.

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Effectiveness and maintenance of technical avalanche protection measures in Switzerland

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ABSTRACT

In Switzerland, supporting structures are the most important structural avalanche protection measure with replacement costs of around CHF 1.5 billion. The analysis of the snow-rich winter 2018 gave new insights into the effectiveness and vulnerability of protective measures. The effectiveness and maintenance are important aspects in the service life of a protective measure. For efficient maintenance, a register of protective structures and periodic inspections are required. In future, maintenance will be more important than the construction of new protective measures.

1. INTRODUCTION

Switzerland has a high natural hazard risk. This is due to the mountain topography, to the very dense population and the large number of infrastructure facilities. Today's settlement patterns and societal functioning would not be possible without the existing protective measures. Around 22% of the Swiss population lives in flood-prone areas. The risk of avalanches is much lower. Less than 1% of the population lives in areas endangered by avalanches. In order to counter this risk, protective measures against natural hazards amounting to around CHF 50 billion have been implemented (Martin, 2009). The proportion of technical avalanche protection measures is much smaller. Estimates show that around CHF 2 billion has been invested in technical avalanche protection over the past 50 years. Supporting structures are the most important permanent structural protection measure in Switzerland. Today, more than 500 km of permanent supporting structures exist, with an estimated replacement value of CHF 1.5 billion. Major efforts are required to maintain the high safety standard. Two important tasks which are discussed in greater detail below are i) the analysis of the effectiveness and vulnerability of mitigation measures during major avalanche cycles such as in winter 2018 especially regarding the rezoning of hazard maps and ii) the management of maintenance to preserve the effectiveness of the mitigation measures.

2. AVALANCHE WINTER 2018

The analysis of avalanche winters provides valuable information to be able to verify the functioning of the protective measures in realistic situations. In January 2018, 2.5 to 5 m of snow fell widely at high elevations in the Swiss Alps over a period of 25 days. This was as much new snow as registered at certain stations every 75 years. On 22-23 January, a north-west storm led to a serious avalanche situation. The highest hazard level (5, very high) was forecasted for a widespread area for the first time since 1999. Many large and several very large avalanches occurred, with the cantons Valais and Grisons being most severely affected.

The humid snowpack at medium elevations slowed down the avalanches, which released as dry avalanches higher up, so that no settlements were hit. In some cases, however, they were only just missed. By the end of April, more than 360 destructive avalanches had been reported to the SLF. No permanently inhabited buildings were destroyed and no people were injured in settlements or on traffic routes. Numerous traffic routes were closed for up to 9 days due to avalanche danger. However, the 2018 avalanche winter was less extreme than the avalanche winter 1999. For the first time satellite images (SPOT 6) with a resolution of 1.5 m of all areas with hazard level 5 (very large) were evaluated to document the avalanche activity (SLF, 2019). More than 18'000 avalanches were mapped in the investigated area of 12'000 km^2, which covers about 50% of the Swiss Alps. Around 16% of the avalanches surveyed had a volume exceeding 80'000 m^3 and started in southern to eastern aspects.

3. PERFORMANCE OF MITIGATION MEASURES IN WINTER 2018

3.1 Snow supporting structures:

In January 2018 the snow distribution was rather irregular due to wind. As a result, several areas with supporting structures were locally overfilled with snow (Figure 1). Since an increase in snow depths was to be expected in the further course of the winter, emergency measures were drawn up in case new snowfall events overfill the structures extensively and reduce the effectiveness of the controlled areas. Surprisingly, relatively large avalanches triggered in around 10 sites with supporting structures during the avalanche cycle of 22/23 January 2018 (Figure 2). The fracture depths of these avalanches were rather small, mostly in the range of 0.5 m. Since the supporting structures were usually not completely filled with snow, the avalanche snow was slowed down and partly stopped by the lines of structures. The steeper the terrain and the more the structures were prefilled with snow, the less avalanching snow could be retained. With regard to the fracture propagation, the lines of structures showed practically no effect in some cases.

Figure 1 Supporting structures in the Valais, in the centre the structure height is 6 m. On 24 January 2018 the snow height was locally > 8 m (Photo J.J. Lugon).

Figure 2 Supporting structures in the Bernese Oberland, on 22 January 2018 a large slab avalanche released within the controlled area (Photo U. Ryter).

The snow masses flowing out of the controlled perimeter were mostly small and caused no or only insignificant damage. As a result of high snow depths and strong snow gliding, the snow pressure loads on supporting structures were high in winter 2018. Consequently several supporting structures were damaged. In most cases, the damage was local and did not or not yet significantly affect the function of the structure. In the winter of 2018, the total amount of damage to supporting structures amounted to around CHF 1.5 million. In comparison to the total number of supporting structures, this figure is in the per mil range. The most frequent damage was to the valley-side buckled steel supports of snow bridges. Around 200 supports from older structures buckled out, because in addition to the normal force, a transverse force occurred (Figure 3; Margreth, 2007). The snow layer below can cling to the supports. In some snow-covered structures, girders and cross-beams broke or were bent. Such damages typically occur if a structure is overfilled with more than 1.0 m of snow. In some locations, where the distance between the lowest crossbeam and the ground was large (> 0.3-0.5 m), the uphill anchor bars were deformed or broken (Figure 4). This damage typically occurred in connection with strong snow gliding.

Figure 3 Buckled supports of end of line structures in the Valais. No lateral snow pressure was considered in the design (Photo Nivalp SA, 2018).

Figure 4 Deformed crossbeams and anchors because of a too large gap between lowest crossbeam and ground, canton Uri (Photo R. Planzer, 2018).

3.2 Snow drift fences

The combination of snow drift fences and wind baffles was efficient in conditions with snowfall and strong winds. Detailed observations are available from the snow drift fence at Tanngrindel in the Bernese Oberland. The 4 m high and about 90 m long fence reduces snow accumulations in an avalanche release area. The fence is located at a distance of 30 m from the edge of the terrain. On 27 January 2018, a laser scan-based snow depth map was prepared. Behind the fence about 40 m^3 snow per m was deposited. The maximum deposition height was slightly over 4 m. A total of about 5000 m^3 of snow was retained by the fence. Significant damage occurred at a 275 m long snow drift fence at Valtschamela in the canton Grisons, which was constructed in a 25° to 30° slope. Since the ground gap of the 4 m high fence was only about 40 cm, the fence was covered with snow relatively early in the winter. As a result snow pressure acted on the fence. Several steel girders and anchors were bent in the direction of the valley (Figure 5). The snow drift fence must be completely rebuilt. In inclined terrain, snow pressure as well as wind loads must be taken into account for the design of snow drift fences.

Figure 5 Snow drift fence damaged by lateral snow pressure acting in the line of slope, Valtschamela, canton Grisons (Photo S. Margreth, 2018).

Figure 6 Deflecting dam made of snow, canton Valais (Photo W. Gitz, 2018)

3.3 Snow sheds and avalanche dams

At least 50 snow sheds were hit by avalanches in January 2018. One problem with snow sheds is their length, which is often planned to be as short as possible for financial reasons. At least ten snow shed portals were overflowed laterally. The structure of a snow shed protecting a railway line was damaged due to lateral snow pressure. A number of avalanches occurred in avalanche tracks protected with dams. However, only few avalanches reached the dams. In the Lötschental (Canton Valais), a site with supporting structures was largely destroyed by an avalanche in winter 1999. In order to protect the village and the supporting structures from avalanches, a 380 m long and 10 m high wedge-shaped deflection dam was constructed on a terrain terrace above. In January 2018, an artificially triggered avalanche reached a similar size as in 1999. The snow masses were completely deflected by the dam. At the upper end of the dam, the snow masses practically reached the top of the dam. In the Matter valley, 3 to 7 m high dams of snow were built in the lower part of four avalanche tracks in order to prevent the railway from being buried by subsequent avalanches, which could have a longer runout than usual in the smoothed out avalanche tracks (Figure 6).

4. MAINTENANCE MANAGEMENT IN SWITZERLAND

4.1 Overview

In Switzerland, protection against natural hazards is a joint task of the Confederation, cantons and communes. For the management of protective structures, this means that the Confederation issues the legal base, defines a minimum data model for the protective structure register and ensures partial funding. The cantons keep the register of protective structures and ensure their maintenance. The communes periodically check the protective measures they own and carry out simple repairs themselves (Frei, 2013). In the case of major maintenance measures, they receive technical and financial support from the Confederation and the canton. In the future, the focus will be on preserving the existing protective structures and not on constructing new ones. The goal of protective structure management is to achieve the longest possible service life for the structures. Since the effect of the protective measures is considered in hazard maps, structural safety and serviceability must be guaranteed. Both are influenced by aging. In the case of supporting structures, the quality of the building materials, the construction work, the climatic conditions, the effect of snow pressure and the geotechnical situation are decisive. Snowy winters and heavy rainfall with erosion can lead to faster aging. Timely execution of maintenance measures can have a positive counter-effect on aging. In order to be able to carry out maintenance measures in time and to know the long-term financial need for maintenance, an overview of the number and condition of all structures is required. A functioning protective structure management system includes a register of protective structures, a manual for structure inspections and multi-year planning.

4.2 Protective structure register

The register is kept by the cantons and gives an overview of "what measure is where and in which condition". An administrative data base contains all relevant information on the project perimeter such as name, commune, owner, person responsible for periodic on-site inspection, inspection cycle, protection goal, year of construction and cost. A spatial database contains the positions of the single structures with attribute tables showing the structure number, structure type, year of construction, structure height, foundation type, anchor length, date of inspections with structure state, observed damages, repair cost and so on (Figure 7). Additionally an archive of the project files such as the extent of the project perimeter, structure drawings, protocols on anchor pull-out tests and grout checks as well as correspondence and photos. The numbering of the structures is very important to allow on-site identifcation.

Figure 7 Protective structure register Canton Graubünden with extract of the map server, overview photo and structure numbering

4.3 Manual for structure inspections

Several cantons have developed a manual for the structure inspections (AWN et al., 2018). The two-stage procedure consists of an inspection of the single structure and an overall evaluation of the protection goal. The inspection on site is carried out visually by going from the general to the detail. Large-scale slope failures, local soil movements or soil erosion can lead to structural damages. The assessment of the geometry of a line of supporting structure often provides indications of possible damage. The single superstructure is analyzed visually typically in regard of deformation or failure of steel members or wire ropes, geometry changes, displacements of steel bed plates, erosion around foundations and cracks in anchor grout or concrete foundations. The manual contains a checklist with photos which show the most relevant and frequent damages or defects of supporting structures (Table 1).

Table 1: Example of a check-list for evaluating the state of crossbeams

Crossbeams	Damage and cause	Maintenance
	Crossbeams with dents, deformation or formation of cracks. Check if the girder is also deformed. Too high snow pressure (snow gliding, overfill with snow), impact of rockfall, impact of avalanches.	None, observation. Repair (straightening) Replacement
	Defect fastening of the crossbeams: broken brackets, missing screws, loose screws, shifted fastening rail. Particularly tricky when the direction of the crossbeams changes (convex position). Snow pressure, rockfall, wind load (vibrations).	Replacement; tighten screws.
	Missing crossbeams. Vibrations because of varying wind loads, avalanche impact, rockfall, overlapping of main and intermediate crossbeams often too small.	Replacement; check that overlap of main and intermediate crossbeam is > 5 cm; the planned distance is typically around 25 cm.
	Filling of the supporting plane with stones and earth. Problematic if the effective height is smaller than approx. 50 cm. Deposit from rockfall, erosion or landslide.	Removal of deposited material if thicker than 50 cm. Evaluate the cause of the ground instability and fix it if necessary.

The inspection made by local foresters or engineering companies is done as a negative check by documenting only damages. It is preferable that the inspection is always carried out by the same person, in order to detect changes better. The corresponding documents exist for reporting. The damages are classified into five condition classes (Table 2). Condition class 1 means very good, it is a new structure. Condition class 5 means alarming, i.e. the structure is heavily damaged or destroyed and should be repaired immediately. The most common forms of damage to supporting structures are deformations of the superstructure and foundations due to great snow pressure resulting from severe snow gliding or when the structure is overfilled with snow. The worst damage occurs during dynamic avalanche impact, especially if an avalanche enters the defense area from the top or the sides.

Table 2 Condition evaluation of snow supporting structures (AWN et al., 2018)

Condition level	State characterization	Urgency for maintenance	Time horizon for consequen-tial damage	Example of damages
1 very good	New structure	None	-	-
2 good	As good as new until first signs for aging	None	-	Natural aging, small deformation of cross beams
3 sufficient	Small damages, structural safety and serviceability fulfilled	Small urgency, observation	> 5 yrs.	Bent cross-beams, erosion around foundation < 10-20 cm, debris on the grate < 50 cm, uniform corrosion (rust)
4 poor	Damages and weak points, reduced structural safety, serviceability mostly fulfilled	Middle urgency, maintenance required in 1-2 yrs.	2-5 yrs.	Slightly buckled posts, a pressed in micropile, eroded anchors > 20-40 cm, displaced cable clips
5 alarming	Risk of collapse, structural safety and serviceability very limited	High urgency , maintenance required in less than 1 yr.	< 1 yr.	Buckled supports, broken or pulled out anchors, broken girders, broken wire ropes

The inspection cycle depends on the geotechnical conditions of the site, the snow situation (e.g. area with strong snow gliding), the complexity of the perimeter, possible rockfall activity, type, age and vulnerability of structures and the results of the former inspections. A rough visual inspection is performed yearly. A more detailed inspection where all structural members and foundation components are closely verified visually is performed at intervals of 1 to 5 years and after snow-rich winters. Specific inspections e.g. performing anchor pullout tests are arranged if the uncertainty on the structural state is very high or if a bigger maintenance project is planned. For future anchor pullout tests additional anchors representative of the types installed are drilled and marked accordingly.

The causes of damage to supporting structures can be systematized by differentiating between internal causes that directly affect the structure and external causes such as effects from the environment (Table 3). Further the two causes can be subdivided into typical causes such as normal aging or normal snow pressure loads and atypical ones such as design errors or the impacts of rockfall or avalanches not considered in the design. Atypical external causes are usually unpredictable, but can cause great destruction.

Table 3: Overview on causes of damage to snow supporting structures (Rudolf-Miklau et al., 2015)

Influence	Internal cause for damage (structure / material)	External cause for damage (effects from the environment)
Typical (predictable): considered in the design process of a supporting structure	Material aging (corrosion, embrittlement), load changes (material fatigue)	Snow pressure, impact of snow slides, erosion
Atypical (often unpredictable): not considered in the design process of a supporting structure	Material defects, design faults, construction defects, planning errors	Avalanche impact, cornice collapse, rock and block fall, falling trees, strong erosion, storm

5. CONCLUSIONS

The compilation of event analyses of avalanche winters is helpful for verification of the performance of protective measures in extreme avalanche situations. The 2018 avalanche winter showed that supporting structures do not provide 100% safety. Each protection measure is designed for a specific scenario. If this scenario is exceeded, there is a residual risk. Winter 2018 showed some weaknesses in protective measures that need to be eliminated. In Switzerland, maintenance will be more important in future than the construction of new protective measures. This requires efficient management of protective structures, which typically consists of establishing a register of structures and carrying out inspections. In the case of older structures, a conceptual review must be carried out from time to time to determine whether the structures still meet current requirements or whether a change in strategy is indicated in the protection concept. It is also conceivable that there are situations in which maintenance is no longer worthwhile and the dismantling of protective measures is envisaged.

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Snow2019_NVE.RN_The Norwegian way of preventing nature hazard

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ABSTRACT

The Norwegian Water Resources and Energy Directorate (NVE) is a directorate under the Ministry of Petroleum and Energy. In 2009, NVE was given the authority and responsibility for natural hazards concerning snow avalanches. The responsibility is connected to spatial planning for the future, risk reduction for existing houses, hazard mapping and avalanche bulletins, flood warnings, landslide warnings and weather warnings. We will describe how this authority is defined and what it means that we are assisting the municipalities in the management of this hazard.

We will also mention the avalanche forecast on www.varsom.no/en and debate how avalanche forecasts can be used as risk assessment.

Geomorphic signatures of different debris-flow release processes in Ísafjörður, north-western Iceland

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ABSTRACT

Debris flows, fast-moving bodies of poorly sorted debris material mixed with water and/or air, pose a direct threat to many towns in Iceland. Distinguishing the release processes of debris flows and their associated geomorphic features help in anticipating new events. Two initiation mechanisms have been recently hypothesised for the debris flows occurring on the slope above Ísafjörður (NW-Iceland): slope failure and the "fire hose" effect. Slope failure is characterised by discrete failures that evolve into debris flows, favoured by steep slopes and high pore-water pressures. The "fire hose" effect arises when debris accumulated within a pre-existing channel is remobilised and transported by a surge of water, developing into a debris flow. We identify the geomorphic evidence to distinguish between these two debris-flow initiation mechanisms. We compare two datasets of airborne LiDAR elevation models and aerial photographs collected in 2007 and 2013. We report that a new generation of debris flows is initiated by slope failure, meanwhile older generations may be regenerated by the "fire hose" effect when debris accumulated in channels is remobilised by a later injection of water. These older channels can store deposits at rest angles over 35°, and form a potential hazard for inhabited areas downslope.

Methods for avalanche protection on roads in Finnmark in Northern Norway

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ABSTRACT

The Northern Norwegian road network often connects remote communities to central parts of the country through avalanche alpine landscape. These communities are often vulnerable to isolation due to avalanche hazard on the road and no detour possibilities. These are mostly low-traffic roads with important transportation such as fresh fish for the European market.

In order to reduce road closures and increase safety for road users due to avalanche hazard in a cost effective approach on low traffic roads, the Norwegian Public Road Administration (NPRA) utilize different methods. The avalanche protection methods are under continuous improvement inspired by new technology and projects from other parts of "the avalanche world". The presentation will show the planning and choice of methods in some projects with avalanche protection in Finnmark County, the northernmost part of Norway at about 71 degrees north.

We will also present some experiences with the use of active avalanche control through the last winter seasons. Conditions are often challenging due to extreme arctic climate and lack of daylight during midwinter.

The importance of the Icelandic Avalanche and Landslide Fund for avalanche-prone areas in Iceland

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ABSTRACT

The Avalanche and Landslide Fund has played an important role in increasing the safety of the inhabitants of avalanche-prone municipalities in Iceland. This has been accomplished by establishing the safety criteria for avalanche and landslide hazard mapping and for the design of protection measures as well as by providing for over 90% of the actual cost of such measures undertaken in local municipalities in Iceland since 1995. After two catastrophic avalanches in two small towns in the north-west of Iceland in the year 1995, the Icelandic Government reorganised its support and at the same time increased public funding to local municipalities for dealing with the threat from avalanches and landslides. The Icelandic Meteorological Office was designated as the expert advisory body and the Government established an Avalanche and Landslide Fund to provide funding for local municipalities to implement the necessary measures.

1. INTRODUCTION

Catastrophic avalanches in the small towns of Súðavík and Flateyri in 1995 caused 34 fatalities and extensive economic damage in areas considered to be outside avalanche hazard zones. The public and political opinion on avalanche safety in Iceland was instantly changed by these tragic events. Hence, the prime minister established a committee in the fall of 1995 to review the legal framework for all aspects of risk assessment, hazard evaluation and protective measures against avalanches and landslides. Furthermore, the administration in this field needed to be strengthened and an improved scientific and technical approach was needed.

This work resulted a complete and radical change in the administration and involvement of the government in the field of avalanches and landslides protection, i.e.:

- Requirements to municipalities to secure protection from avalanches and landslides.
- The administration in the field of avalanches and landslides was transferred from the Ministry of Social Affairs to the Ministry for the Environment.
- Research and advice on preventive measures and responsibility for hazard zoning, regular snow observations and hazard monitoring was given to the Icelandic Meteorological Office (IMO), an institute under the Ministry for the Environment.
- A new Avalanche and Landslide Committee was established under the Ministry for the Environment.

2. THE AVALANCHE AND LANDSLIDE COMMITTEE

An act on protective measures against avalanches and landslides was approved by the parliament (Althing) in 1997 (no. 49/1997). Public meetings were organized in all communities where avalanche hazard was known to introduce the new measures in the field of avalanche protection and to raise public awareness of the problem. Comprehensive plans on monitoring and evacuation schemes were developed for all the communities in question and it was informed that the implementation of permanent protection structures would take several years.

The main thrust of the legislation on protective measures against avalanches and landslides was to aim for permanent structures unless cost–benefit analysis showed that it would be considerably less costly to purchase the buildings in the respective hazard zone. The new act established a national fund, the Avalanche and Landslide Fund. The main income of the fund derives from an annual fee levied on all property insured against fire, 0.3‰ of the insured value which amounts to around 2.5 billion ISK (ca. 21 million €) in 2019. However, the actual expenditure from the Avalanche and Landslide Fund is determined annually by the Icelandic Parliament, Alþingi. The key role of the fund is to assist municipalities to deal with protective measures for existing populated areas within towns and villages, mainly the domestic rather than the industrial areas.

The new act also established an Avalanche and Landslide Committee. The role of the committee is to decide on proposals from municipalities for protection measures and to allocate funding from the Avalanche and Landslide Fund. Assets of the fund can be used to pay the cost of protection against avalanches and landslides and other relevant measures in accordance with the following:

a. total cost of hazard zoning of populated areas considered to be at avalanche risk,
b. total cost of measuring equipment for research and monitoring of areas considered to be at avalanche risk,
c. up to 90% of the cost of preparation, design and construction of protection structures,
d. up to 60% of the cost of maintenance of protection structures,
e. up to 90% of the cost of buying houses and apartments and transportation of property to areas outside hazard zones.

The act on protective measures against avalanches and landslides was modified in 2014 and again in 2017 allowing the use of funds for hazard zoning regarding other natural hazards than snow avalanches and landslides, i.e. eruptions and river and ocean floods (see Figure 1 for an overview of the different natural hazards that need to be considered in Iceland). Extensive research under the direction of IMO is ongoing in the fields of these new tasks. A further modification of the act occurred in 2018, stipulating that the annual fee levied on all property will no longer go to the Avalanche and Landslide fund and that government funding in this field will be the determined directly by the Icelandic Parliament each year.

3. CAPACITY-BUILDING

The reorganisation of the management of avalanche problems in Iceland was carried out in collaboration with several international avalanche research institutes and experts, in particular from Norway, Switzerland, France and Austria. Several international research projects supported by the European Commission have also been important in the build-up of expertise in avalanche science in Iceland. An experiment on supporting structures under Icelandic conditions was carried out in Siglufjörður at an early stage of the preparations. This experiment was primarily intended to study the loading and foundation conditions for supporting structures in typical Icelandic environmental conditions. Important lessons were learned from this experiment, such as regarding snow load, wind load, corrosion and installation of the structures. The experience gained through the experiment was formalised into an Icelandic annex to the Swiss Guidelines for Supporting Structures to be applied when designing such structures for Icelandic circumstances.

An implementation plan for protection measures was drawn up by the Avalanche and Landslide Committee in consultation with the local municipalities in 1996 and 1997. According to this original plan, the most urgent tasks were to be finished before 2010. However, this plan was revised, and the target year changed to 2020. The plan now needs to be revised again with a new target to be set. The prioritization took into consideration the estimated hazard level in the different threatened settlements, the wishes of the municipalities, different local circumstances and the financial capabilities of the Avalanche and Landslide Fund each year and the various actions needed. The framework plan was adopted by the Government in 1996 and revised in 1997. The actual implementation of the protection measures has largely been according to this plan with some deviations due to practical circumstances. The plan with its detailed prioritization has proved to be a valuable tool for organizing the various tasks and for distributing the available funding between the various municipalities.

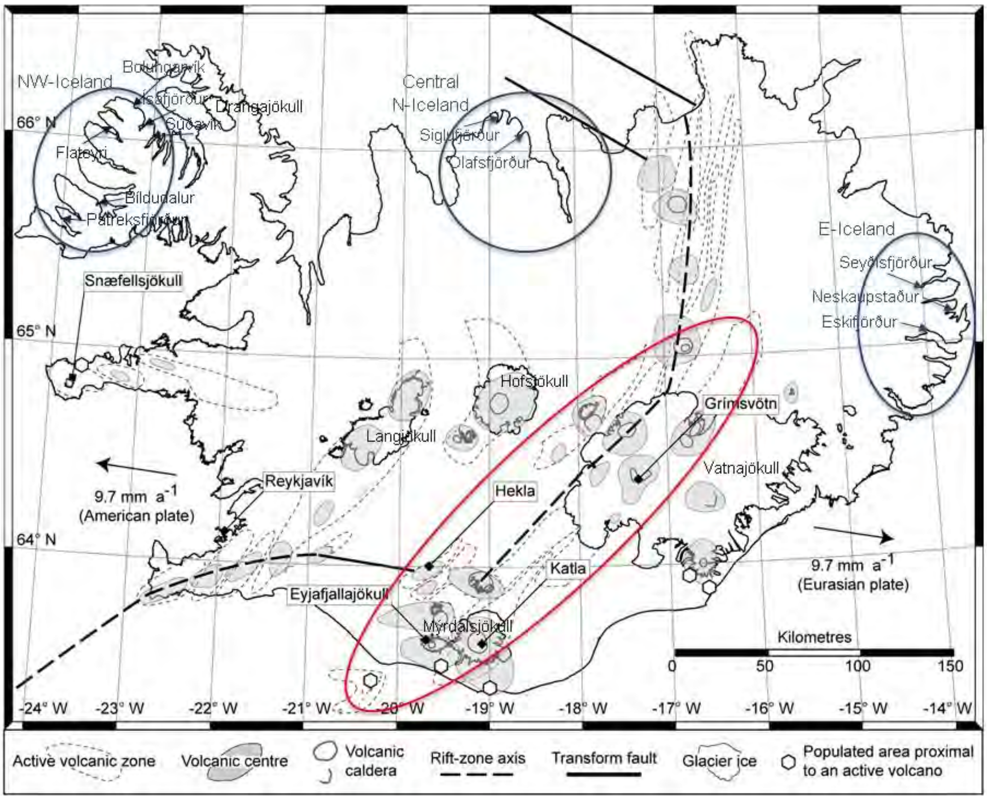

Figure 1 Geological characteristics of Iceland that determine natural hazards in different areas of the country. The map shows transform faults in SW-Iceland and central N-Iceland (earthquakes), the central volcanic zone that strikes across Iceland from SW to NE (volcanic eruptions, the most active volcanic area is indicated with an oblique, red ellipsoid), the glaciers (jökulhlaups) and the mountainous regions in NW-, central N- and E-Iceland (snow avalanches and landslides, dark blue oval areas). The main villages threatened by snow avalanches and landslides are shown with dark blue labels. (Map from the Icelandic Meteorological Office.)

4. ACCEPTABLE RISK AND HAZARD ZONING

A definition of acceptable risk from avalanches and landslides for living quarters in towns and villages was needed before permanent protective structures could be designed for the areas in question. This required the involvement of several experts and eventually a political decision.

The regulation no. 505/2000 on hazard zoning due to avalanches and landslides, classification and utilization of hazard zones defines acceptable risk.

> "Local risk to humans in residential dwellings, schools, day-care centres, hospitals, community centres and similar locations is considered acceptable if it is less than 0.3×10^{-4} annually. For commercial buildings where there is steady activity, the risk is acceptable if local risk is less than 1×10^{-4} annually. For recreational homes, risk is acceptable if local risk is less than 5×10^{-4} annually. In determination of these limits an exposure of 75% is assumed for residential dwellings, 40% for commercial buildings and 5% for recreational homes. In addition, it is assumed that children do not generally occupy commercial buildings, except for schools and day-care centres."

Based on the above definitions a hazard map on the scale 1:5000 shall show a hazard line, *i.e.* on one side an area of acceptable risk and on the other upslope areas marked with A, B or C with increasing local risk according to the following table:

	Lower limit	Upper limit
Hazard zone A	0.3×10^{-4}	1.0×10^{-4}
Hazard zone B	1.0×10^{-4}	3.0×10^{-4}
Hazard zone C	3.0×10^{-4}	–

The term "local risk" is defined as the "annual probability of death because of snow- or landslides for an individual, dwelling continuously in a non-reinforced single-family building", *i.e.* it is essentially individual risk of accidental death but without regard to the so-called "exposure", which is the probability of being in hazard zone when a snow- or landslide falls.

In areas protected by permanent structures, risk with and without the structures shall be shown. Furthermore, the map shall especially identify structures and landscape features which reduce risk and hence may not be altered for safety reasons.

No residential, recreational or commercial activities may be planned unless it has been established that the risk due to avalanches and landslides is acceptable. An existing detail and/or master plan which is not in accordance with the hazard map must be revised. Disputes regarding revised plans can be referred to the Ruling Committee for Environment and Natural Resources.

Since 1996 hazard zoning has been completed for the following towns and villages:

Ólafsvík	Hnífsdalur	Tálknafjörður
Patreksfjörður	Súðavík	Drangsnes
Bíldudalur	Siglufjörður	Akureyri
Þingeyri	Ólafsfjörður	Kirkjubæjarklaustur
Flateyri	Seyðisfjörður	Vík
Suðureyri	Neskaupstaður	Mosfellsbær
Bolungarvík	Eskifjörður	Reykjavík
Ísafjörður	Fáskrúðsfjörður	

Hazard zoning is currently in preparation for the village of Stöðvarfjörður in E-Iceland.

When the present efforts to improve safety due to avalanches and landslides were initiated, it was generally considered that mainly 8–10 local communities were threatened by avalanches or landslides in Iceland. However, the total number of local communities that are now considered endangered to some degree is 24 after further evaluation.

5. PROTECTIVE MEASURES

According to the *regulation no. 505/2000 on hazard zoning due to avalanches and landslides, classification and utilization of hazard zones*, protection structures are only to be built to ensure safety of people in already populated areas. Within six months from the completion of hazard zoning, the municipality must make an action plan to ensure safety of people in residential buildings. In hazard zone C, security shall be ensured with permanent protection structures or the purchasing of residential housing. For hazard zones A and B, the safety of people can be ensured through monitoring and evacuation.

One of the first tasks supported by the Avalanche and Landslide Fund after revision of the legal framework was the relocation of the small town of Súðavík. This task was approved in the fall of 1995 and mostly completed in the spring of 1997. A total of 55 new residential units were built in a safe area and a few houses were relocated in the process.

6. CONSTRUCTION OF PROTECTION STRUCTURES

The first permanent protection structures were built in Flateyri and completed in 1998. The Avalanche and Landslide Fund has since then supported the construction of protection structures at more than thirty locations in fifteen municipalities. Several of those structures have been hit by avalanches and hence have already proven their value.

Protection structures have been constructed or houses purchased in the following towns and villages:

- Súðavík – relocation project completed in 1997.
- Flateyri – construction of two deflecting dams and a catching dam was completed in 1998.
- Ísafjörður:
    - construction of a deflecting dam for Seljaland area was completed in 2004.
    - construction of a catching dam for the Kubbi area was completed in 2013.
    - construction of catching dams for the Gleiðarhjalli area was completed in 2017.
    - construction of supporting structures for the Kubbi area was completed in 2018.
- Hnífsdalur – purchase of houses and demolition completed in 2007.
- Siglufjörður:
    - construction of deflecting dams for the Strengsgil area was completed in 1999.
    - construction of supporting structures for the Gróuskarðshnjúkur area (phase 1) was completed in 2004.
    - construction of several catching dams above the entire town north of Strengsgil was completed in 2007.
    - construction of supporting structures for the Hafnarhyrna area (phase 2) was completed in 2015.
    - construction of supporting structures for the N-Fífladalir area (phase 3) was completed in 2018.
- Seyðisfjörður – construction of a catching and a deflecting dam in the shelf Brún the Bjólfur mountain was completed in 2004.
- Neskaupstaður:

    - construction of a deflecting dam, braking mounds and supporting structures for the Drangagil area was completed in 2001.
    - construction of supporting structures for the Tröllagil area was completed in 2012.
    - construction of a deflecting dam, a catching dam and braking mounds for the Tröllagil area was completed in 2015.
- Ólafsvík – construction of supporting structures, a small dam as well as landscaping was completed in 2009.
- Eyjafjarðarsveit – construction of a small deflecting dam for Grænahlíð was completed in 2009.
- Bíldudalur – construction of a deflecting dam in the Búðargil area was completed in 2009.
- Bolungarvík – construction of catching dams and braking mounds was completed in 2012.
- Ólafsfjörður – construction of a deflecting dam was completed in 2010.
- Patreksfjörður:
    - construction of a catching dam for the Klif area was completed in 2015.
    - construction of protection measures for a river Litladalsá were completed in 2015.
    - construction of experimental snow fences above the Urðir, Hólar and Mýrar area was completed in 2017.
- Eskifjörður:
    - construction of protection measures for the river Bleiksá were completed in 2015.
    - construction of protection measures for the river Hlíðarendaá were completed in 2016.
    - construction of protection measures for the river Ljósá were completed in 2018.
- Fáskrúðsfjörður – construction of a catching dam and a low deflecting dam in Nýjabæjarlækur was completed in 2014.

Protection structures are under preparation in the following towns:

- Patreksfjörður – design of deflecting and catching dams in the Urðir, Hólar and Mýrar area will be completed in 2019.
- Patreksfjörður – preparation of the construction of additional snow fences above the Urðir, Hólar and Mýrar area.
- Neskaupstaður – construction of catching dams in under Urðarbotnar will start in 2019.
- Siglufjörður – preparation of the construction of supporting structures for the Hafnarhyrna area (phase 4).
- Neskaupstaður – preparation of the construction of additional supporting structures in Drangagil.
- Eskifjörður – design of protection measures in the river Lambeyrará will be completed in 2019.
- Eskifjörður – design of protection measures in the river Grjótá will be completed in 2020.
- Seyðisfjörður – design of deflecting and catching dams for the Aldan and Bakkahverfi area will be completed in 2020.

Protection structures in a preliminary stage of preparation:
- Ólafsvík – preparation of the construction of snow fences.
- Patreksfjörður – protection measures in the Geirseyrargil and Sigtún area.
- Bíldudalur – protection measures in the Gilsbakkagil and Milligil area.
- Tálknafjörður – protection measures in the Geitárhorn area.
- Hnífsdalur – protection measures in the Bakkahyrna area.
- Siglufjörður – supporting structures (phase 5).

- Seyðisfjörður – protection measures in the Þófar and Botnar area.
- Neskaupstaður – catching dam in the Nes- and Bakkagil area.

The completion of the construction of protection structures for residential settlements in the C-zone in the various municipalities will take around 30 years if the current annual expenditure is not increased. This delay is partly because that more towns and villages are threatened by avalanches or landslides than was initially realised and partly because the government decided to slow down the construction in the years 2004 to 2007 due to general economic expansion and again after the economic crisis in 2008. The estimated cost of the remaining effort now appears to be around 19 billion ISK (140 million €) whereas the total accumulated cost of protection measures, relocation of settlements and other mitigation measures since 1995 is 21 billion ISK (150 million €). Figure 2 shows an example of the revised hazard zoning at Seljalandshverfi in Ísafjörður, NW-Iceland, after the construction of a deflecting dam.

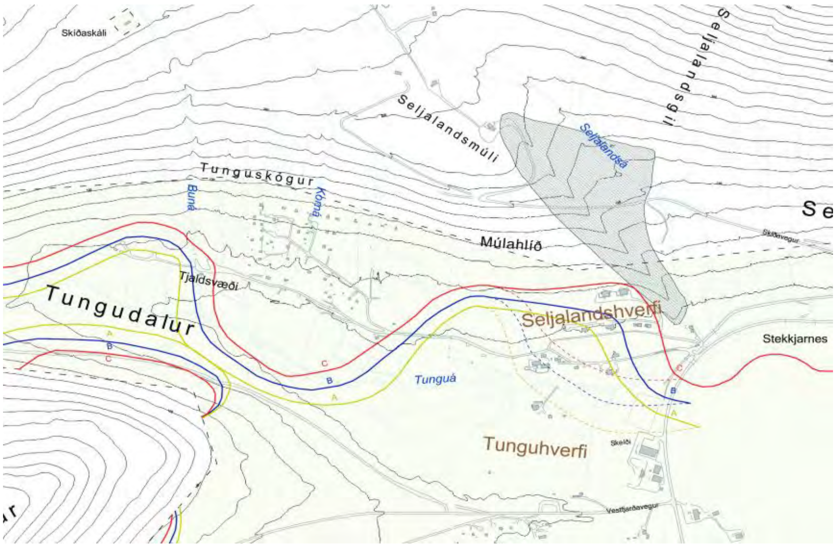

Figure 2 Snow avalanche hazard zones for Seljalandshlíð in Ísafjörður, NW-Iceland. The solid lines show the boundaries of the A (yellow), B (blue) and C (red) zones of the Icelandic hazard zoning regulation. The dashed lines show the zones before the construction of a deflecting dam at Seljalandsmúli, seen as kinks in the contour lines in the shadow area on the map. (Map from the Icelandic Meteorological Office.)

7. CONCLUSIONS

The establishment of the Icelandic Avalanche and Landslide Fund for avalanche-prone areas has proven to be of vital importance for the safety of the inhabitants of the concerned municipalities. Substantial improvements have been made in safety against avalanches and landslides for the communities that were endangered by snow avalanches and landslides in Iceland by the actions taken during the past two decades. Invaluable knowledge on hazard zoning, design of permanent structures and construction of the same has been gained, awareness has been raised at the municipal level and with the public at large. Permanent protection structures have already been established in almost all the affected communities and several have already proven their value. The local municipalities would never have had the resources to deal with the threat of avalanches and landslides without the support of the Icelandic Avalanche and Landslide fund.

The design of slushflow barriers: OpenFOAM simulations

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ABSTRACT

Understanding the dynamics of slushflows and snow avalanches plays a major role in estimating their flow in natural terrain and their effect on obstructions and man-made structures and, and more importantly, risk assessment regarding people's safety. Several factors contribute to the high complexity of such flows, among them the geometrical complexity of the flow path (ground), the physical behaviour of free-surface flows where complex hydraulic jumps occur, and the non-Newtonian fluid properties in the case of snow avalanches. Finally, the understanding of the flow dynamics is fundamental in the design of flood mitigation structures, both in terms of their strength and effectiveness in directing floods away from sensitive structures and people.

Experiments with scaled-down models have been used for decades to visualize floods and estimate their effect on sensitive structures. The scaling itself must be carefully conducted in order to preserve the fundamental behaviour of floods, which can be difficult in some cases, e.g. when both the dynamic similarity of the Reynolds and Froude numbers should be preserved. Nevertheless, experiments and measurements are considered the best method of acquiring accurate results, but they are in most cases quite time-consuming and costly to perform.

Computational fluid dynamics (CFD) have become an important tool in flow simulations because of increased number-crunching abilities of modern computers and the use of clusters for large-scale computational problems. Despite this, modelling of complex phenomena such as turbulent flow and free-surface flows still poses a great challenge. Nevertheless, many free-surface flow problems have been investigated using CFD methods, some of which resembling slushflows and to some extent snow avalanches.

In the current work, two CFD models have been constructed, using the public domain OpenFOAM CFD software, in order to simulate results from a slushflow laboratory experiment where different set-ups of barriers were tested. The purpose was to determine an efficient design for a slushflow mitigation structure (see the paper by Hákonardóttir and others in this volume). One of the models assumes a wide uniform channel, and is therefore implemented as a 2D problem, but the other is fully three-dimensional. Both models simulate the full Navier–Stokes equations, with two phases present (liquid and air), and using a surface-capturing algorithm to model the interface between the two phases.

The results show that the CFD models can replicate some of the actual results from the laboratory experiments remarkably well, which indicates that three-dimensional CFD models could be a valuable tool in the designs of slushflow mitigation structures and in the design of experiments. It appears possible to conduct initial laboratory experiment to calibrate a suitable CFD model, which is then used in a series of numerical experiments to optimize the design of the structure being considered, and finally perhaps verify the optimized design with a series of laboratory experiments. Further work could involve simulating a non-Newtonian fluid with properties that resemble the granular rheology of snow in a dry-snow avalanche.

Analyzing and mitigating the impact of avalanche protection structures on their local wind climate

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ABSTRACT

The wind field during severe winter storms was analyzed in Bolungarvík municipality on the Westfjords peninsula, northwest Iceland, using computational fluid dynamics. The simulations allowed for investigation on reported adverse changes in wind forcing on residential houses near a large avalanche protection structure following its construction.

The simulations show that under certain circumstances an accelerated wind field develops along the steep mountain hills in the outskirts of Bolungarvík. The strong wind along the hill side is diverted by the large-scale avalanche structure towards the buildings in its closest proximity, resulting in elevated wind forcing and thus negative impact to the residential area.

The characterization and mapping of the wind climate following the completed avalanche protection in Bolungarvík municipality will be discussed along with an analysis forming the basis of potential mitigation measures. Furthermore, the benefits of detailed wind field analysis using computational fluid dynamics for examining potential adverse effects of protection structures on their local wind climate will be outlined. Emphasis will be given to how this methodology may assist during the planning and design phases of avalanche structures in severe wind climates.

Use of OpenFOAM and RAMMS Avalanche to simulate the interaction of avalanches and slush flows with dams

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ABSTRACT

We explore the possibilities of using two different programs to aid with the design of protection dams against snow avalanches and slushflows. The RAMMS 1.6 Avalanche module, developed by the SLF in Switzerland, was used to back-calculate large and medium sized avalanches on the Flateyri deflecting dams. We find that the program reproduces the observed avalanche run-out for the avalanches studied with an appropriate choice of avalanche volume and oblique shocks are formed in the interaction with deflecting dams. A full 3D simulation is, however, needed to study the interaction of avalanches and dams, when ballistic overflow is important for realistic results of the simulation. OpenFOAM is an open source CFD software, commonly used to simulate complex flows for engineering purposes. The software was used to simulate the interaction of a slushflow with a row of mounds and a catching dam, as a two-phase flow of Newtonian fluids, in three dimensions. The numerical solution was compared with experimental results of the interaction of water with mounds and dams. The study showed that the software may be successfully used to simulate the water–obstacle interaction and optimize the engineering design.

1. INTRODUCTION

1.1 Interaction with a deflecting dam

We use the program RAMMS Avalanche module to simulate the interaction of avalanches and deflecting dams. The frictional parameters used in the simulations have not been calibrated for large Icelandic avalanches, as was done for the program Samos (Gíslason and Jóhannesson, 2007). The software has, however, been tested for a number of large and medium-sized historical Icelandic avalanches, with the recommended frictional parameters for Swiss avalanches (Bartelt et al., 2016) with promising results. We have chosen to study in some detail two medium-sized avalanches that hit the deflecting dam at Flateyri in 1999 and 2000 and a catastrophic avalanche that hit Flateyri in 1995, see Figure 1.

The three avalanches were compared and analysed in terms of the effectiveness of the dams in a paper by Jóhannesson (2001) and the 1999 avalanche was discussed and analysed by Jóhannesson et al. (1999). An overall agreement is found in the observed run-up of the avalanches and the run-up based on back calculations of flow speed and the traditional formulation for run-up, based on energy conservation of a point mass. It is concluded that the dams will be effective for substantially larger avalanches. It is also noted that the estimated flow marks on the dams may be an overestimate of the highest run-up of the dense part of the avalanche. Both avalanches were channelized at the dam, but the avalanche upstream of the channelized part appeared unaffected by the dams. This has been interpreted in terms of the formation of an oblique shock at the dam, analogues to oblique hydraulic jumps for high Froude number free-surface flows of water or oblique shocks for high Mach number flows of gas. An abrupt change in thickness, flow direction and density, occurs and a thicker and more dense current flows along the dam.

The oblique shock, formed at the Flateyri dam in 1999, was studied numerically by Cui et al. (2007). They found good agreement between the observed indications of an oblique shock and the simulated shock, but less so between the highest run-up marks on the dam and the maximum simulated flow depth and the observed run-out.

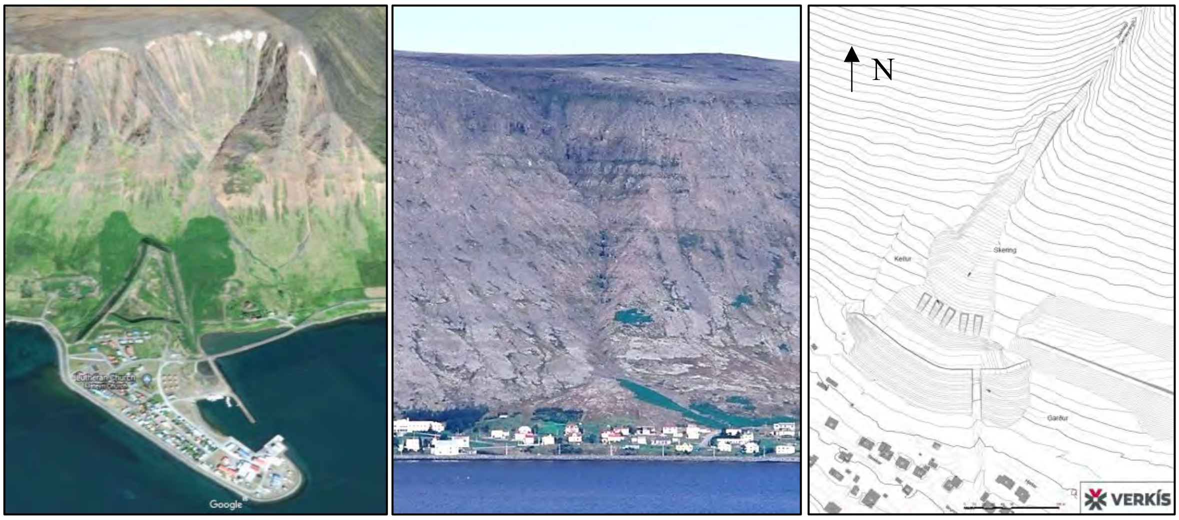

Figure 1 To the left: The Flateyri avalanche deflecting dams, built in 1996–1999 (Google Earth image, 2019). To the right: The Stekkagil ravine in Patreksfjörður, North-western Iceland (photo: Hákonardóttir, 2006) and the proposed design of defence structures for stopping slushflows from the gully (Verkís, draft from 2016).

1.2 Interaction with mounds and a dam

Previous numerical simulations of slushflows include studies of Gauer (2004) who simulated slushflows in three dimensions as a two-phase flow of a fluid and air, with the fluid as a multi-component fluid, in CFX, with and without erosion of the surrounding snow-pack and also, the much simpler approach, in RAMMS Avalanche using a single-phase, depth-averaged model, determining frictional parameters to fit observed flow speeds (Jónsson and Gauer, 2014). We choose an approach that is between the two in terms of complexity.

A full 3D simulation, using the opensource software package OpenFOAM, is used to study the interaction of a slushflow with braking mounds and a catching dam, due to the ballistic nature of the overflow. We study the proposed defence measures below the Stekkjargil ravine in Patreksfjörður, Northwestern Iceland, Figure 1. The design entails one row of 5 pc of 5.5 m high and 6 m wide, steep braking mounds and a 12 m high, steep catching dam located 70 m below the mounds. An opening in the dam, with rails, similar to debris flow defences, ensures an escape for water to the East and a spillway for water to the West. The mounds are located on the 15° slope of a debris cone. The row of mounds is located sufficiently far away from the mouth of the gully, such that debris, carried down the gully during spring and autumn flooding will not block the mounds. The distance between the mounds is 5 m, allowing vehicles to excavate debris. The design slushflow is approximately $50 \cdot 10^3$ m^3, flowing at a speed of 10 to

20 m/s, with a depth of 1 to 3 m. The design was tested in laboratory experiments described by Hákonardóttir and Ágústsdóttir (2019).

The OpenFOAM simulations allow calculations of the impact pressure at the mounds and at the dam, which is especially important for the mound design in Patreksfjörður. Pressure measurements have shown that the interaction between the dense core of a snow avalanche and an obstacle can be divided into two periods (Salm, 1964; Kotlyakov et al., 1977; Schaerer and Salway, 1980). During the first few milliseconds of the impact, a pressure peak is observed. The peak is followed by a lower base pressure with much longer duration. Pressures, on a 20 m high and 0.6 m wide pylon with a 62° wedge upstream, have been measured at the Vallée de la Sionne experimental site in Switzerland for 20 years. Sovilla et al. (2018) report pressure measurements for a slowly-moving avalanche characterized by a warm plug regime. They measure maximum pressures at the base of the pylon. The measurements do, however, not show a single pressure peak in the impact, but rather many peaks measured during the first 10 s of the flow. Jaedicke et al. (2008) measured impact pressure on an obstacle in the flow path of a slushflow, in large-scale experiments on a 30 m long chute at Weissfluhjoch, Davos, and found the highest pressures as the flow front hit the obstacles.

2. THEORY

2.1 Flateyri: Deflecting dams

The Flateyri dams were designed based on the traditional run-up equation, based on energy conservation of a point mass

$$h_u = \frac{(u \sin\gamma)^2}{2g} + h + h_s, \qquad (1)$$

where u is flow speed, γ is deflecting angle between the dam and the avalanche and g is gravitational acceleration, h is the flow depth and h_s is the thickness of the snowcover on the ground (Salm, 1990). Since 2005, dams in Iceland have been designed according to the European guidelines (Jóhannesson et al., 2009), based on the formation of an oblique shock at the dam, as has been observed in experiments with dams and granular flows (Gray et al., 2003, Hákonardóttir and Hogg, 2005). The flow depth by the dam, H may be derived from:

$$H = \frac{\tan\beta}{\tan(\beta-\gamma)} \quad \text{and} \quad \tan\gamma = \frac{4\sin\beta\cos\beta\left(1-Fr^2\sin^2\beta\right)}{-3+4\cos^2\beta\left(1-Fr^2\sin^2\beta\right)-\sqrt{1+8Fr^2\sin^2\beta}} \qquad (2)$$

where (β–γ) is the shock angle, measured from the dam axis.

The Froude number of a free-surface flow, upstream of the dam is given by

$$Fr^2 = \frac{u^2}{g h \cos\xi}, \qquad (3)$$

where u is flow speed, h is flow depth and ξ is the slope angle.

The European guidelines also provide a formula for the spreading of an avalanche downstream from the dam and the added flow depth due to curvature of the dam axis. Spreading is given by:

$$\varphi_{lsp} = \frac{2}{\mathrm{Fr}} - \frac{5}{3\mathrm{Fr}^3} + O\left(\frac{1}{\mathrm{Fr}^5}\right), \qquad (4)$$

which yields 11–21° for Froude numbers between 5 and 10. A value of 20° is often used for large dry-snow avalanches (Jóhannesson et al., 2009). For slower flows with Fr between 2 and

4 the formula yields 25–45°, which is consistent with observations of slower and wetter avalanches (Jóhannesson et al., 2009; Sovilla et al., 2012).

2.2 Patreksfjörður: Mounds and dam

The pressure in the initial impact of the flow with a dam or mound may be compared with pressure impact theory, derived by Cooker and Peregrine (1998). They found that the maximum value of the pressure impulse at the wall was

$$P_{max} = 0.742\rho u h, \qquad (6)$$

for a rectangular wave, with the maximum located at the base of the wall. The magnitude of the dynamic pressure, that follows the pressure peak, and the avalanche exerts on an obstacle may be written as

$$P_{ref.} = c\rho u^2/2, \qquad (5)$$

with the drag coefficient c and the density ρ. Schearer and Salway (1980) found $c = 1$, for an impact with a dam.

Jets of fluid or granular flows over relatively low obstacles, such as braking mounds, with the ratio of obstacle height to the flow depth between 1 and 5, have in laboratory experiments been observed to follow ballistic trajectories (see discussion by Hákonardóttir and Ágústsdóttir, 2019). The launch angle may be determined implicitly from an expression, derived by Yih (1979), for inviscid, irrotational flow, when the effect of gravity is negligible. The theory predicts that the deflection of the jet asymptotically approaches the angle between the upstream face of the dam and slope as the height of the dam relative to the flow depth increases.

Scaling between laboratory scale experiments, and the real situation in Patreksjförður, is discussed by Hákonardóttir and Ágústsdóttir (2019).

3. NUMERICAL APPROACH

3.1 RAMMS: Deflecting dam

The RAMMS 1.6 Avalanche module was developed by the SLF in Switzerland (Christen et al., 2010). The core of the program is a second-order numerical solution of the depth-averaged avalanche dynamics equations (identical to the shallow water equations), with a Voellmy-Salm type rheology. The following simplistic approach was chosen: Frictional parameters were chosen according to Swiss calibration recommendations (see Table 1) and the volume was chosen to fit the desired run-out. The density was kept constant at 300 kg/m^3. No entrainment was assumed. A 5x5 m grid was used, as recommended by Christen et al. (2010).

Table 1 Frictional parameters in RAMMS simulations with volume over $60{\cdot}10^3$ m^3.

	Open slope	Channel	Gully	Flat
Coulomb friction, μ	0.19	0.24	0.30	0.17
Velocity dependent friction, ξ (m/s^2)	2000	1500	1200	3000

3.2 OpenFOAM: Mounds and a dam

OpenFOAM is used to study the impact of a large slushflow down the Stekkagil ravine, with a row of braking mounds and a dam. We do not attempt to model the slushflow down the entire ravine, due to numerical complications, but rather tune the flow speed and depth at the inlet, approximately 20 m above the mounds, to the desired value. Three-dimensional multiphase simulation model, using the Volume of Fluid Method is constructed were the two-phases simulated are air and liquid. Kobayashi et al., (1994) and Jaedicki et al. (2008), concluded in their study that slush is a non-Newtonian fluid. For the sake of clear comparison with experiments and simplicity, the fluid in this study is modeled as a Newtionan fluid, with a density of 800 kg/m^3 and the viscosity of water at 0° C. OpenFOAM, however, facilitates different rheological models (OpenFOAM source code, 2018).

The simulation domain is 115 m x 32 m x 22 m (length x height x width) see Figure 2. We adopt a similar approach as in the experiments discussed by Hákonardóttir and Ágústsdóttir (2019), to study the three-dimensional nature of the fluid-mound interaction. Instead of computationally heavy, fully 3D geometry of the ravine, the cross slope is studied with two mounds, normal to the flow direction. The domain is broken into two sections (separation patch) where each section is less computationally demanding than the whole domain. Firstly, a simulation is carried out for the upper half of the domain, which includes the braking mounds. The focus is on a high resolution of the initial impact with respect to pressure at impact and the evolution of the upward propagating jet. Secondly, the two domains are merged together, and the solution of the upper half is mapped onto the lower half of the domain. The focus in the lower half is on the impact with the catching dam and the evolution of the fluid–dam impact at the upstream dam face.

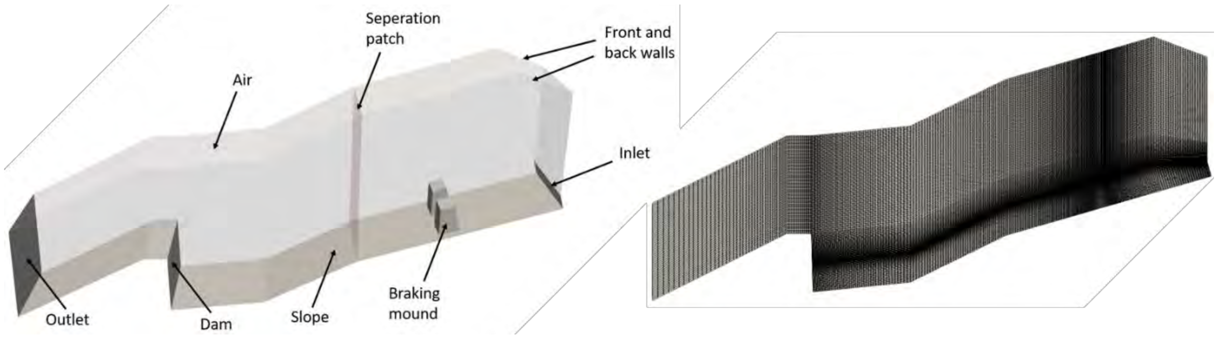

Figure 2 Left: Computational domain. Distance from the mounds to the front and back walls is 2.5 m. Right: Computational grid.

The computational grid is shown on Figure 2. The total grid size for the modelled domains are respectively for the upper domain and combined upper and lower domain: $2.51 \cdot 10^6$ and $4.35 \cdot 10^6$ cells. The grid is created using *blockMesh* meshing tool which results in a good quality mesh and facilitates adjustments to the geometry shapes.

Multiphase simulations are carried out with OpenFOAM v1812 using the *interIsoFoam* solver. The solver uses the isoadvector algorithm which captures the interface between two incomepressible, isothermal, unmixable fluids (OpenFOAM source code., 2018). The method was developed by Roenby, Bredmose and Jasak (2016), where one of the main goals in their study was to improve the available VOF solver in OpenFOAM, *interFoam*. The isoadvector algorithm proved promising in preserving shapes and creating sharp interfaces between two-phases (Roenby et al., 2016). The k-ω SST model with wall functions is used for turbulence modelling.

One of the wall functions used is the *nutkRoughWallFunction*, it allows control of the roughness of the surface and is used in this project to mimic the rough terrain of the slope and resistance due to snow on the slope, using a high value for Nikuradse's sand-grain roughness, 0.25 m (OpenFOAM source code., 2018). The added roughness influences the front thickness and velocity at the tip of the slush. A slip boundary condition is applied at the the front and back walls, preventing the slush from escaping the domain but not affecting it in any other way. Second order accurate schemes are used for all divergence terms, and the first order accurate Euler scheme is used for time stepping.

4. RESULTS

4.1 Flateyri: Interaction of dry snow avalanches with deflecting dams

RAMMS simulations of the 1999 and 2000 avalanches, without and with the deflecting dams, are shown in Figure 3 and summarized in Table 2.

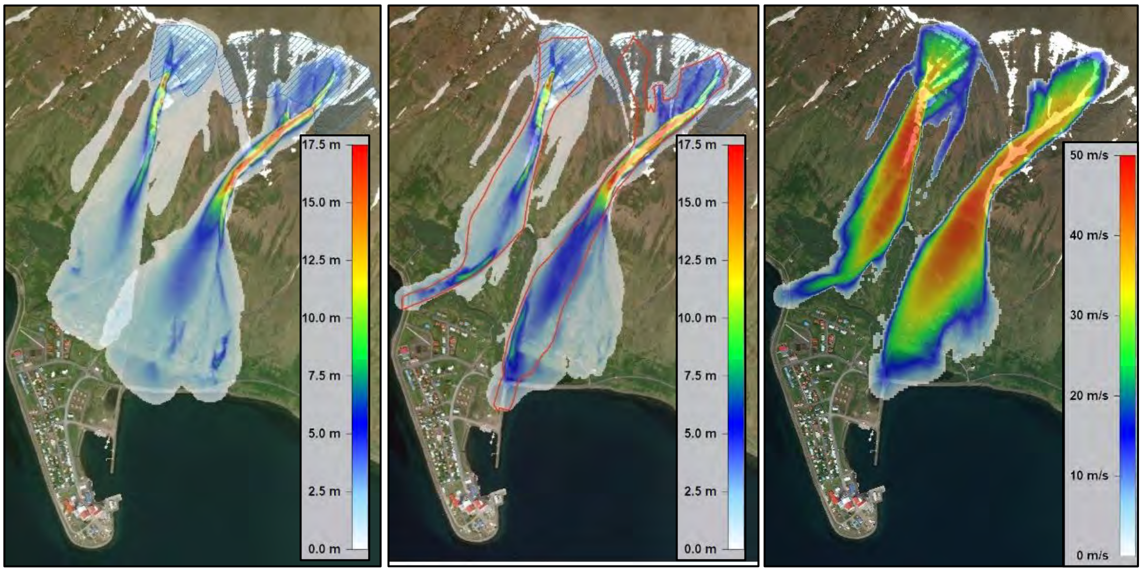

Figure 3 Maximum flow depth without and with dams (left) and maximum flow speed (right) with dams. Simulations of a dry-snow avalanche from Skollahvilft and Innra-Bæj-argil Flateyri. The red lines denote the outlines of the avalanches.

Almost twice the volume in the avalanche tongue was needed to recreate the run-out of the 1999 avalanche. We conclude that a different set of frictional parameters is needed to recreate the run-out for the actual volume of snow. The curvature effects in the gully, above the dam, may also be retarding the flow too much (Fischer et al., 2012). Simulations with curvature turned off yielded higher flow speed at the dam and extended the run-out. The location of the maximum flow depth at the dam is similar between observations and simulations. The simulated flow depth at the dam is 7.5–8 m. This is comparable with the debris thickness at the dam and the thickness of the oblique shock, calculated theoretically, but not the highest flow-marks that reached 13 m. We conclude that the highest flow-marks on the dam may have been created in the initial impact and perhaps by a saltating layer on the top of the dense core of the avalanche. There is a tendency for too much lateral spreading in the simulated flow on the debris cone below the mouth of the gully as compared with the measured outline of the 1999 avalanche.

Table 2 Avalanches above Flateyri. Density in simulation $\rho = 300$ kg/m^3, h_s is the snow-depth on the ground

Year	Estimated volume in tongue (10^3 m^3)	Maximum run-up on dam - h_s (m)	Snow depth in release zone (m)	Volume (10^3 m^3)	Maximum run-up on dam (m)	Deflecting angle (°)	Flow depth at dam, h_1 (m)	Flow speed at dam (m/s)	Froude no.	Jump height (m), eq. (2)	Energy height + h (m), eq. (1)
	Observations			**Simulations**						**Theory**	
1995	430	-	4.5	630	17.5	23	4.0–4.5	46	7.5	19	20
1999	130	13	3.5	235	7.5–8	14	3–3.5	32	7.5	7	5
2000	110	12	1.25	90	7.5–8.5	18	2.5–3	41	7.0	12	11

The 2000 avalanche is better represented in the simulation. A similar volume was needed to recreate the observed run-out, and the highest flow marks were located at similar locations on the dam. The maximum simulated depth at the dam was 8–8.5 m. The highest flow-marks on the dam reached 12 m. The theoretically calculated maximum thickness of the oblique shock at the dam is 12 m. This flow-depth was not reached in the simulations, probably because of the narrow stream flowing towards the dam at the maximum flow speed. The simulated highest run-up on the dam is approximately 140 m farther downstream, like the flow marks on the dam suggest, and may be attributed to the curvature of the dam of approximately 700 m at that point, and centrifugal forces. No spreading to the side at the end of the dam is observed.

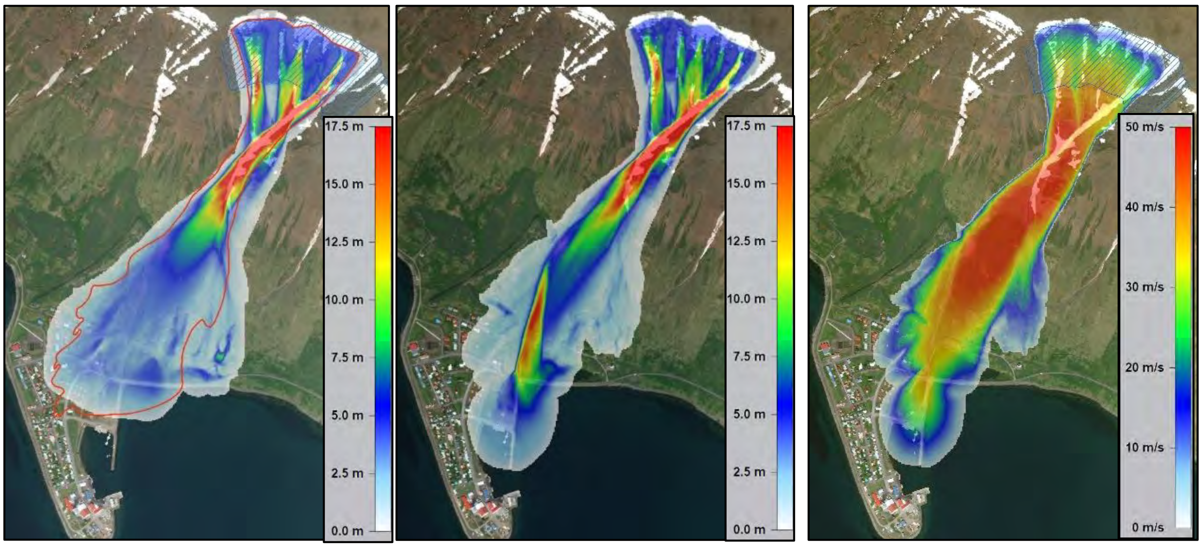

Figure 4 Maximum flow depth without and with dams (left) and maximum flow speed (right) with dams. Simulations of a dry-snow avalanche from Skollahvilft, Flateyri, with a similar run-out as the avalanche in 1995 (red line denotes the avalanche outline).

The RAMMS simulation of the 1995 avalanche is shown in Figure 4. We find that an avalanche with $630 \cdot 10^3$ m^3 is needed to reach the run-out of the avalanche, which equals 1.5 times the estimated volume in the avalanche tongue. We note more spreading to the sides, due to the larger volume in the simulations. In the interaction of the avalanche with the now-existing deflecting dam we note that an oblique shock is formed at the dam face and the body of the avalanche is deflected to sea. The depth of the flowing stream at the dam is approximately 17.5 m, which is in agreement with back calculations of the jump depth from equations (2) and (3).

A thin part overtops the dam and at the end of the dam we find that the flow spreads at an angle of 40° from the direction of the tip of the dam, but at an angle of approximately 20° from the main dam axis. We calculate a spreading of 15°, from equation (5). We question whether the spreading may be overestimated in the simulations, due to cohesion in a denser stream flowing along the dam face. Very little spreading was observed for the 1999 avalanche that extended ca. 100 m beyond the lower end of the dam.

The flow over the dam is not correctly represented in the simulations. This part of the flow may become airborne before landing on the "wrong" side of the dam, as has been observed in experiments with granular flows (Hákonardóttir and Hogg, 2005). The simulation, however, indicates the overtopping volume that may be expected.

4.2 Patreksfjörður: Interaction of slush with braking mounds and a catching dam

In this chapter, the simulations of Stekkjargil ravine carried out with OpenFOAM are shown and discussed.

4.2.1 The impact with braking mounds

The flow front is 0.75 m thick, travelling at a speed of 22 m/s. The Froude number of the front is approximately 8.1. The bulk of the flow that follows has a constant flow depth of approximately 3 m, flow speed of 17 m/s and a Froude number of 3.1. The ratio of the mound height to the flow depth is approximately 2. The simulated flow may be categorized as a plug flow, with a thin shear layer, comparable to the cell size at the base, 0,25 m.

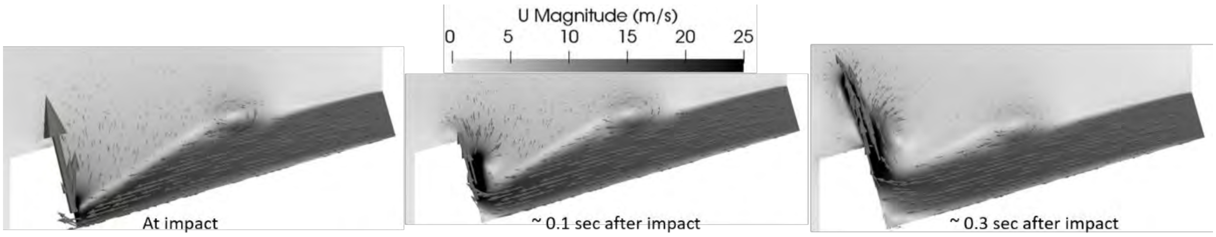

Figure 5 The upper figures show the flow speed and velocity vectors for both the fluid and the air, in the initial impact of the flow and the mounds. The boundary between the phases are clearlu visible as the fluid moves towards the mounds.

A high splash is observed upon the impact with the mounds, moving upward and to the sides, see Figure 5. An enormous velocity spike is observed with a magnitude of over 6 times the inlet speed. The speed has dropped to twice the inlet speed only 0.3 s later. The splash is abrupt and rises in the direction of the mound face for 1.9 s. The splash reaches a height of 28 m, 2.9 s after impact., or 37 h_{front} and 9 h_{bulk}. The splash collapses and lands approximately 22 m upstream of the catching dam. A low velocity, circulation cell is generated at the basis of the mounds and serves as a ramp for the incoming flow and a semi-steady jet is launched over the mounds, following the initial splash and lands 15 m upstream of the catching dam, approximately 7 to 8 s after the impact with the mounds, see Figure 7. We observe identical flow behavior in the experiments presented by Hákonardóttir and Ágústsdóttir (2019), conducted at a length scale that is approximately 10 to 20 times smaller. The Froude number in the simulations is slightly higher, but the geometry is comparable to the setup A.1.

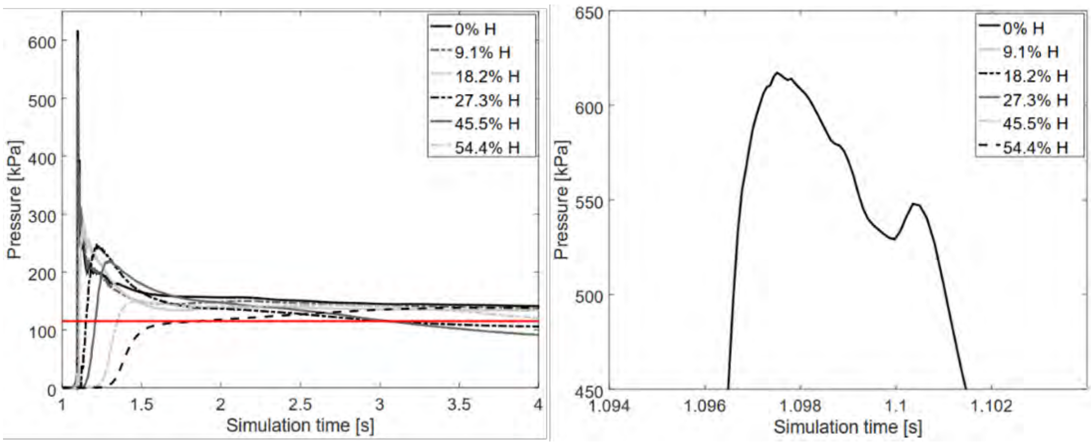

Figure 6 The pressure at the mound face as a function of time for the initial 0.4 s. The different lines show the pressure at different height at the mound face. The reference pressure for the bulk of the flow of 115 kPa is noted with a red line.

The pressure on the mounds in the impact is shown on Figure 6. The maximum pressure on the dam face is 620 kPa lasting for only approximately $5 \cdot 10^{-3}$ s. It is only the base of the mounds, lowest 0.5 m, that experience the pressure spike. The pressure spike abruptly reduces to 140 kPa and reduces further as the circulation cell enlarges. The pressure continues to reduce, due to the formation of the circulation cell, which groves with time. One may calculate the reference pressure on the mounds after the initial impact by equation (6) is 115 kPa, with $c = 1$. The maximum pressure in the initial impact may be compared with pressure impulse theory and is calculated from equation (7) to be $P_{max} = 590$ kPA, which is of the same order as in the simulations.

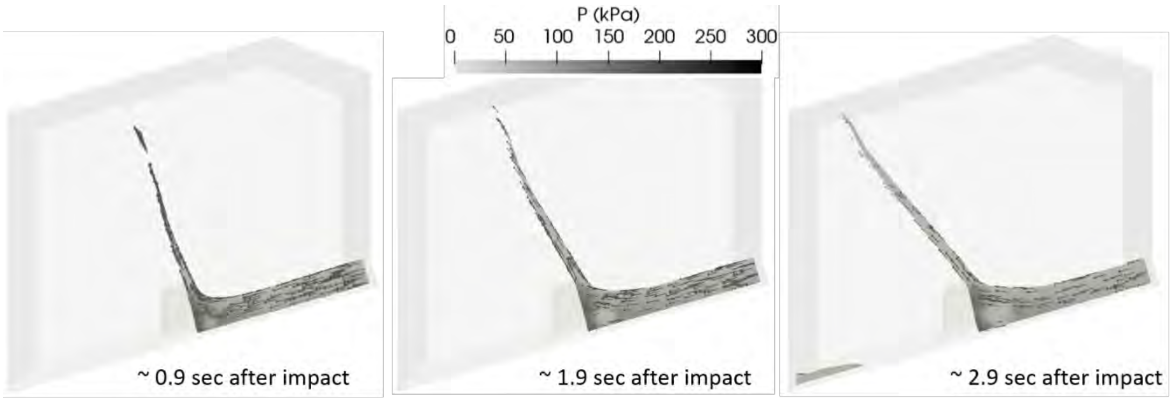

Figure 7 Time lapse figures of the impact with the mounds, 0.9, 1.9 and 2.9 s from the initial impact. The colours show the pressure and the arrows the size and the direction of the velocity vector.

The evolution of the jet over the mounds and pressure on the mound face is shown in Figure 7. A steady jet is launched over the mounds at an angle of 55° to the slope, after approximately 9 s. The angle is somewhat lower than the 65° predicted by Yih's derivation (1970) for $H/h_{bulk} = 1.8$, discussed briefly in section 2.2. The jet follows a ballistic trajectory discussed in section 2.2. No dissipation of energy takes place at the mound face. The jet rises to a maximum height of 11–12 m, or 4 h_{bulk}, and lands approximately 45 m downstream from the mound. Drag from surrounding air does not seem to affect the trajectory of the jet.

4.2.2 *The impact with the catching dam*

The flow shoots between the mounds and impacts the dam, see Figure 8. A small amount of the flow spills over the dam. The part of the flow that is launched over the mounds impacts later and does not overtop the dam. A hydraulic jump, moving upwards develops after the initial impact. The flow speed downstream from the landing location of the jet is much lower than the flow speed between the mounds. It indicates that energy dissipation occurs in the landing of the jet on the slope and as the hydraulic jump moving upwards interacts with the flow shooting over the mounds.

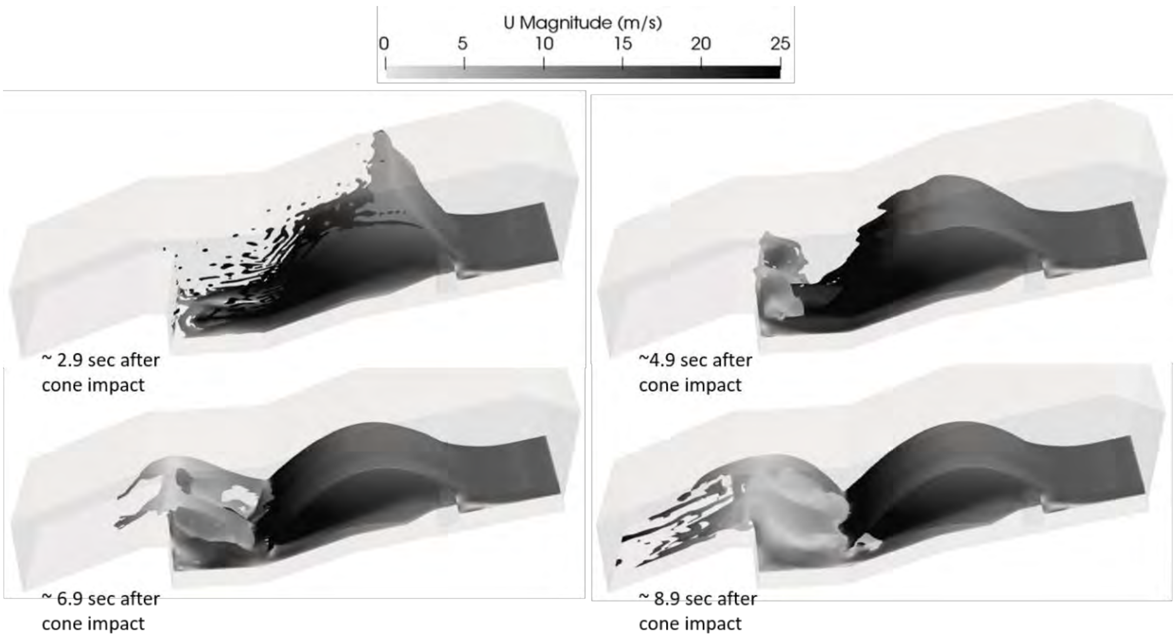

Figure 8 Time lapse figures of the flow impacting both mounds and the dam. The colours denote velocity.

CONCLUSIONS AND FURTHER STUDIES

We find that the RAMMS avalanche reproduces the observed avalanche run-out for the avalanches studied with an appropriate choice of avalanche volume. We find that 1.5 to 2 times the volume of debris in the avalanche tongue is needed to attain the desired run-out for the avalanches from Skollahvilft, while the volume of the Innra-Bæjargil avalanche was well represented by the volume in the tongue. The run-up on the dams agrees with the theory and oblique shocks are formed in the interaction with deflecting dams and the effects of dam curvature are realistic. We note that spreading downstream from the end of the dam needs to be analysed further for large avalanches with thick stream at the end of the dam. Overflow over the dam may not be correctly represented by the depth-averaged modelling.

We conclude that OpenFOAM is a valuable tool to study the interaction of fluids and obstacles and may be important in understanding the run-up onto obstacles of different shapes and the pressures exerted on the obstacles. We find that simulations in OpenFOAM reproduce the flow phenomena observed in laboratory experiments with water and mounds (Hákonardóttir and

Ágústsdóttir, 2019) and the scaling arguments presented by Hákonardóttir and Ágústsdóttir (2019) hold. We observe that energy is not dissipated at the upstream mound face, due to the formation of a circulation cell, which creates a ramp for the flow to pass smoothly over the mounds. Energy is, however, dissipated at the dam face.

Further simulations of slushflows may include studying different types of rheologies and comparing them with the Newtonian fluid used here, using a multi-component fluid for the fluid phase and ultimately being able to simulate convincingly the flow down the gully, from its release zone, with erosion of the surrounding snow-pack. For now, we will use the model for the engineering design in Patreksfjörður and look into: Different mound setups, *e.g.* with the mounds closer together, thinner and slower flows and the effects of secondary waves/releases or wave trains.

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An integral avalanche safety concept for Goms region, Valais, Switzerland.

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ABSTRACT

The Goms region, situated in the north-west of canton Valais, is one of the most avalanche affected regions of Switzerland. 68 avalanche paths endanger transportation corridors (road and train) as well as villages. Its documented history of catastrophic avalanche events reaches back to the 16th century, with one of the largest events in Alps being the Bächi avalanche 1970 with 30 fatalities. This well documented history allowed for diverse avalanche mitigation projects to be undertaken: Dams, galleries, tunnels and avalanche barriers have been constructed in the past, and more recently avalanche release, detection and warning systems have been employed.

All these mitigation measures must be considered in the safety concept of the valley. To achieve this, and to maintain a manageable level of complexity for the daily use, a specifically tailored, integral safety concept was developed. It incorporates all relevant information, starting from weather station data to detection systems, as well as avalanche path specific information on historical events and protection measures. All this information is finally merged together into a digital decision scheme to support the local warning service.

We will present a detailed overview of the safety concept and how it could be applied to other regions, as well as experience from the first operational winter season 2018/19.

Hybrid modeling of debris flows – Focusing on initial and boundary conditions

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ABSTRACT

Debris flows are mixtures of water, sediments and debris that initiate on mountain sides, travel down a confined steep channel at high velocity, and may turn into natural disasters for communities and infrastructure. To prevent any destructive effect, precautionary measures are often employed, wherefore a fundamental understanding of the debris flow processes, e.g. velocity profiles, erosion and bulking, impact forces, etc., are needed. The relevant parameters of initiation and runout differ widely in characteristics. Thus, setting initial and boundary conditions for physical and numerical modeling is challenging. The aim of our investigation is hence to analyse velocity profiles and shear stresses of debris flows using variable but repeatable initial and boundary conditions. We built a Plexiglas flume, constructed like a seesaw that can tilt to either side. Each side is equipped with a sediment reservoir and the roughness of the flume base can be modified. Ultrasonic probes measure water levels, and high-speed cameras record the flow velocity distribution, using the Large-Scale Particle Image Velocimetry (LSPIV)-method. The results provide the basis for 2D depth-averaged numerical modeling using a Finite-Volume-method. Combining and hybridizing both, the physical and numerical model will lead to a better process understanding of these natural phenomena.

Avalanche deflection berm and stopping wall at a hydroelectric facility in British Columbia, Canada

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ABSTRACT

Avalanches pose significant risk to an ongoing construction project at Rio Tinto's Kemano hydroelectric facility in the Coast Mountains near Kitimat, British Columbia, Canada. Horetzky Landing is host to a workers' camp, offices, equipment laydown areas, and the primary adit for current tunnelling operations that will twin existing water supply to Kemano by 2020. Two reinforced-earth avalanche defence structures have been designed and constructed at Horetzky Landing to protect infrastructure and equipment in the runout zone of a large avalanche path. The structures consist of a 10 m tall, 150-m long deflection berm in the upper runout zone, and an 8 m tall, 120 m long, reinforced Gabion-faced stopping wall immediately above the tunnel adit in the lower runout zone. The deflection berm was designed to divert the dense flow of a 10-year return period avalanche, and the stopping wall to resist a 30-year return period design avalanche. Geotechnical design considerations included a constrained footprint on the congested Landing, variable-quality subgrade conditions as a result of past site work, sources of suitable fill for construction, and a short design life. Construction was completed in fall 2018.

Keyword: *avalanche defence structure; avalanche engineering; stopping wall; deflection berm*

1. INTRODUCTION

Multiple large avalanche paths threaten infrastructure and ongoing construction works at the Kemano hydroelectric facility in the Coast Mountains near Kitimat, British Columbia, Canada. The facility is operated by Rio Tinto Alcan (RTA) and has been providing electricity to the aluminium smelter at Kitimat as well as neighbouring communities since the 1950's. Construction of a second water-intake tunnel (T2) for the Kemano generating plant has recently resumed after initial construction was halted in the early 1990's. Current construction works began in spring 2018 and are scheduled to be completed within three years.

Construction of the T2 tunnel and supporting operations are staged from Horetzky Landing (Fig. 1), situated at the head of a steep mountain valley northeast of Kemano. The Landing is accessible via an 11 km long access road ascending the valley. Horetzky Landing supports the primary adit (access portal) for the Tunnel Boring Machine (TBM) and is host to a workers' camp, offices, concrete batch plant, TBM maintenance shed, wastewater treatment facility, and multiple equipment laydown areas.

Numerous avalanche paths threaten Horetzky Landing and the access road. A path known as 28.0N directly affects Horetzky Landing and is capable of producing large avalanches that have the potential to impact infrastructure across the Landing and fill the T2 adit with debris. To maintain the current T2 construction schedule, project specifications stipulated that avalanche closure times at the Landing were to be minimized, and the T2 adit should remain operational throughout the winter even if the Landing was impacted by a large avalanche.

Mitigating avalanche risk to Horetzky Landing involves a combination of an active forecasting and control program, Remote Avalanche Control Systems (RACS) in the start zones of 28.0N, and passive defence structures at Horetzky Landing. The structures consist of an avalanche deflection berm and stopping wall designed and constructed in 2018, and described herein.

Figure 1 Horetzky Landing, viewed from the start zone of avalanche path 28.0N during late-stage construction of the deflection berm and stopping wall (Photo: October, 2018).

2. AVALANCHE RISK AT HORETZKY LANDING

2.1 Snow Avalanche Geoclimate

The T2 Project area is located in the Maritime snow climate of the Northern Coast Range of British Columbia, which is generally characterized by heavy snowfall and relatively mild winter temperatures. Local winter weather patterns are historically severe due to latitude and the amplifying effects of local mountain topography that ascends abruptly from sea level to over 2000 m causing rapid orographic lift of inbound Pacific coastal weather systems. The region receives some of the heaviest snowfalls in North America, with settled seasonal snowpack depths ranging from 3–8 m.

2.2 Avalanche Risk Assessment

Avalanche risk to Horetzky Landing was assessed using a combination of field studies, historical avalanche observations from previous phases of construction (Alcan, 1991), dynamic and statistical avalanche models, and expert judgement. Avalanche runout distance, velocities, flow depths and widths were estimated using multiple dynamic runout models, including PCM Model (Perla et al., 1982), PLK Model (Perla et al., 1984), and RAMMS (Christen et al., 2010).

Path 28.0N has multiple alpine start zones ranging in elevation between 2000 m and 1300 m with east, south and west aspects. The runout is below treeline, much of which covers Horetzky Landing at an elevation of roughly 760 to 820 m. The path is capable of producing avalanches up to size 3.0 (destructive scale) annually and larger size 3.5 to 4.0 avalanches are expected with 10 and 30-year return-periods.

Without defence structures at Horetzky Landing, the runout of a 10-year return-period avalanche would reach the upper Landing, impacting a large equipment laydown area. The runout of a 30-year event was expected to reach 40–50 m beyond the T2 adit on the lower Landing, filling the adit with debris and impacting the TBM maintenance shed, wastewater treatment facility and additional equipment laydown areas. Larger avalanches would completely cross the Landing, with the largest events crossing Horetzky Creek and running up the opposite side of the valley. The workers' camp and offices are situated east of the avalanche runout, sheltered behind mature forest.

Construction and tunnelling works staged from Horetzky Landing are expected to take 2–3 years to complete. The encounter probability of a 10-year-return-period event occurring in that time is 27% and the encounter probability of a 30-year event is nearly 10%.

3. DEFLECTION BERM AND STOPPING WALL DESIGN

3.1 Design Criteria

The objective of the avalanche deflection berm and stopping wall were to reduce the exposure of critical infrastructure and minimize closure times at Horetzky Landing during the 3-year construction period. The deflection berm was designed to deflect the dense flow component of size 3.5 avalanches with 10-year return periods, and partially deflect but be overtopped by 30-year and larger avalanches. The stopping wall was designed to stop the dense flow of the 30-year return-period size 4 avalanche about 40 m short of its estimated runout distance. The powder component of the design avalanche will overtop the stopping wall and impact structures beyond the T2 adit. Additional design criteria included:

- Locating the structures where they would be most effective against avalanches;
- Minimizing land-use (footprint) on the crowded Landing;
- Minimizing environmental impact and disruption of natural drainage courses;
- Using on-site stockpiles of TBM muck or drill/blast waste-rock for construction fill;
- Satisfying established geotechnical stability Factors of Safety (FOS).

3.2 Geotechnical Parameters

Much of Horetzky Landing is constructed on stockpiled drill/blast waste-rock and TBM muck fills from previous T1 and T2 tunneling operations in the 1950's and early 1990's, respectively. These materials were used for construction of the structures and also formed the underlying foundation soils. Available geotechnical information was sparse and outdated in the areas of the stopping wall and deflection berm, since relevant reports predated the early 90's T2 construction works in which large volumes of waste rock and TBM muck were disposed across the site.

From available reports and drawings, it was understood that most of the deflection berm would be situated atop the existing 1950's drill/blast waste-rock stockpile that formed the upper Landing and large equipment laydown area (Fig. 1). This material consisted of gravel, sand, angular cobbles and boulders with old wood waste and project materials encountered sporadically amongst the fill. The stockpile slopes south of the berm location were up to 20 m tall with 2.5 horizontal to 1 vertical (2.5H:1V) grades.

At the stopping wall location, the depth of existing fills and native colluvium overlying bedrock was unknown but assumed to be 1 to 5 m thick. A series of 3 m test pits along the length of the wall conducted in Spring 2018 revealed free-draining granular fill soils mixed with significant organics, wood waste and metal. Shallow bedrock was encountered at the east end of the wall.

Expected gradations of the 1990's TBM muck and drill/blast waste rock materials were provided by RTA and formed the basis of shear strength calculations in the design of the structures. The TBM muck was expected to be well-graded with a maximum particle size of 100 mm and less than 8% fine silts and clay. Drill/blast waste-rock was reported to be up to 450 mm in particle size with roughly 5–10% oversize and negligible fines content.

Geotechnical Factors of Safety (FOS) against deep-seated global instability of the structures were based on project specifications provided by the RTA. The near-vertical Gabion-face of the stopping wall was designed to a FOS of 1.5 under static conditions, while the backslope of the wall and the side-slopes of the deflection berm were designed to a FOS of 1.3. A minimum FOS of 1.1 for both structures under avalanche impact loading or pseudostatic seismic loading was also specified.

3.3 Deflection Berm Design

The deflection berm (Fig. 2) is located in the upper runout zone of Path 28.0N on the upper edge of Horetzky Landing and is oriented at 33 degrees to the primary avalanche flow direction. The berm is a 150 m long and 10 m high with a 3 m crest and steep side-slopes shaped at 1.3H:1V to minimize the footprint and fill requirement, and to prevent avalanche run-up. The berm required roughly 23,400 m^3 of fill to construct. It has a gentle dog-leg to the west at the downhill end. At the uphill end, the berm ties into a steep natural bank of mature forest that helps channel the dense flow of the design avalanche toward the berm. The toe of the berm was set back a minimum of 10 m from the crest of the tall fill slopes of the 1950's waste-rock stockpile on which it was situated.

Figure 2 Construction of the deflection berm with temporary access ramp (October, 2018).

The steep side-slopes of the berm necessitated geogrid reinforcement within the structure in order to satisfy the 1.3 FOS requirement. Primary layers of uniaxial geogrid were placed at 2 m vertical spacing with each layer spanning the entire width of the berm and continuously along the length. Shorter, 3 m lengths of the same geogrid were spaced between the primary grid for added facing stability.

3.4 Stopping Wall Design

The stopping wall (Fig. 3) is located lower in the runout, immediately above the T2 adit. The wall is 8 m high with a near-vertical Gabion-basket face, a 3 m crest, and a 1.3H:1V backslope to minimize the footprint next to the adit. It is 120 m long and required nearly 10,000 m^3 of fill and roughly 490 Gabion baskets to construct. The length of the wall followed the naturally sloping terrain parallel to the T2 adit at an average grade of 19% which required stepping the Gabion layers at every third or fourth basket along the wall. Continuous layers of uniaxial geogrid reinforcement with were placed between each Gabion layer and extended back through the structure to stabilize both the Gabion face and 1.3H:1V backslope. The short design life of the structure and the potential for damage to the geogrid in the coarse fill were considered when factoring the tensile strength of the geogrid.

Deleterious subgrade soils beneath the Gabion face were over-excavated to 2 m (or shallow bedrock) and replaced with crushed gravel interbedded with two layers of biaxial geogrid to strengthen and stiffen the foundation of the wall.

The wall was evaluated for global stability and sliding under the design avalanche impact load. The avalanche impact was conservatively modelled as a static load with an even distribution of 32 kPa representing the dense flow from 0 to 3 m height, and a triangular distribution of 32 to 5 kPa from 3 to 8 m height representing the transitional saltation and powder flow layers. A static design snow load of 13.9 kPa was also applied as a surcharge to the crest and backslope of the stopping wall structure under some conditions. In addition to satisfying global stability, the FOS against sliding and bearing failure were calculated, and internal factors of safety against geogrid rupture and pullout were also verified.

Figure 3 Final construction of the avalanche stopping wall (November, 2018).

4. CONSTRUCTION

Construction of the deflection berm and stopping wall took place simultaneously in the fall of 2018. Weather during the construction period (September to early November) was favourable, with unseasonably mild temperatures and relatively low rainfall for the region and time of year. Snow and freezing temperatures were not a factor during construction.

Material gradation and developing a consistent source of suitable quality fill was a challenge at the start of construction. The 1990's TBM muck, for which the structures had been designed to use as fill, turned out to have a much higher fines content than the gradation curves provided by RTA during the design stage. Although suitable compaction could be achieved in dry conditions, the material quickly degenerated during wet weather, becoming unworkable. Furthermore, the siltier material had a lower friction angle than had been assumed in design. This was recognized in the first week of berm construction and an alternative source of material was sought. Instead, careful regrading and some sorting of the 1950's drill/blast waste-rock stockpiles around the upper Landing provided sufficient coarse, granular fill for construction.

Compaction efforts were specified based on standards for rock-fill (e.g. Breitenbach, 1993) that included lift thickness, compactor ratings and recommended number of passes. Adequate compaction was confirmed in the field by the settlement-per-roller-pass method described by Breitenback (1993).

5. CONCLUSIONS

The two geogrid-reinforced, earthen avalanche defence structures designed and constructed at Horetzky Landing form part of a comprehensive avalanche risk mitigation strategy for the Kemano T2 Completion Project that also includes active winter forecasting and control work and remote avalanche control systems in the start zones.

The 10 m high, 150 m long deflection berm in the upper runout was designed to defect the dense flow of a 10-year return-period avalanche away from the upper Landing, while the 8 m high, 120 m long, gabion-faced stopping wall in the lower runout was designed to stop the dense flow of a 30-year return period avalanche. The structures consume a minimal footprint on the crowded landing, satisfied specific geotechnical factors of safety, and successfully used local stockpiles of available drill/blast waste-rock fill for construction.

Construction took place over two months in the fall of 2018 and was completed prior to the first winter avalanche season.

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Hazard managing in Austrian ski areas

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ABSTRACT

The first decree concerning avalanche protection of cableways in Austria was published in 1975. Based on experiences and the continuous development of artificial avalanche releases, avalanche forecasting and avalanche warning, an updated Avalanche Decree was put in force 2011.

Even through the implementation of permanent technical avalanche protection measures, absolute safety cannot be achieved. The residual risk after the implementation of the permanent technical protective measures must be taken into account when planning the safety measures. The remaining residual risk must be minimized through temporary measures such as closing the ski slope or cableway shutdown. For each individual ropeway a specific assessment must be developed, and measures to minimize the residual risk in the best possible way must be provided. The Avalanche Decree regulates not only the safety for the system components but also the operational safety, guaranteeing the use and the access of a cableway under avalanche safe conditions. The regulations of the Avalanche Decree and their implementation in Austrian ski resorts will be explained in more detail using the example of the Raintal ropeway in Kitzbühel.

1. INTRODUCTION

After several serious avalanche accidents in the area of cableways, the Federal Ministry of Transport, Innovation and Technology created an Avalanche Decree for the first time in 1975 to maximise avalanche protection. According to this decree, the construction of new cableways was only permitted on sites safe from avalanches or protected by permanent protective measures. The same applied to at least one ski slope associated to the cableway (Fritz, 2011).

The avalanche expertise gained, the improvements and further developments of artificial avalanche release as well as avalanche forecasting and avalanche warning created the base for a new regulation of avalanche protection for cableways in the Avalanche Decree 2011. As experience shows absolute safety cannot be achieved with permanent avalanche structures, it is now an issue of minimising any residual risks as far as possible by implementing temporary measures (BMVIT, 2011). Therefore closures or artificial avalanche releases can be used to secure the associated ski slope, station access areas, station exit areas and rescue access. The aim is a measure or a combination of measures that minimise the residual risk as far as possible and optimise the avalanche protection. For this purpose each individual ropeway project has to be evaluated separately. Such an assessment has to be done in analogy to the hazard zone planning according to the Austrian Forestry Law 1975. This offers the advantage that experts from the Austrian Federal Service for Torrent and Avalanche Control can use a well proven assessment method for the evaluation (Fritz, 2011).

2. METHODS

Before a new cableway can be constructed, a safety analysis with regard to natural hazards has to be carried out as part of the permit procedure. If the planned cableway or the associated ski slope is not inherently avalanche safe, the applicant must prepare a so-called **avalanche protection concept** in cooperation with the local avalanche commission. This concept refers to the facilities and operational safety in the context of the Avalanche Decree. The suggested avalanche protection measures (permanent and/or temporary) are described and assessed in terms of their effectiveness. During the approval procedure the suitability of the planned protective measures requires an avalanche expert assessment by the department of the Austrian Federal Service for Torrent and Avalanche Control (BMVIT, 2011).

The **facility safety** required in the Avalanche Decree includes the structures and components of the cableway itself (mountain and valley stations, pylons, ropes). These components are not allowed to suffer any damage up to an event with a 150-year return level. This also applies outside operational times. The stations have to be installed primarily on inherently avalanche safe sites. If this is impossible the risk situation of a red avalanche hazard zone must be reduced to that of a yellow avalanche hazard zone by implementing permanent technical protective measures (BMVIT, 2011). A pressure of 10 kN/m² was defined as the limit between yellow and red avalanche zones (BMLFUW, 2016). The remaining residual hazard (corresponding to the yellow hazard zone) must be eliminated by applying additional object protection measures (e.g. reinforced side walls). The pylons must be dimensioned to resist the calculated avalanche and snow pressures. The rope guide has to be designed in such a way to prevent the rope from being dropped as a result of an avalanche (BMVIT, 2011).

Operational safety refers to the safety to be ensured for persons (passengers and staff) when operating the cableway or using the direct station entrance and exit areas. In addition, rescue operation for blocked systems have to be possible under avalanche safe conditions. It also must be possible for skiers to use the cableways ski slope under avalanche safe conditions. To ensure this operational safety, temporary safety measures can be used in addition to permanent safety measures (BMVIT, 2011). According to the Avalanche Decree guidelines, the sole blocking of the ski slope as a safety measure is not permitted for frequent avalanches with a 30-year return level (BMLFUW, 2011).

For replacement or modification of already existing ropeways, it is possible to invoke a specific **exceptional procedure** (not further discussed in this paper).

3. RESULTS

In the following section, you will find a practical example for the application of the Avalanche Decrees regulations. For this purpose the new construction of the 10 EUB Raintal by Bergbahn AG Kitzbühel was selected. The new Raintal ropeway will replace the old chairlift "Raintal". The lifts location and length have been redefined.

3.1. Facility safety according to Avalanche Decree

3.1.1 Stations

The planned **mountain station** will be built on the ridge of the Kitzbühler Horn. According to the Avalanche Decree terms this site is classified as inherently avalanche safe, so no measures are required.

Above (north of) the planned **valley station** there is a 170 m high, south-facing slope with an inclination between 30 and 34 degrees. Avalanche simulations with the numerical model RAMMS show the planned valley station being overflowed by avalanches from the largest release area AG 03 (Figure 1). The avalanche pressures in this area represent an endangerment in the form of a red hazard zone with a pressure of more than 10 kN/m² (Figure 2).

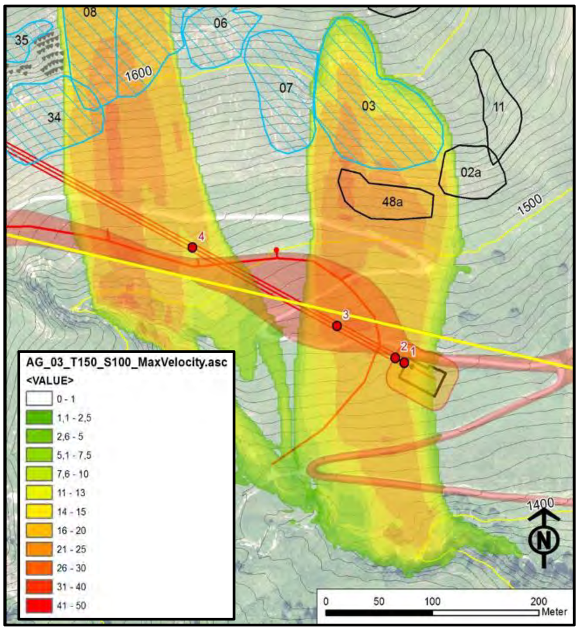

Figure 1: Maximum flow velocity for release area AG 03 (blue polygon) modelled with RAMMS. Release areas for snow glides are marked in black. The new Raintal ropeway, its valley station and the according ski slope is marked in red. The yellow line shows the old chairlift "Raintal" (Illmer, 2018).

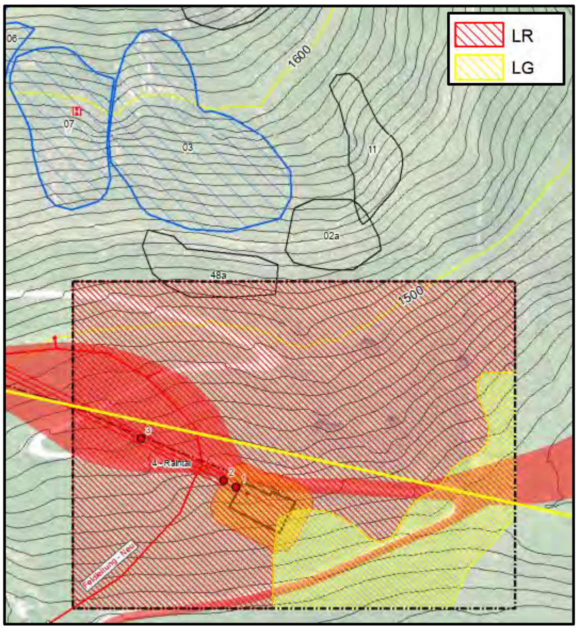

Figure 2: Hazard zone map for the valley station including the red (pressure ≥ 10 kN/m²) and yellow avalanche hazard zones (Illmer, 2018).

In order to protect the planned valley station, release area AG 03 was secured through permanent avalanche barriers (Figure 3). From the smaller release areas (AG 48a and AG 02a) local snow slides still occur in warm weather conditions. The danger level can be minimized by a terrain modification next to the valley station.

3.1.2 Pylons

As the new cableway line diagonally crosses the slope, snow pressure from sliding and creeping movements act on the planned pylons. The forces were calculated for each individual pylon according to the specifications of the Austrian Standards Institute (ONR) 24805 (2010). Detailed avalanche simulations were performed and evaluated for pylons affected by avalanches (analogous to Figure 1). Based on dense flow avalanche intensities and the position of the pylons in the avalanche path, pressures and impact heights of powdered snow were calculated in accordance to ONR 24805 (2010).

Figure 3: Support structure to protect the valley station built in the release area AG 03 (KitzSki, 2019)

Figure 4: Elevated and wedge-shaped foundations to protect the pylons against flow avalanches (KitzSki, 2019)

These snow and avalanche pressures had to be considered as separate load cases in the pylons structural analysis. For those pylons with high impact pressures from the dense flow avalanche, the foundations were elevated and built wedge-shaped towards the avalanche impact direction (Figure 4). This way the largest pressures can be transferred directly to the foundation.

3.1.3 Rope guide

Since no rope shedding may occur as a result of an avalanche up to the size of the design event, the powder snow heights and pressures from the powdered layer along the rope line was calculated in accordance to ONR 24805 (2010) and to the Avalanche Decree guidelines. If the rope line (height of the rope) is reached by a powder snow avalanche, the pressure has to be considered by the cableway manufacturer. In our case, powder snow avalanches only reach the height of the rope guide in the area of pylon number four. This effect was considered by the manufacturer during planning.

3.2. Operational safety according to Avalanche Decree

3.2.1. Access of the new ropeway

The planned ropeway is located in the developed ski area and is safely accessed via the inherently avalanche safe mountain station, therefore no further measures were required.

3.2.2. Station entry and exit areas

The mountain station entrance and exit area is inherently safe from avalanches. The valley station is now secured by supporting structures. However, a yellow hazard zone at the northern side remains due to the two snow slide areas. This residual risk is covered by temporary measures such as the preparation of a snow wall with grooming equipment.

3.2.3. Rescue in the case of an immovable system

As a requirement for any rescue the systems avalanche safety must be guaranteed. The assessment of avalanche safety has to be carried out by the local avalanche commission. If necessary, this commission recommends appropriate measures to be taken by the lift operator. The safety required to rescue the Raintal ropeway is ensured by artificial avalanche release (temporary measures). Therefore, two avalanche blasting masts have been installed to be used in combination with the helicopter-based "Daisy Bell" system.

3.2.4. Associated ski slope

The ski slope from the mountain station to the valley station is endangered by avalanches in several areas. The slope is secured with temporary avalanche protection measures, e.g. helicopter blasting, manual blasting or rolling with a groomer. Also the already existing avalanche blasting cableway will be used further on.

4. CONCLUSIONS

The avalanche safety of a new cableway and at least one associated ski slope is an essential requirement for a cableway license or permit. The applicant has to prepare a so-called avalanche protection concept, if the planned cableway or the associated ski slope is not inherently avalanche safe. The involvement of the local avalanche commission in the development of the avalanche protection concept is an important part. In the context of the avalanche decree the facility and the operational safety must be assessed in detail. Furthermore appropriate avalanche protection measures (permanent and/or temporary) have to be planned and evaluated in terms of their effectiveness. A very central part of the license procedure is the suitability assessment of the proposed avalanche protection measures. This is done by the Austrian Federal Service for Torrent and Avalanche Control. Such an assessment has to be done in analogy to the hazard zone planning according to the Austrian Forestry Law 1975. Due to consistent compliance to the strict regulations of the Avalanche Decree 2011, a very high level of avalanche safety has been achieved in Austria's ski resorts.

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Avalanche and landslide hazard zoning committees in Iceland

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ABSTRACT

In Iceland, landslides and avalanches have resulted in catastrophic consequences with loss of lives as well as economical losses. After two tragic events in 1995, an act on protective measures against avalanches and landslides was passed in 1997, revised in 2000 and followed up with the issue of a regulation. The regulation embraces hazard zoning, classification and utilisation of hazards zones, as well as preparation of provisional hazard zoning. These require an assessment of the risk associated with snow avalanches and landslides in communities where such have fallen on or near settled areas, or where the threat of this can be deduced from the topographical and meteorological conditions. Furthermore, a Hazard Zoning Committee (HZC) is to be assigned for each specific case. The HZC shall decide, in consultation with the local authority, which areas the hazards zoning shall cover, and subsequently request the Icelandic Meteorological Office to carry out the hazards zoning. This paper outlines the responsibility of the HZC as mandated by the laws. Furthermore, it provides an overview of the extent of work carried out by the different committees in conjunction with hazard zoning of altogether 23 urban areas/communities, since the first committee was established in the year 2000.

1. INTRODUCTION

In Iceland, mass movements, mainly snow avalanches, have resulted in catastrophic consequences with loss of lives as well as economical losses. Several catastrophic events have occurred in recent decades in East- and West-Iceland, mainly in villages by fjords dominated by steep mountain sides. After two catastrophic avalanches at Flateyri and Súðavík in West-Iceland in 1995, a governmental fund, the Icelandic Avalanche Fund, was strengthened considerably. Furthermore, an Act on Protective Measures against Avalanches and landslides was passed in 1997 (Alþingi, 1997) (referred to in the following as the Act), revised in the year 2000 and followed up with the issue of a regulation on hazard zoning due to snow and landslide (Umhverfisráðuneytið, 2000) (referred to in the following as the Regulation). The aim of the Act is to prevent damage to property and persons resulting from avalanches and landslides.

The Act and the Regulation embrace collection and process of data on avalanches and landslides, measurements of snowpack properties and research regarding avalanche dangers, hazard zoning, classification and utilisation of hazards zones, as well as preparation of provisional hazard zoning. These require an assessment of the risk associated with snow avalanches and landslides in communities where such threat lies in the topographical and meteorological conditions. Furthermore, a Hazard Zoning Committee (HZC) is to be assigned for each specific case. This paper will outline the responsibility of the HZC committees as mandated by the laws by summarizing the framework given by the Act and Regulation. Furthermore, report on the work that has been carried out in conjunction with hazard zoning of, to this date, 23 urban areas/communities, since the first HZC committee was established in the year 2000.

2. FRAMEWORK

The local authorities in communities threatened by snow- or landslide shall according to the Act have the initiative to request the Minister for the Environment (referred to as the Minister in the following) for an assessment of the risk involved. Following such a request the Minister appoints a Hazard Zoning Committee (HZC) of four members. The HZC is to direct the preparation of a hazard zoning in the community requesting the assessment. Two of the HZC members are nominated by the local authorities, while the Minister appoints two without nomination. One of those appointed without nomination shall, according to the Act, be the Chairman of the committee and cast the deciding vote in case of a tie vote. The Regulation additionally requires the other person without nomination, to be a Specialist with expert knowledge of snow- and landslide danger.

The HZC shall direct the preparation of the hazard zoning and decide, in consultation with the local authority, which areas the hazards zoning shall cover. Furthermore, the HZC shall request the Icelandic Meteorological Office (IMO) to carry out the hazards zoning and conclude a contract with the IMO in this regard.

The hazard zoning must be based on the following data collection: maps of the area, extensive documentation on snow- and landslides in the area, investigation of weather conditions, examination of local settlement history and on-site inspection (Umhverfisráðuneytið, 2000) (the Regulation). The IMO is by law (Alþingi, 1997) (the Act) responsible for collecting and processing data on avalanches and avalanche danger. Thus, in most cases the work of the IMO relating to the data collection and hazard assessment has started and been ongoing for some time before the HZC is appointed by the Minister.

When the IMO has completed a proposal for the hazard zoning, the local authority, in consultation with the HZC, is responsible for advertising and arranging the presentation of this at an open meeting in the local community (see the Regulation). Usually, a flyer is prepared in conjunction with the open meeting, containing relevant information and summary from the hazard zoning, including a small map. The hazard zoning and the basis of this is usually presented by the IMO specialists conducting the assessment. After the presentation, the hazard zoning and associated report is to be available to the public for four weeks at the office of the local authority (see the Regulation). During this period, comments and questions may come from the public, which the HZC usually answers in consultation with the IMO and the local authorities. Furthermore, the report may be revised to make some points clearer in light of the comments and questions.

At the end of the four week open public access to the hazard zoning, the HZC sends this to the Minister for the Environment for attestation. The hazard zoning enters into force upon publication in the Official Journal of Iceland (Stjórnartíðindi).

3. HAZARD ZONING COMMITTEES

3.1 Overview and urgency of hazard zoning

The inhabited areas threatened by avalanches are mostly located close to the coast in western, northern and eastern Iceland. These areas were prioritized in the time line set for the hazard zoning (See Figure 1). Furthermore, the Regulation (Umhverfisráðuneytið, 2000) issued in 2000 had temporary provisions requiring that the HZC assigned for certain ten centres of populations to conclude the hazard zoning no later than the end of the year 2001. The centres of population given this urgency were the following: Bíldudalur, Bolungarvík, Eskifjörður, Ísafjörður including Hnífsdalur, Neskaupsstaður, Ólafsvík, Patreksfjörður, Seyðisfjörður and Siglufjörður. However, the HZC for these places were appointed in the time period 2000 to 2003, and thus obviously the specified deadline could not be adhered to. Still, these places were prioritised and the first ones to have a hazard zoning attested.

Figure 1. Centers of population threatened by avalanches and for which historical data along with population density indicated the highest associated risk. (Figure from Jóhannesson and Arnalds, 2001). These centers of population (with the exception of Flateyri and Súðavík) were given an urgency in the hazard zoning procedure by the Regulation issued in 2000 (Umhverfisráðuneytið, 2000).

The first two HZC were assigned in the year 2000 for Neskaupstaður and Eskifjörður, the open meeting was held in 2001 and the hazard zoning attested in 2002. In 2002, the hazard zoning for four of the ten (effectively nine considering that Hnífsdalur is a part of Ísafjörður) prioritized centres of populations entered into force. In 2004 all of these had a hazard zoning attested and into force, the last ones being Ólafsvík and Bíldudalur.

Notably, the villages Flateyri and Súðavík were not listed in the temporary provisions of the Regulation. But after the tragedies in 1995, measures were taken to reduce the avalanche risk. In Flateyri, avalanche protection measures were installed, and in Súðavík, the populated area within the hazard zone was relocated. Nevertheless, a HZC was assigned for these places, Flateyri and Súðavík, respectively in 2003 and 2004 with the hazard zoning in force in 2004 and 2005. By 2007, HZC had been assigned for all populated areas in North-, East- and West Iceland severely threatened by avalanches. In the years that followed, HZC were assigned for areas with a lower risk relating to avalanches and or landslides.

3.2 Appointed Hazard Zoning Committees

Altogether twenty-three HZC have been appointed in the period from the year 2000 to 2013. The two members of the HZC nominated by the local authorities are inevitable represented by different persons. However, a certain stability has been in the appointment of the Chairman and the Specialist. Gunnar Guðni Tómasson has been a member of all the HZC appointed, the Chairman of fifteen of these and the Specialist in eight. Snjólfur Ólafsson has been the Chairman in eight of the committees and the Specialist in thirteen. Fjóla Guðrún Sigtryggsdóttir has been appointed as the Specialist in the last two HZC appointed. Thus, of the twenty-three HZC, twenty-one have had the same two persons appointed as the Chairman and/or the Specialist, and the same person has been in all HZC either has Chairman or a Specialist. This arrangement has ensured consistency in the work of the HZC.

3.3 Work of the HZC and attested hazard zoning

The location of the twenty-three populated areas that have had a hazard zoning attested within the framework of the Act and Regulation, is given in Figure 2. Additionally, Figure 3 gives an overview of the apparent comparative urgency given to the hazard zoning, assuming that this is represented by the year of appointment of a HZC for the location specified. The urgency relates to the potential associated risk identified from historical data, topography, climate, and the population of the respective areas.

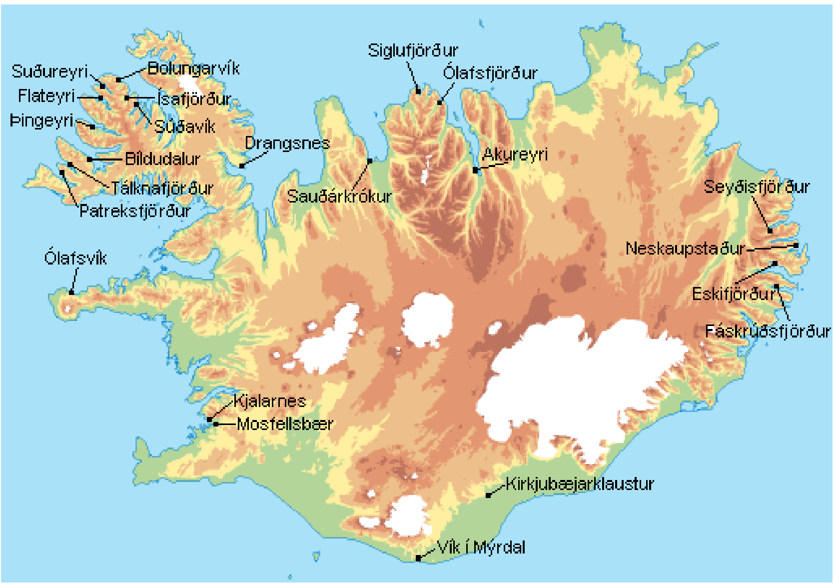

Figure 2 Populated areas for which a hazard zoning has been attested and entered into force. (Figure from IMO: https://www.vedur.is/ofanflod/haettumat/).

An overview of the work conducted by the different HZC is provided in Figure 4. The figure presents timeline and gives for each year the number of HZC appointed as well as the number of attested hazard zoning. The appointment of the HZC marks the initiation of the work relating to the hazard zoning, while the attestation marks the end of the committee’s work. The urgency of the early hazard zoning as described above in section 3.1 can be realized from the Figure 4, with a peak in the number of HZC appointed in the year 2003, and a steady number of attested hazard zonings in the years 2002 through 2005 or about three to four per year in that period.

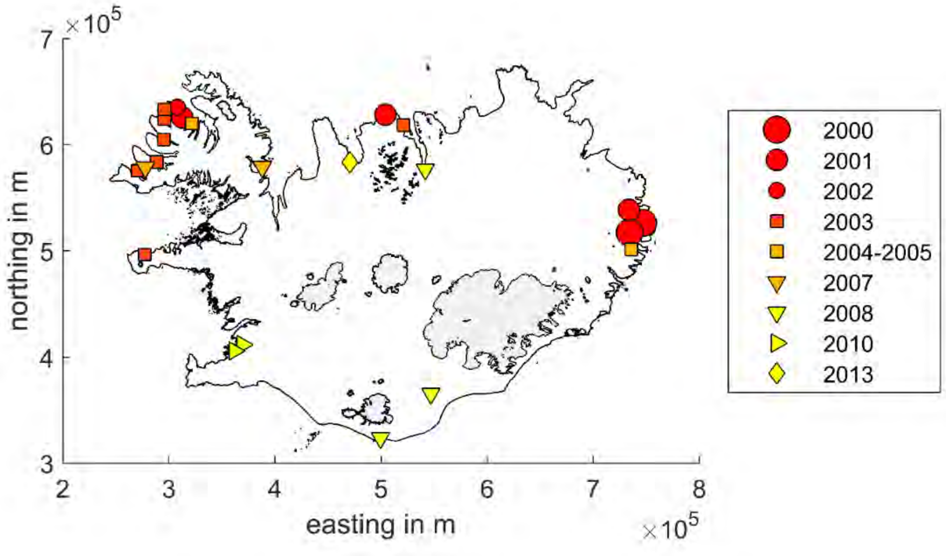

Figure 3 Location of places with hazard zoning in force. The comparative urgency of the hazard zoning is apparent from the year of Hazard Zoning Committee appointment. The most urgent hazard zoning was initiated in the period 2000 to 2003.

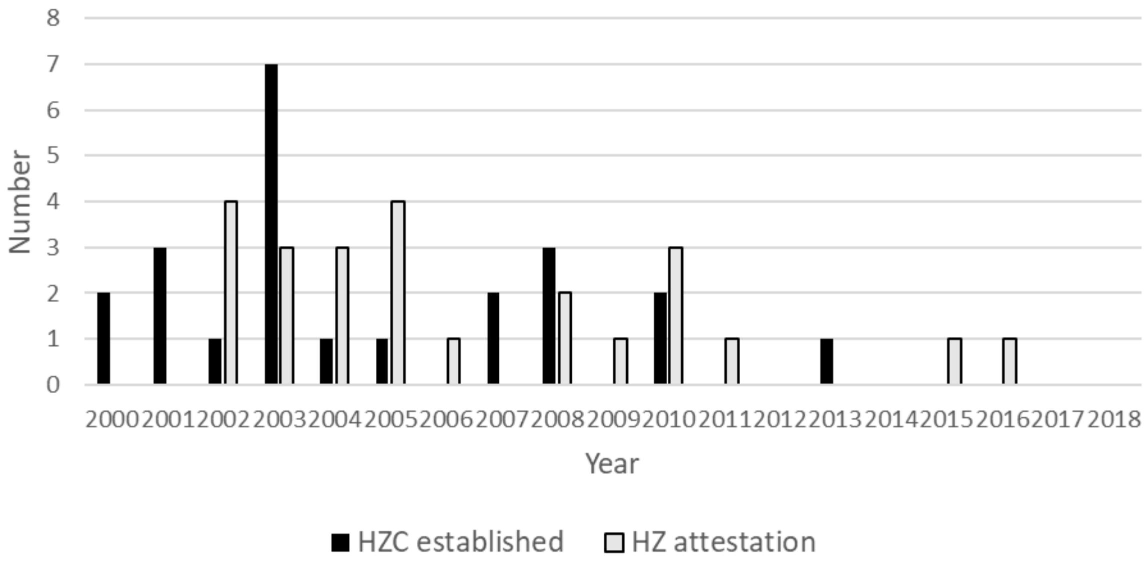

Figure 4 Timeline showing for each year the number of hazard zoning committees appointed and the number of attested hazard zoning.

The work of each HZC from appointment to attested hazard zoning, typically spans one to two years. An exception to this is the five year period for the hazard zoning of the Kjalarnes area at the outskirts of Reykjavík City. The area in question is scarcely populated and revision of the Act was required for clarification relating to this, hence the delay.

The intensity of the work carried out, since the first HSC till the last appointed hitherto, has been uneven and from Figure 4 three periods can be roughly identified in this regard. The first and most intensive period relating to the work overseen by the HZC initiates with the first committees assigned in the year 2000 and extends throughout 2006. During this period the most urgent hazard zoning was carried out and attested. The second period from 2007 to 2011 was of moderate intensity, while the third and last period was the least intensive and embraces the work overseen by the last two HZC appointed and spans from 2010 to 2016.

The information used to create Figures 3 and 4 was extracted from the hazard assessment reports available at the website of the IMO (IMO, 2001 to 2016) for the locations given in Figure 2.

4. CONCLUDING SUMMARY

The Act and Regulations for the hazard zoning of populated areas threatened by avalanches and landslide has provided an important framework for the hazard assessment and zoning conducted in twenty-three communities. Consistency in the work has been ensured, on one hand with the appointment of the same one or two persons as the members of the four-person Hazard Zoning Committee overseeing the work, and on the other by requiring the HZC to conclude a contract with the Iceland Meteorological Office (IMO) on carrying out the hazard assessment. Furthermore, the two members of the HZC nominated by the local authorities have been important for local knowledge and communication. The work overseen by the HZC and carried out by the IMO is clearly presented on the website of the IMO, where all the hazard assessment reports as well as the attested hazard zoning can be assessed. Successful execution of the hazard zoning is largely attributed to the work of the experts and specialists at IMO.

ACKNOWLEDGEMENT

The contribution of IMO in the hazard assessments and hazard zoning is acknowledged, as well as the work of Snjólfur Ólafsson as a member of twenty-one hazard zoning committees, either as a specialist or chairman. Furthermore, the contribution of the many HZC members nominated by the local authorities is acknowledged.

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Avalanches on Icelandic roads

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1. ABSTRACT

The Icelandic Meteorological Office (IMO) and the Icelandic Road and Coastal Administration (IRCA) have worked together on avalanche issues for roads since 2011. IMO has delivered daily avalanche forecasts for specific roads since 2013, as a service to IRCA.

The forecast is one of the tools IRCA uses to make decisions on openings and closures of the roads, to issue warnings or send information to travellers. A system for disseminating information to road users has been developed, and road users can sign up to receive text messages in their mobile phones regarding the avalanche situation on the roads. The information is not only about openings and closures but also on possible upcoming danger and avalanche warnings during periods when the road is still open.

2. INTRODUCTION

The history of road construction in Iceland is brief, especially in rural areas. In the areas where the risk of avalanches is the highest, road construction is very difficult due to steep mountain slopes. This is especially the case in the Westfjords, part of the North and in the Eastfjords. Many of the roads in these areas were not opened until 1950−1970. Roads with heavy snow were not always cleared and, therefore, closed for a large part of the winter. It wasn't until after 1960 that snow removal on roads started to any extent.

For a long time, the responsibility and supervision regarding avalanches and avalanche danger rested on the shoulders of the supervisor for each area. The supervisors achieved good experience, got to know the circumstances well and led successful careers in general. It became known what sort of weather would be likely to lead to avalanches in each area and at which point, after the weather calmed, it was safe to be back on the roads. Many roads, where avalanches are likely to occur, lie in or under steep slopes with many avalanche paths threatening a short stretch of the road. Commonly, many avalanches occur within a short period of time.

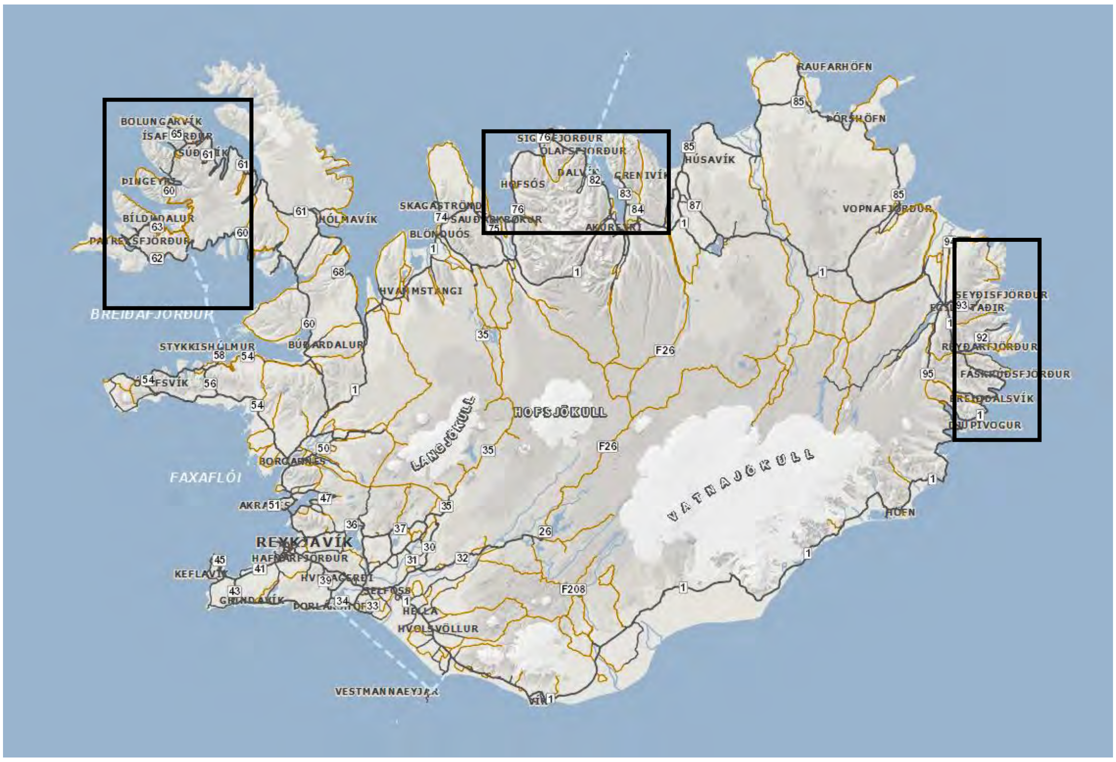

Figure 1. Three areas in Iceland where avalanches on roads are most frequent.

Different types of mitigation have been used to reduce risk on roads in Iceland. One of the main solutions is to widen channels beside the roads to make room for the snow. Often a steel bulkhead is installed as well to reduce the number of avalanches reaching the road. In some cases, dangerous roads have been replaced by a tunnel.

Figure 2. Steel bulkhead by the road below Óshlíð between Bolungarvík and Hnífsdalur.

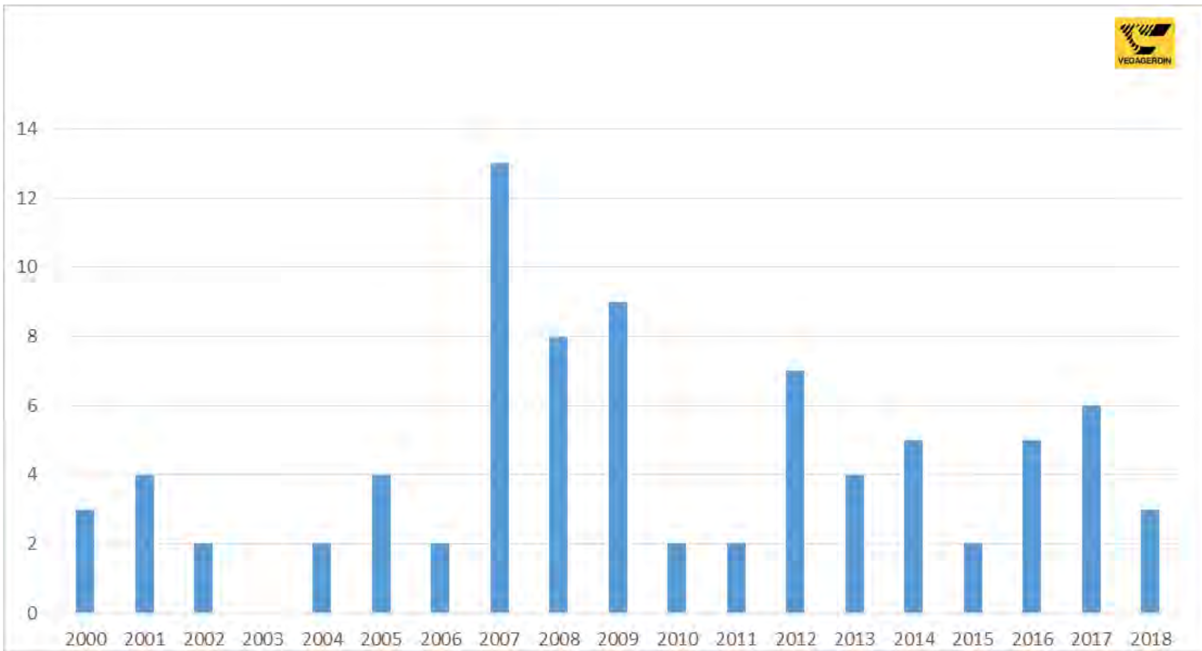

Figure 3. Number of accidents where vehicles encountered avalanches or rockfall, 2000−2018.

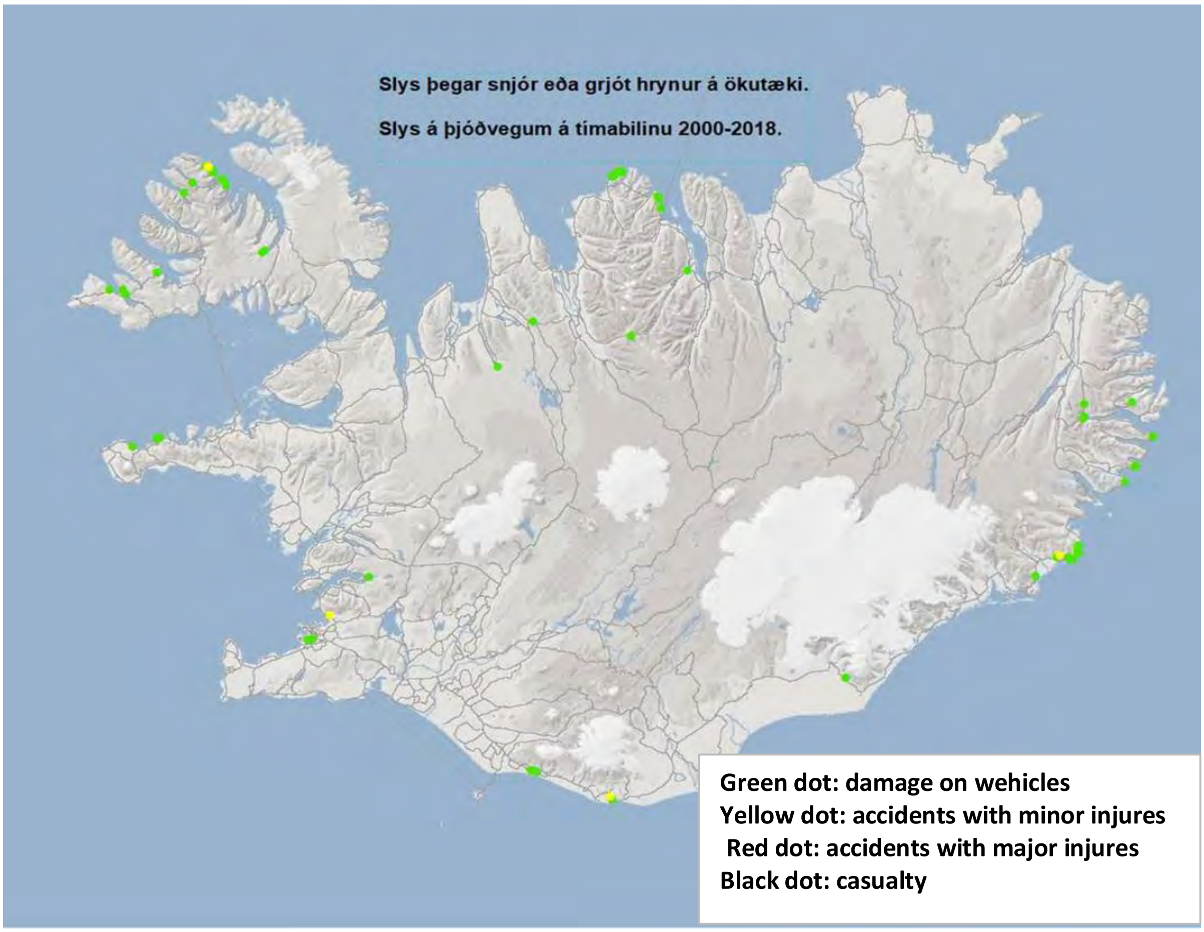

Figure 4. Locations where accidents where vehicles encounter avalanches or rockfall on Icelandic roads, 2000−2018.

2.1 Records on avalanches and statistical analyses.

The Icelandic Road and Coastal Administration (IRCA) has kept records on avalanches on roads since 1975. The avalanche danger was evaluated informally and typically a road was not closed due to avalanche danger until at least one or two avalanches had overrun the road. In the year 2011, the IRCA and the IMO started developing more formal avalanche forecasts for selected road stretches as well as a system for disseminating information to road users. This was through the Nordic collaboration project SNAPS (Snow, Ice and Avalanche Applications) that was partly funded by the EU Northern Periphery Programme.

At the IMO, statistical analyses were done on avalanche- and weather records for the roads 61 Súðavíkurhlíð and 82 Ólafsfjarðarvegur (Jónsson and others, 2014; Jónsson and Brynjólfsson 2015). Similar analysis is planned for road 64 Flateyrarvegur in 2019. The results are an important input for formal avalanche forecasting for these roads that started in 2013 as a service to the ICRA. Today, the IMO makes daily avalanche forecasts for four road stretches and less formal warnings are also issued for two more roads when the danger is estimated high. The roads in question are marked on the map in figure 2.

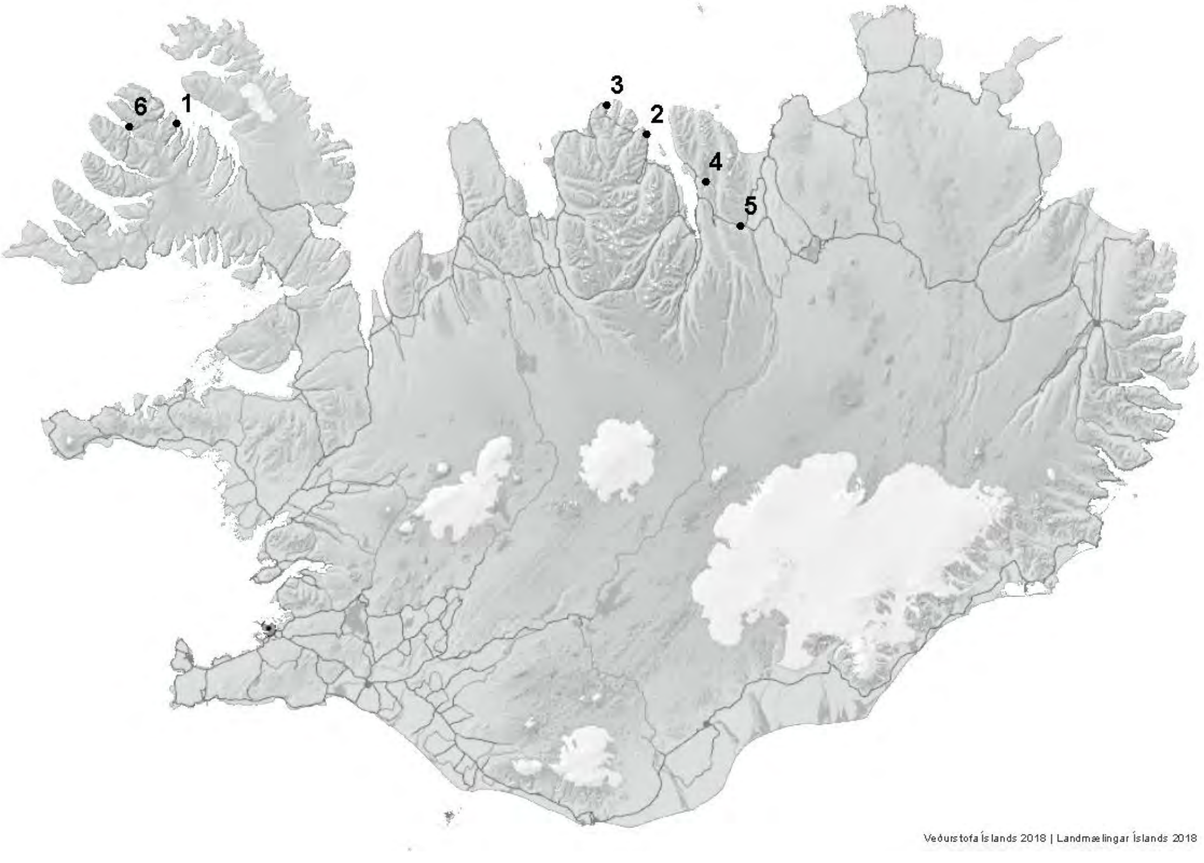

Figure 5 1. Súðavíkurhlíð, 2. Ólafsfjarðarvegur, 6. Flateyrarvegur: daily avalanche forecast and information service with text messages.

3. Siglufjarðarvegur: daily avalanche forecast.

4. Dalsmynni, 5. Ljósavatnsskarð: avalanche warning when the danger is considered high.

The IRCA, in cooperation with the local police, closes roads during periods of high danger and informs travellers of possible avalanche danger. For three of the roads people can sign up to receive text messages from the IRCA in their mobile phones regarding the avalanche situation on the road.

In addition to the avalanche forecast from the IMO it is important for the IRCA to have local supervisors to assess the situation and help making decisions based on the forecast as well as other factors such as visibility, road conditions, traffic etc.

3. AVALANCHE FORECAST

Avalanche forecasts for four road stretches are made daily at IMO as a service to IRCA. Four predefined danger levels are used for the forecast. Three of them state the current danger level while danger level 2 warns about upcoming avalanche danger. The danger levels are based on the estimated probability of avalanches hitting the road:

1. No/minor avalanche danger within the next 24 hours (<10% probability probability for an avalanche to reach the road).
2. Possible avalanche danger within the next 24 hours.
3. Considerable avalanche danger (10−40% probability for an avalanche to reach the road).
4. High avalanche danger (more than 40% probability probability for an avalanche to reach the road).

The forecast is recorded into a database at the IMO every day. When the danger level is 2 or higher an e-mail is sent to the ICRA.

Figure 6. Clearing of road 60 Hrafnseyrarheiði. A recently fallen avalanche is clearly seen. Workers are assessing the snow conditions ahead.

4. INFORMATION DISSEMINATION ON AVALANCHE DANGER

The IRCA receives the avalanche forecast from the IMO and decides on roads closures and information to road users on upcoming or current avalanche hazard. For some of the roads, people can sign up to receive text messages in their mobile phones regarding the avalanche situation on the road. Information about avalanche hazard on roads can also be displayed on map on IRCA's website that shows road conditions in the whole country.

Four predefined types of text messages are sent (underlined text is mutable):

A. Ólafsfjarðarvegur: Avalanche is possible <u>later today, Saturday.</u>

B. Ólafsfjarðarvegur: Avalanche: Warning phase is declared <u>today, Saturday at xx o'clock.</u>

C. Ólafsfjarðarvegur: Avalanche: Alert phase is declared <u>today Saturday at xx o'clock. Road closed.</u>

D. Ólafsfjarðarvegur: Avalanche: Alert phase is cancelled <u>Saturday at xx o'clock.</u> Road is open.

Thus, the roads are not just open or closed, more levels are defined. A warning phase is used when there is danger of avalanches, but the road has not been closed. It is not considered feasible to close the roads every time there is some chance of avalanches hitting the road. The idea with the warning phase is to inform road travellers, helping them to evaluate conditions and make decisions. This should reduce traffic on the roads during periods of avalanche danger. Road maintenance workers use full caution while clearing the road and the one carrying out the clearing is often accompanied by an escort or he/she must be in radio contact with his supervisors at all times.

Alert phase is used when avalanches have already fallen, and/or the risk of avalanches is considered great. The roads are closed during alert phase.

A formal survey has not been carried out amongst road users on the experience with the text message system, however, the general feedback is very positive. Road users are happy with better information and use this information to make risk reducing decisions for themselves. When a person receives message A and intends to drive the road in the next hours, he or she can postpone the journey or go before danger arises. People who receive message B can simply cancel trips that are not absolutely necessary. This reduces road traffic and hence the overall risk.

Table 1 shows the number of people that receive the text messages. It can be assumed that a great portion of commuters on those roads receives information about avalanche danger.

Table 2. Number of people that receive text messages for the two road sections and average daily winter traffic.

Road	Road users on SMS list	Traffic pr. winter day
61 Súðavíkurhlíð	200	325
82 Ólafsfjarðarvegur	400	443
64 Flateyrarvegur	160	149

Figure 7. Clearing of an avalanche on road 61 at Óshlíð. The road was replaced by a tunnel in 2010.

5. CONCLUSION

Avalanche danger is a problem at many roads in Iceland. In some cases, the roads lie along steep mountainsides with several avalanche paths. Different types of permanent mitigation have been used to reduce risk for the most dangerous roads. In recent years, the road authorities and the Icelandic Meteorological Office have collaborated on formal avalanche forecasts for roads as well as a system for disseminating information on avalanche danger to road users. Avalanche forecasts from the IMO works towards more systematic decisions on road closures and warning issues. The goal with the avalanche service for road users is to reduce the risk for road travellers without reducing the effectiveness of the road system too much. The warnings should reduce traffic when avalanche danger is increased but roads are still open. Those who need to travel are not stopped but others can choose to cancel or postpone trips may decide to do so.

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Landslide detection and mapping by remote sensing

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ABSTRACT

Landslides are an example of natural disaster of geological nature that seriously threaten and influence socio-economic conditions around the globe. Geology of the region, land cover, soil type, spatial distribution of heavy rainfalls and topography are relevant elements that, when monitored with help of remote sensing, can advance our understanding and prediction capabilities to detect adverse conditions that can trigger landslides. After a landslide event, timely delivery of remote sensing based maps may be of aid for disaster response, documentation and understand of processes involved. Remote sensing data for damage assessment of landslides is mainly of interest if high spatial resolution imagery can be timely obtained, processed, and delivered to the actors involved.

We have tested change-detection algorithms for identification and outline mapping of landslides. The clay landslide on 13 March 2009 in the Gullholmen coastal area in Namsos, Norway, was chosen for an experimental case study applying synthetic aperture radar (SAR). The landslide-affected area could be detected and outlined in a pair of Radarsat-2 backscatter images (VH polarisation), acquired on 7 March 2009 and 31 March 2009. The analysis also revealed differences in the backscattering signal due to other events in the region. Another experiment tested a candidate algorithm for very-high resolution optical data. It successfully mapped landslides-affected areas after a tragic event that took place in Nova Friburgo, Brazil, in 2001.

The presentation will discuss SAR and optical remote sensing techniques for detection and mapping of landslides from satellite observations. It will also discuss the prospects of providing early warning based on land-cover and accumulated rainfall. Algorithm approaches for detection and outline mapping will discussed and supplemented with examples.

Mapping snow surface hoar by optical remote sensing

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ABSTRACT

About 40% of the snow avalanches in Norway are assumed to be associated with weak layers in the snowpack originating from surface hoar. Mapping the formation of surface hoar combined with meteorological observations might in the future be used to predict where weak snow layers most likely are present. This information might then, in combination with snow loads and weather data, be used in a warning service to provide information about danger of snow avalanches.

We have developed a prototype algorithm for mapping of snow surface hoar based on moderate resolution satellite data. The algorithm has been tested extensively for a few years of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite. The algorithm combines information about surface skin temperature of the snow and snow grain size. Snow surface temperature is retrieved from thermal data where the atmospheric contribution is removed by using two different wavelengths which are differently attenuated by the atmosphere. For grain size we have used a normalized index. Surface hoar is then detected as extremely large snow grain sizes under low surface temperature conditions. The detection is robust as large grain sizes from melt-induced metamorphism usually can be discriminated from surface hoar.

We have validated the algorithm with in situ observations of surface hoar for a dozen of dates all over Norway. We were also able to detect past formation of surface hoar in a dataset where field workers concluded that weak layers most likely were involved in avalanches that had resulted in fatalities and/or destruction.

The avalanche flow regimes and their pressure on infrastructures

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ABSTRACT

New high-resolution radar measurements performed at the Swiss test site "Vallée de la Sionne" have allowed a reclassification of snow avalanches into 7 different flow regimes. Multiple flow regimes are often simultaneously present in different regions of a single avalanche, and avalanches can change the dominant flow regime as they descend the slope as a result of the entrainment of colder snow at higher altitudes and warmer snow at lower altitudes. 4 of these flow regimes are particularly important for the design of infrastructures impacted by avalanches. These include three dense regimes, namely the cold dense regime characteristic of fast moving dry avalanches, the warm plug and warm shear regimes characteristic of slow moving warm/wet avalanches and one dilute/dense regime, the intermittency regime, characteristic of fully developed powder snow avalanches. Each regime has a distinct impact dynamics, which requires a different modeling approach. The new data suggest that the assumptions underlying current avalanche simulation models and pressure calculation procedures may be too simple. The research community now faces the challenge of developing a better understanding of the physical processes that characterize the individual flow regimes, their transitions, their connection to the snow properties and their interaction with infrastructures.

1. INTRODUCTION

To improve our knowledge on the avalanche dynamics and the interaction between avalanches and structures, impact pressures and other dynamical variables have been measured at the Vallée de la Sionne experimental site (VdlS) in Switzerland since 1998 (Figure 1). In these years of operation we have measured events with an approximate return period of 10-20 years, as well as more frequent events, which may have a return period of one year or less.

In the last years, measurement techniques have considerably improved. Since the winter season 2010-2011, a new radar system, the GEODAR, has measured more than 200 avalanches of all sizes and different flow types (Ash et al., 2014; Köhler et al., 2018a, 2016).

The GEODAR is designed to localise the position of an avalanche with a spatial horizontal resolution of 0.75 m. The radar wavelength is around 5 cm, causing the beam to penetrate the powder cloud and to reflect the dense, basal flow or large snow blocks, underneath. This frequency modulated continuous wave radar is installed inside a shelter and monitors the whole avalanche path (Figure 1 right panel).

Figure 1. The Vallée de la Sionne test site. The left panel shows the obstacle zone and the release area. The right panel shows the measurement setup at the 20 m high pylon and at the 5 m high wedge. The red circle indicates the position of the shelter with the GEODAR radar (Pictures P. Huguenin).

The GEODAR data together with high-resolution measurement of velocity, pressure, density and temperature made on a 20 m high pylon located in the middle of the avalanche path (Figure 1) allow gaining unprecedented details into the avalanche physics both in term of avalanche dynamics and impact with infrastructures. With this contribution we aim to summarise the results of these recent researches.

2. THE NEW AVALANCHE REGIME CLASSIFICATION

In 2014, Steinkogler and colleagues showed that the temperature of the snow entrained along the avalanche path significantly affected the development of the avalanche front velocities at the Vallée de la Sionne test site. A snow temperature warmer than −2 °C could be identified as critical value where large changes in the flow dynamics took place. In 2015, Steinkogler and colleagues confirmed that the reason of this transition was due to snow granulation by mixing snow of varying temperatures and water content in a concrete tumbler. The experiments showed that granules only formed when the snow temperature exceeded about −1°C. No evolution in the granule size was observed at colder temperatures. Depending on the conditions, different granulation regimes were obtained, which were qualitatively classified according to their persistence and size distribution.

This abrupt change in the avalanching snow properties immediately prompted the idea to divide avalanches into two main categories, warm and cold depending on the temperature of the snow and its tendency to granulate (Steinkogler et al., 2015a, b).

In 2018, Köhler and colleagues realized by analysing the measurements from the GEODAR that the radar signals generated by the avalanches could show very different patterns (Figure 2).

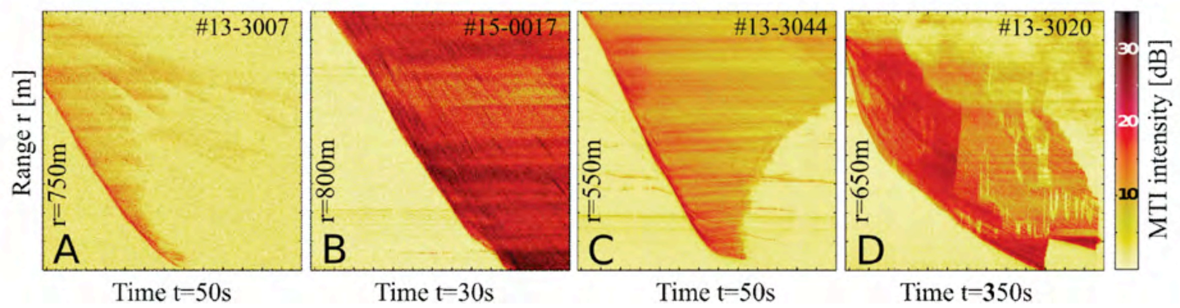

Figure 2. Typical GEODAR data signatures for the avalanche type: A) Cold dense regime, B) Intermittent regime, C) Warm shear regime and D) Warm plug regime. Note: Each panel has a different scale in range and time (Picture from Köhler et al., 2018c).

These differences confirmed the presence of the warm and cold behaviour suggested by Steinkogler et al. (2014), but stressed the need to divide avalanches into more categories, and more specifically into 7 flow regimes (Köhler et al., 2018a):

(1) The warm plug regime occurring when the snow cover temperature is mostly isothermal, T = 0°C. These avalanches are characterized by relatively low velocity, but cohesion between granules is large so that snow granules can easily stick together and give rise to large flow depths and flow units, which behave like gliding solid-like blocks.

(2) The warm shear regime occurring at snow temperatures slightly below 0°C. The matrix of the flow is still granular as in the case of the warm plug regime, but the relatively high velocities reached by these flows suggest that the cohesive forces acting between granules are not sufficient to glue particles together into larger units.

(3) The cold dense regime occurring at snow temperatures below -1°C. Their behaviour is similar to the warm shear regime but the snow temperature is lower and the velocity can be higher. Granulation is not expected.

(4) The intermittency flow regime occurring at snow temperature below -1°C. This is typical for the frontal zone of powder snow avalanches and it is characterized by large fluctuations in impact pressure, air pressure, velocity and density. The intermittency is caused by mesoscale coherent structures, i.e. an organized motion of particles, which evolves into the turbulent flow (Sovilla et al., 2018b).

(5) The suspension regime characterizing the motion of the dilute snow cloud in powder snow avalanches.

(6) The sliding slab regime characterizing the initial phase of the avalanche motion when the initial slab start to accelerate and to fragment into snow clods.

(7) The snowball regimes occurring when avalanches contain warm snow can give rise to individual snowballs or snow wheels rolling down the slope.

Particularly relevant for the flow dynamics and the impact pressures are the first 5 flow regimes, namely warm plug, warm shear, cold dense, intermittency and suspension.

2.1 **Flow regimes transitions**

The GEODAR measurements coupled with measurements of avalanche dynamics variables performed at the pylon have further suggested that a single avalanche can be characterized by multiple flow regimes (Köhler et al., 2018a). Powder snow avalanches give the most complex example of flow regime transitions, where all the 5 most relevant regimes may be present at the same time (Sovilla et al., 2015, Köhler et al., 2018a).

At the front region, powder avalanches have an intermittent region, which is characterized by large fluctuations in impact pressure, air pressure and density. Data collected at the VdlS show that the intermittency is caused by mesoscale coherent structures, an organized motion of suspended particles. These structures can have velocities as much as 60% larger than the avalanche front speed and are characterized by an air/particle mixture whose average density can be as high as 20 kg/m^3 (Sovilla et al., 2018b). Each structure can maintain denser snow clusters and single snow granules in suspension for several seconds providing an efficient mechanism for moving superficial cold snow from the snowcover or the dense layer to the powder cloud.

Immediately behind the avalanche front a dense basal flow layer exists. This is formed by direct erosion of the snow cover and by sedimentation of the snow transported by the coherent structures. Toward the avalanche front the dense layer in normally characterized by a cold dense regimes, but toward the tail can transform into a warm shear or warm plug regimes if warmer snow is entrained from deep layers in the snowcover (Sovilla et al., 2015, Köhler et al., 2018b).

Finally, a turbulent suspension cloud of fine particles surrounds the denser regimes.

At the VdlS, the snow cover characteristics control the relative development of the different flow regimes. Indeed, when a lot of snow is cold and cohesionless, powder avalanches tend to develop a large intermittent region that in extreme cases can extend for almost the whole avalanche length. On the contrary, when only a small portion of the snow cover is cold, the intermittent region develops only marginally to give space to a more important basal dense layer. This flow regime balance controls the avalanche dynamics and the pressure the avalanche exerts on infrastructures.

Further, Köhler and colleagues (2018b) also observed from the GEODAR measurements that transitions between dominant avalanche typologies could happen from release to deposition. Indeed, large avalanches may encounter different snow conditions along their track, releasing from a cold snowpack but entraining warm snow at lower altitude. The conclusions of this recent research suggest that many avalanches undergo a transition along the path, thus strongly influencing the avalanche dynamics and the impact with infrastructures in the run-out zone.

3. FLOW REGIMES AND IMPACT PRESSURES

The flow classification presented by Köhler el al. (2018a) appears to be appropriate also to classify pressure measurements at the VdlS. Indeed, 20 years of pressure measurements on a 20 m high pylon show that the warm plug, warm shear, cold shear and intermittency regimes are all relevant in term of impact pressure and thus important for the design of structures (Sovilla et al, 2008, 2010, 2016, 2018a).

The results of a recent investigation (Sovilla et al., 2018a) to estimate which of these regimes is more destructive in terms of impact pressure and bending moment on the pylon of VdlS has surprisingly concluded that the maximum long-lasting bending moment at the pylon was exerted by a warm plug avalanche characterized by relatively low velocity (up to 10ms-1) and large flow depths (up to 7m). Indeed, in spite of the low velocity, warm plug avalanches are able to produce force amplifications on narrow structures as a result of formation of force chains (Sovilla et al., 2010, Sovilla et al., 2016; Kyburz et al., submitted). Furthermore, they exert hydrostatic-like forces that are flow depth dependent, thus these avalanches can become decisive if the flow depth is large.

On the contrary, fast cold dense avalanche, considered so far as the most dangerous in term of structure design, turned out to have a thinner flow depth in comparison to warm plug avalanches, so that their maximum bending moment is small. Nevertheless, cold dense avalanches are still important since they can exert maximum local pressures, which may locally damage the structure and endanger its stability. Further, cold dense avalanches can have longer run out compared to warm avalanches and thus they are decisive for the design of infrastructure, which are located outside the reach of the warmer flow.

In particular, a cold dense regime is particularly important if it is coupled with the intermittency flow regime, as normally happens in the frontal region of large powder snow avalanches. In this case dense snow clusters from the dense layer can be lifted up to significant heights by the coherent structures causing very large forces at large heights above the basal dense layer (Sovilla et al., 2018a). However, these forces are intermittent and last only for a fraction of a second and may rather be dangerous when the resonance frequency of the structure matches the pressure fluctuations (Bartelt et al., 2018).

4. CONCLUSIONS

The measurements performed at the Vallée de la Sionne test site in the last years of operation have shown that the avalanche motions cannot be simply split into the conventional binary definition between dense and powder snow avalanches, which is used today as a basic criteria for avalanche dynamics calculations (Faug et al, 2018), but that more sophisticated criteria are needed. The understanding of the physics explaining the nature and origin of the different flow regimes and their behaviour during the interaction with infrastructures is the next step to improve our modelling tools and pressure calculation procedures.

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Avalanche commissions in Austria at the interface between locals and authorities

Embedding, decision process and quality assurance

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ABSTRACT

In former times avalanche risk assessment was predominantly influenced by outcomes of snow cover tests and by information obtained by the observation of local weather and snow conditions. Nowadays technical development enables us to gather in short sequences detailed data about snow depth, wind and temperature all over the Alps. Nevertheless, all technical progress doesn't replace local observations, local experience and risk assessments based on local knowledge.

Recently often discussed and promoted is the idea of regional risk governance that addresses a balance between governmental risk prevention and that of civil society. While solitary risk prevention seems to lie in many cases far in the future, it is daily practiced in Austrians avalanche risk management. The avalanche warning services are state run and responsible to offer forecasts daily. Their focus is on the regional level. In contrast to that, avalanche commissions are volunteers who are assessing the local level over a whole winter season.

In this paper we want to focus on the voluntary avalanche risk management. Thus, we explain the avalanche commissions embedding in the larger risk prevention network, their responsibilities and how their decision process look like. Finally, we discuss already realized actions and further possibilities to assure quality in volunteer services.

Structure of Austrians avalanche risk management

We want to explain in brief the structure of Austrians avalanche risk management. Figure 1 visualizes the Styrian case, that is quite similar to other federal states in Austria. Long term hazard zone planning at the local and regional level, avalanche danger assessment at the regional level and national and international risk prevention is managed by the state. This means, that avalanche risk prevention is predominantly organized by public authority. However, civil engagement (observer, avalanche commissions) is crucial for a successful and complete risk assessment.

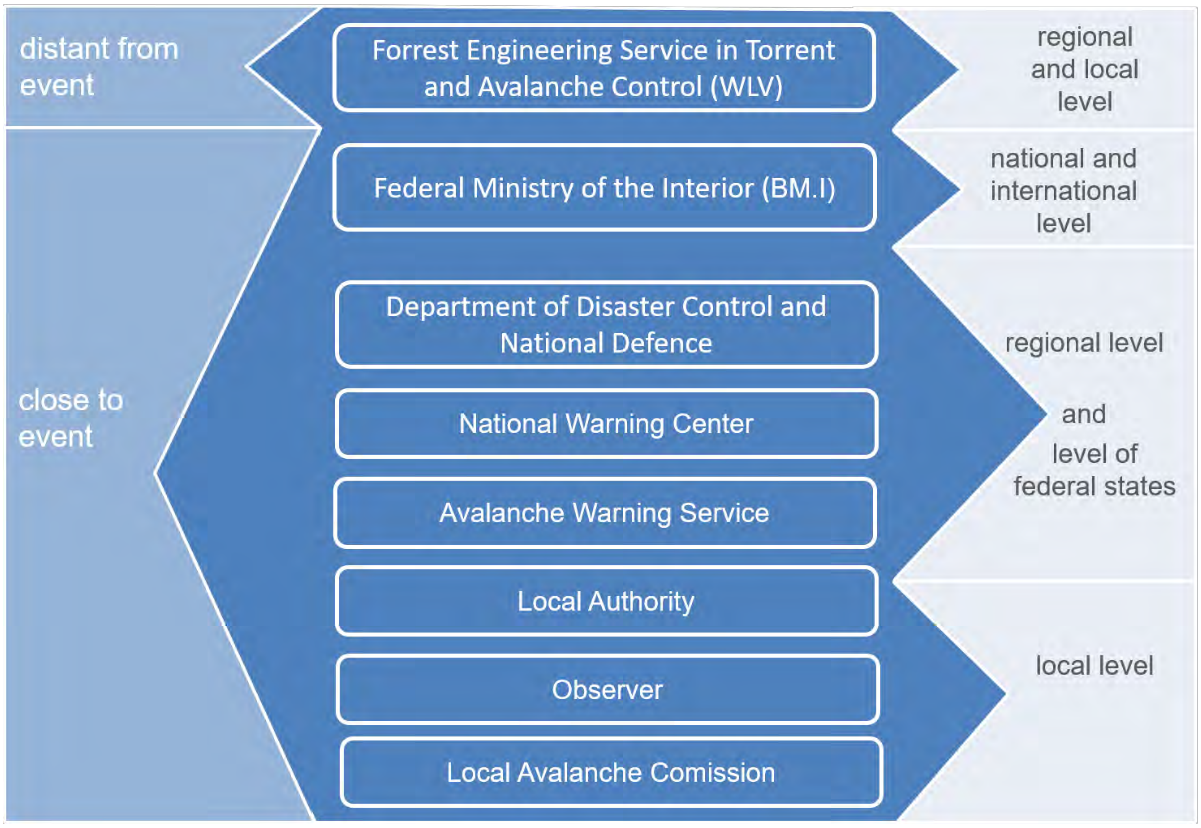

Figure 1: Avalanche risk prevention structure in Styria, Austria.

Collaborative risk prevention demands a good interconnectedness within the expert network consisting of volunteers and official representatives. Avalanche commissions become regularly educated by the Departments of Disaster Control. Lecturers are predominantly members of the state run risk prevention institutions, e.g. the avalanche warning service, the alpine police, the Forrest Engineering Service in Torrent and Avalanche Control etc. Thus, training sessions for avalanche commissions have two functions: first, they ensure professional qualification of volunteers and second, all risk prevention experts (volunteers and public representatives) get to know each other. Informal exchanges are enabled.

Local avalanche commissions are the interface between locals and the authorities and therefore they are embedded in a larger network that is responsible for natural hazard management. Figure 2 shows formal contacts within the avalanche risk prevention network. The avalanche commission consults the local authority and shares information with or uses support by the alpine police, the avalanche warning service and local observers.

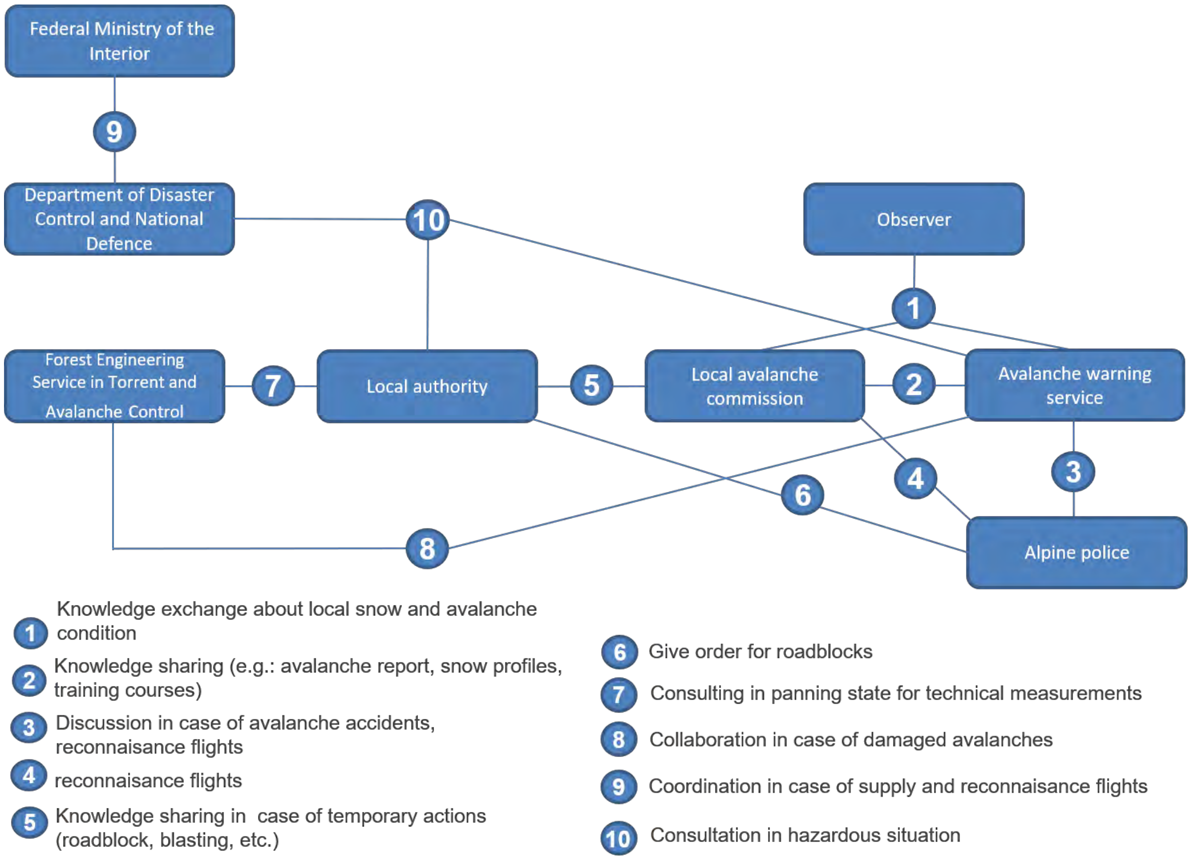

Figure 2: Formal contacts within the avalanche risk prevention network.

Organization and responsibilities of avalanche commissions

While in some federal states of Austria, rights and obligations of local avalanche commissions are regulated by law, there are only official recommendations in others. Despite a different regulatory intensity, the composition and appointment of the members, the areas of responsibility and the avalanche commissions' duties are to a great extend identical in content. The mayor of a region exposed to avalanches is primarily responsible for founding an avalanche commission in his/her municipality. Commission members need to have professional experience and must be available on-site during the winter season. In practice, members of Austrian avalanche commissions are locals who mostly professionally work in the mountains e.g. ski-lift operators, people from the snow ploughing service, mountain guides etc.

The area of responsibility is the organized ski area (cross country skiing trails, ski slopes), traffic routes and the settlement area of the respective municipality. Local avalanche commissions exercise an advisory role; hence they are responsible for continuous evaluation of avalanche risk. Commissions' advisement enlarges public authorities' knowledge about the local circumstances and supports them by making dispositions. It is commonly practiced to not only advice decision makers but also recommend concrete solutions, if this is necessary.

Diversity of decision process in avalanche commissions

Risk prevention practice of avalanche commissions depend on local conditions but also on network internal factors (Renner and Lieb, 2016). As already mentioned, the local authority become consulted by avalanche commissions. In a best case scenario (see figure 3), their consulting will be based on intensive internal and external discussion processes and the professional interpretation of systematically collected observation and measurement data. Nevertheless, the discussion and decision processes differ considerably and can also proceed rather authoritarian than democratically and unthinking than deliberated. The internal and external degree of cross-linking and knowledge sharing and the form of youth development can be diverse, too.

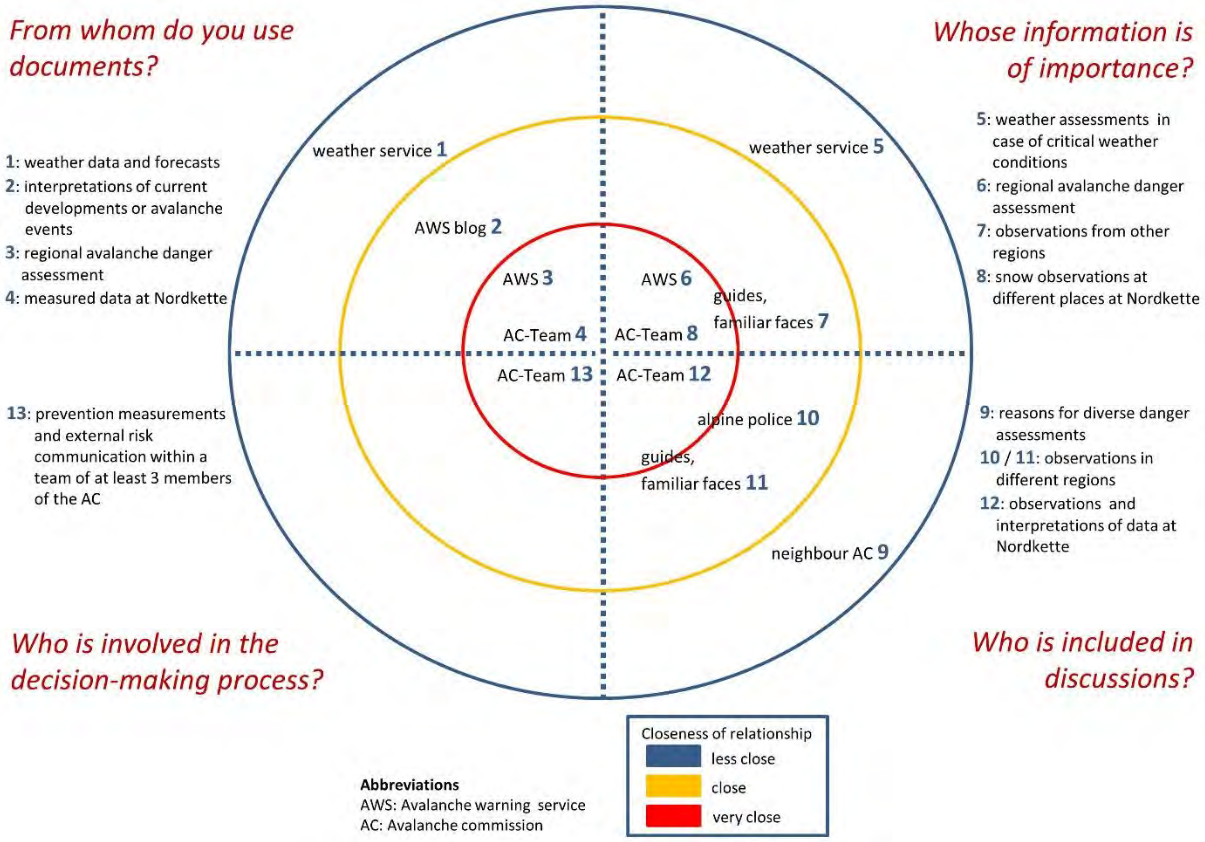

Figure 3: External and internal interconnection of an avalanche commission during the decision making process. Best case scenario. Renner and Lieb, 2016.

Quality assurance

Although tasks and regulations of the commission teams are similar, investigations have shown a considerable range of the decision making practice and the gap between an officially-presented picture and its practical reality. This finding points out the need to consider how to assure quality in the future. Closely linked with the quality assurance is the importance of communication skills and trusting relationships, which have been proven to be significant but understudied components in risk assessment.

Well-functioning and trusting internal and external relationships improve both data quality and quantity of data used for decision-making. Constructive team work allows critical reflection of personal opinions and perceptions, thus improving both final decisions and the quality of risk prevention. This aspect aligns with previous work on social capital in which it is understood to be embedded in social networks (Lin, 2001) and increases access to social support and information. It also corresponds to the so called "social and organizational capacities" (Höppner et al. 2012: 1757) or "network capacities" (Kuhlicke et al. 2011: 806) which emphasizes the importance of skills for communication, cooperation and building up trustful relationships.

Also based on our research (Renner and Lieb, 2016; Renner and Studeregger, 2018), there is an ongoing development process, in which training courses and also the education concept for avalanche commissions become revised. A special focus will lie on social capacity building, especially in terms of social and mental capacity. Moreover, also the legal situation is changing, e.g. in Styria will a concrete law replace the official recommendations for avalanche commissions. An ongoing discussion and investigation process is followed in Austria in order to improve the volunteers' capacity and, thus, the quality of avalanche risk prevention.

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Snow avalanche history of rural areas in Iceland

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1. ABSTRACT

The Icelandic Meteorological Office has since 2008, with support from the Avalanche and Landslide Fund, worked on avalanche chronicles and avalanche hazard evaluation for rural areas threatened by snow avalanches. The purpose of the work is to gather available information about the avalanche history and assess the general avalanche conditions so that the most heavily threatened farms and other buildings can be identified and listed in response plans to be used under impending avalanche danger. A rough evaluation indicates that more than 300 farms in Iceland are threatened by snow avalanches to some degree.

The main result of each assessment is a list of farms that are consider "severely threatened" by snow avalanches or landslides. This means roughly that the risk corresponds the C-zone in formal avalanche hazard assessment for dense settlements according to the Icelandic hazard zoning regulation. A list of farms considered to be possibly endangered under extreme conditions is also produced. The approach in this assessment for rural areas is less formal than required by the regulation for towns and villages and the results do, therefore, not have a legally binding effect regarding areal planning or building permits. The assessments, nevertheless, provide important information to the local authorities that is useful during avalanche cycles and an essential background for areal planning in the respective regions. Formal avalanche hazard assessments are then often conducted in relation to planning of new farm or recreational buildings. It is typically found in areas, where this type of analysis has been carried out, that much more avalanches are known by the local inhabitants than were previously listed in published documents or the avalanche database of the IMO.

At present, assessment have been completed for the districts of Svarfaðardalur, Öxnadalur and Hörgárdalur in N-Iceland. Work is on-going for Skagafjörður, Eyjafjörður and Ólafsfjörður in N-Iceland; Syðridalur in NW-Iceland and Mýrdalur in S-Iceland. The avalanche history has been gathered for Önundarfjörður and Dýrafjörður in NW-Iceland, as well as for Fnjóskadalur, Laxárdalur, Bárðardalur in N-Iceland. In many of these areas, interesting information about the run-out of large avalanches and interaction of avalanches with terrain obstacles is revealed by the work on the updated avalanche chronicles, which will be useful for future research on avalanche hazard and the effectiveness of avalanche protection measures.

Monitoring rock avalanche hazard from the Svínafellsheiði mountainside in SE Iceland

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ABSTRACT

During the last five decades, three large rock slope failures have taken place onto outlet glaciers in Iceland, in 1967 on the Steinsholtsjökull outlet glacier in the northern part of the Eyjafjallajökull ice cap, in 1972 on the Jökulsárgilsjökull outlet glacier in the southern part of Mýrdalsjökull ice cap and in 2007 on the Morsárjökull outlet glacier in southern part of the Vatnajökull ice cap. The volume of two of these landslides has been estimated. The rockslide, which fell on Steinsholtsjökull, was about 15 million m^3 and part of it fell into a proglacial lake, causing a large glacier lake outburst flood (GLOF). The rock avalanche, which fell on Morsárjökull, was around 4.5 million m^3. The causes of these three rock slope failures can be related to undercutting of mountain slopes and fast retreat and thinning of the glaciers.

Today, the retreat and thinning of outlet glaciers in Iceland is fast and in front of most of the outlet glaciers proglacial lakes have formed and many of them are growing year-by-year. The consequence of this retreat is often unstable mountain slopes, which increases the risk of slope failures and mass movements onto the glaciers and possibly into their proglacial lakes.

In 2014, a 115 m long and up to 30 cm wide fracture was detected at 850 m height on the Svínafellsheiði mountain, above the Svínafellsjökull outlet glacier in SE Iceland. The fracture was mapped in 2016 and survey points were installed in bedrock on both sides of the fracture. In the spring of 2018, another fracture was discovered, on recent aerial photographs, in the lower part of the Svínafellsheiði mountainside. Field surveys showed that these two fractures are connected and form up to 1.7 km long fracture system, which can be traced from 850 m height down to the surface of the Svínafellsjökull glacier at around 300 m a.s.l. It is assumed that around 1 km^2 of the mountain slope is unstable, which might mobilize around 60 million m^3 of bedrock, but the depth to the sliding surface within the bedrock is not know at this point.

From 2016 to 2018, the total widening of the upper fracture is around 2.6 cm and similar rate of movement was detected by satellite radar interferometry (InSAR) in the upper slope between 2016 and 2017. Interestingly, the same data reveal 4–5-cm displacement on the lower fracture during the same time interval.

Data that have been obtained since 2016 indicate that an area of ca. 1 km^2 in the Svínafellsheiði mountainside is potentially unstable and if it would collapse as single rock slide it would be one of the largest rock slope failures during the Holocene in Iceland.

TDR used for the first time to monitor slope movements in Iceland. A case study from the Almenningar landslide in central North Iceland

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ABSTRACT

The Tjarnardalir landslide is in the Almenningar area, in the outermost part of the Skagafjörður fjord, in central North Iceland. The landslide, which is a part of extensive landslide area extending about 4 km from the farm Hraun in the south, northwards to the Almenningsnöf, have shown signs of large displacements since a road was constructed in 1965. Almost every year, severe damages occur on the road often causing hazardous condition. These damages manifest themselves as the opening of large transversal and lateral crevasses. In 1977, the Icelandic road authorities started monitoring the sliding movements, and from 2003, extensive studies have been carried out to look for the cause for these displacements.

The front of the Tjarnardalir landslide reaches the present coast, forming up to 60 m high coastal cliffs that show clear indications of extensive coastal erosion. The stratigraphic record shows that the old rockslide deposit rests partly on a fine grained glaciomarine deposits (silt/fine sand) in exposed sections along the shoreline. It also confirms that the compact and lithified glaciomarine deposits forms an impermeable boundary which prevents groundwater penetrating through the old rockslide deposit to percolate farther down. Geomorphological indications show that the landslide mass has a constant westward movement towards the sea, with a maximum rate in the Skógar area up to 70–80 cm/year.

In late 2018, a 43 m deep hole was drilled trough the landslide mass. A coaxial cable was installed in the borehole to be able to use the TDR (Time Domain Reflectometry) method to measure the deformation and detect subsurface deformations in the old Tjarnardalir landslide. This is the first time that this technique is used in Iceland.

Landscaping of avalanche dams in Fjarðabyggð and Vestfirðir

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ABSTRACT

The landscape design of avalanche protection dams often involves the reshaping of the back yard of the entire community. This means that the nature closest to the village, and sometimes part of the village itself, must be excavated during the construction phase. Wildflower slopes, creeks, small waterfalls and blueberry plots disappear forever.

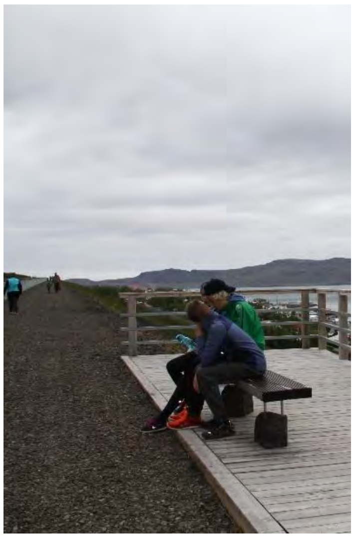
The landscape architect's role and her main challenge is to work out how to reduce the impact of these drastic changes and how the new and different landscape with the avalanche defence structures can benefit the community.

In Iceland, landscape architects are usually involved in the entire preparation and design process of avalanche projects, often the only design team members to do so. Starting with the appraisal team and the local authorities on initial ideas for the mitigating measures and preparing the Environmental Impact Assessment, making plans and ideas for possible use of the new landscape and creating presentation material for meetings and other introduction of the project to the community. And finally, working with the technical design team on tender documents and making plans for revegetation and planting. This secures continuity of the landscape design all the way from the Environmental Impact Assessment to the finished project.

The local authorities are ambitious about the final touches and understand that good design is important for the acceptance of the modified environment by the inhabitants.

The landscape design of large avalanche dams and waterways close to populated areas is both challenging and exciting, the finishing must be of good quality, safe and beautiful. The changed landscape creates possibilities for new use, the dams make good viewpoints and the tracks laid during construction can be future hiking trails, if this is thought out from the beginning.

Landscape architecture of avalanche protection dams may involve the design of hiking trails, resting places, viewpoints, small parking places and outdoor educational areas. We have also redesigned parts of privet gardens, made room for camping sides, community gardens and a memorial plot.



The inhabitants have started to view "the dams" as part of the environment of the community, using them as recreation areas, showing them to visitors, and even giving them special names based on local history or language traditions.

The presentation will outline the experience encountered in the landscaping at several construction sites of avalanche dams in Iceland over the last 20 years.

From the pilot study to the practical implementation – A case study from the Oberalppass in Switzerland

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ABSTRACT

The Matterhorn Gotthard Bahn railway line over the 2044 m asl high Oberalp pass is one of the most important east–west transportation corridors in Switzerland, being the only direct winter connection between the Cantons of Uri and Graubünden. Passing from Andermatt to Sedrun, more than 30 avalanche paths must be crossed, some of them reaching the railway line up to five times per year.

In a detailed hazard analysis, the five most dangerous paths were selected, and the protection targets were defined. The potential risk as well as the cost efficiency were calculated using EconoMe 4.0 to compare different mitigation measures such as avalanche towers, protection barriers and dams. Based on this analysis, the best protection measure for each avalanche path were selected, their dimensions defined and their impact on the environment assessed. The construction phase will start in Spring 2019, with the call for tenders and the monitoring of the construction process.

We will present the whole process from the pilot study to the risk assessment up to the practical implementation of the project as a case study for an integrated project management approach.

Hybrid innovative protection structures with optimized foundations and field adaptation

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ABSTRACT

In the French Alps the latest generation of high performance protection barriers and guidelines recommendations have been developed taking a relatively versatile and lightweight approach, from intensive experience for decades with more traditional protection structure.

Adaptation to the field with minimal foundations and anchoring requirements allow effective mitigation including installation in difficult ground conditions, slope accessibility or sensitive environment. Protections are designed to be simple and safe to install quickly in any location, including by rope access workers higher on the slope near the hazards source where energy are lower. System components have been kept as simple and strong as possible to ensure maximum lifetime, minimise maintenance and to facilitate repairs in the field when necessary.

Moreover many protective structures are exposed to both snow avalanches, and rockfall or debris flow. However conventional rigid or flexible barriers design with limiting standards reduce the performance of the protection. Indeed rockfall nets could often be damaged by avalanches and snow barriers by rock impacts for which they have not been designed. This requires significant maintenance costs and reduce protection level expected.

In addition to first experiments on hybrid defence structures, this paper provides new engineering methods with practical feedback and case studies on projects recently conducted worldwide.