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Study trip 2011 Iceland

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Tomas Johannesson
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Hannes Burger,
Karl Kleemayr

Front row, left to right:
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Maria Patek,
Ivo Schreiner,
Gebhard Walter,
Markus Mayerl

Foto:
Pilot project area above
Siglufjörður, taken by
Eduard Kotzmaier

CHRISTOPH SKOLAUT

From the editor

Iceland – the volcanic island in the Northern Atlantic Sea was the place to visit during the 2011 study trip of the Society of Engineers in the Austrian Torrent and Avalanche Control. Until the end of the 19th century, most people in Iceland were killed on the sea; but in the 20th century over 200 people perished in avalanches. The majority of fatal avalanches occurred in and around coastal villages located on narrow, flat terrain between steep mountainsides and the shoreline.

Following two avalanches which devastated the villages of Flateyri and Súðavik and killed 34 people in 1995, the Government of Iceland set an aggressive goal to orchestrate the development and coordination of protection against avalanches.

One of the first measures taken was the installation of an expert commission to evaluate these avalanches and propose further plans for protection and prevention measures. One of the experts involved was Josef Hopf, at this time head of the Torrent and Avalanche Control in Tyrol.

From this time on contacts grew between experts in the field of natural hazards in Iceland and Austria. Based on this, a group of 20 experts visited Iceland in 2011 to see what had been done during the last 15 years and to get further knowledge for their daily work in Austria.

This issue of Wildbach- und Lawinenverbau is, on one hand, a documentation of this study trip from the eastern part of Iceland via the northern to the western part and, on the other hand, should help carry out the similarities and also the different approaches in avalanche hazard mapping and on avalanche control measures.

A journey in pictures at the end of this issue will help to complete the picture of a scenic and informative technical trip around Iceland.

Thank you especially Tomas and Eirikur for guiding us during this week.

JOSEF HOPF

A Review

Avalanche events in Iceland – reported since the year 1118 – killed more than 680 persons by 1995 and several hundred may be assumed as uncounted victims in that period. However, the biggest disaster shocked the country in 1995, when two avalanches, in Súðavik in January and in Flatyeri in October, claimed the life of 34 people – a national tragedy that was comparable with the Galtür avalanche four years later in Austria that had the same number of victims. In total, 52 human beings lost their lives in Iceland between 1974 und 1995.

Pilot project Siglufjörður

In April 1995, this author was invited for a lecture on “Rescue Regulations in Austria” on the occasion of the annual meeting of one of the rescue organizations in Iceland. After visiting Súðavik, an Icelandic expert group was invited to tour to Western Austria at the beginning of October to study the methods of avalanche protection in this country. At the end of this visit, the draft of an avalanche dam project for Flatyeri was discussed, shortly before the catastrophic event on 26th of October claimed 20 human lives in that village.

After the catastrophic events in Súðavik and Flatyeri, the Icelandic Meteorological Office (IMO) was requested by the Ministry of Environment in February 1996 to investigate the avalanche situation in Iceland and to make proposals for avalanche defense works and measures in the future. The expert group for that study was headed by Tomas Johannesson (IMO), members from abroad were Karstein Lied and Frode Anderson (NGI – Norwegian Geotechnical Institute) and Stefan Margreth (SLF – Eidgenössisches Institut für Schnee- und Lawinenforschung).

After fieldwork in May/June 1996, the report “An overview of the need for avalanche protection measures in Iceland” was submitted in October. This indicated preliminary proposals for safety measures against avalanches in 8 communities with estimated costs of 7000 million Icelandic Kroner (IKR). Activities for snow and avalanche research in Iceland were also recommended in that report.

Already during the expert group’s field trip it became evident that in addition to deflecting and catching dams in the runout zones supporting structures in the starting zones of avalanches will be a main method against avalanches according to the principle “keep snow in rest to prevent snow in motion”.

Due to a lack of experience in this field of work in Iceland, it was decided to install a test field in Siglufjörður (Northern Iceland) to investigate different types of supporting structures. This author was invited to assist in the organization and implementation of this project. Within a working period of six weeks in August/September 1996, a total of 201.5 metres of snow bridges and nets were installed by an Austrian work group in cooperation with an Icelandic company using snow bridges from Austria and nets from Switzerland and France. Total costs of the supporting structures and their units were documented in a detailed report. The results of the investigations in the test area in the following decade were presented at the “International Symposium on Mitigative Measures against Snow Avalanches” in Egilstadir, Iceland, in March 2008. Differences in snow gliding and density of snow under alpine and Icelandic conditions were pointed out in a paper. A formal recommendation was given that galvanized snow bridges in general are a more suitable type for supporting structures than nets in Iceland.

Based on the proposals of the expert report from 1996, intensive avalanche defense works in Iceland were started in a national programme in the following years. The problem in Súðavik was solved by resettlement of the endangered area and the village of Flatyeri was protected with deflecting and retarding dams. Dams were also constructed mainly in Neskaupstaður and Siglufjörður and a big one is now under construction in Ísafjörður. Parallel to these works, supporting structures are being installed in the release zones of avalanches and will be continued by using steel bridges in the next future. These constructions – adapted to Icelandic conditions – are produced in Austria and in South Tyrol (Italy) and galvanized in Iceland in a successful international cooperation. Shape and dimension of the dam constructions were decided on the basis of the actual experiences, avalanche dynamic calculations and models. At the end of 2011, up to 50% of the planned avalanche protective measures in Iceland will be implemented. For the total completion of the national programme, a further period of roughly 10 years is estimated.

Parallel to the avalanche defense works, hazard zoning was started and implemented for permanent settlements after 1996. In this field of work, Siegfried Sauermoser from the Tirol Section of the Austrian Federal Service for Torrent- and Avalanche Control (WLV) assisted in cooperation with IMO during several visits to Iceland. Knowledge and experience was exchanged between Austrian and Icelandic experts at mutual visits in the past period. The “driving force” for these contacts on the Icelandic side was Tomas Johannesson from the IMO as a geophysicist. Since 1996 he has been engaged in the field of avalanches with cool enthusiasm, energy, knowledge and experience. His engagement not only has determined the Icelandic avalanche defense programme but also has enriched the international level in this scope of work.

Even if the whole national programme for avalanche defense works in Iceland were to be implemented, the snow and avalanche conditions in this “weather kitchen” for (central) Europe will provide enough topics for further investigations and observations in this field of work. The visit of the Austrian expert group this summer could be a step in that direction.

Thanks to IMO and to Tomas for their cooperation, confidence and friendship.

Good luck!

Josef Hopf
Retired member of WLV

GEBHARD WALTER, IVO SCHREINER, FRANZ ANKER

Report on Monday, June 20th
Protection measures in Neskaupstaður and visit to a reinforced 420 kV power line

Bericht Montag, 20.06.
Schutzmaßnahmen in Neskaupstaður und Besichtigung einer verstärkt ausgeführten 420-kV-Stromleitung

Summary:
The first day of our study trip lead us from Reykjavík to Egilsstaðir after an inland flight. On the way to Neskaupstaður our first stop was at Áreyjadalur to inspect a new electrical power line with posts reinforced to withstand avalanches. Later we had a short stop in the town of Eskifjörður where slush flows have caused accidents and damages. After an outdoors lunch by the catching dam and braking mounds below Drangagil in Neskaupstaður, we climbed up to the starting zone in Drangagil to inspect the supporting structures. From Drangagil a part of the group walked to the west to the starting zones in Tröllagil. Because of the bad weather during the past days and the snowfall in the upper regions it wasn't possible to meet the installation workers on site.

In the evening we met in a small conference room by the harbour where Eiríkur Gíslason from IMO gave us a presentation about avalanche conditions in Iceland, forecasting, evacuation plans, hazard zoning, protection measures, etc.

Zusammenfassung:
Der erste Tag unserer Exkursion führte uns nach einem Inlandsflug von Reykjavík nach Egilsstaðir. Auf dem Weg zu unserem ersten Etappenziel in Neskaupstaður hielten wir in Áreyjadalur, um eine neue elektrische Stromleitung zu besichtigen, deren Maste in verstärkter Ausführung hergestellt waren, um Lawinen standhalten zu können. Die Reise führte uns weiter nach Eskifjörður, wo „Schneematsch"-Lawinen Unfälle und Schäden verursacht haben. Nach einem Mittagessen im Freien beim Lawinenauffangdamm und den Bremsverbauten bei Drangagil in Neskaupstaður stiegen wir bis zu den Anbruchsgebieten der Drangagil-Lawine auf, um die Anbruchsverbauungen zu besichtigen. Ein Teil der Gruppe ging im Anschluss von dort Richtung Westen zu den Anbruchsgebieten der Tröllagil-Lawine. Aufgrund der schlechten Witterung der vergangenen Tage war die Arbeit an den dort in Bau befindlichen Stützverbauungen unterbrochen worden.

Am Abend trafen wir uns noch in einem kleinen Konferenzraum am Hafen. Eiríkur Gíslason, IMO, präsentierte Einblicke in die allgemeinen Lawinenverhältnisse in Island, Prognosetechniken, Evakuierungspläne, Gefahrenzonenplanung, Schutzmaßnahmen, etc.

After an inland flight, the first day of our study trip lead us from Reykjavík to Egilsstaðir and our first excursion point. The perfect flight conditions allowed us to see the impressive landscape of Iceland with the monumental volcanoes.

Fig. 1: Cockpit view from the flight

420 kV power line for aluminium smelter

The first stop was at Áreyjadalur to inspect a new electrical power line, which is heavily endangered by several avalanches.

These 420 kV lines in north-eastern Iceland are the only source of electrical power to a large aluminium smelter located at the coast. The smelter uses bauxite, which comes by great container ships from Jamaica or Australia, to make aluminium.

Forty-four km of the two lines are parallel with a spacing distance of 60 metres. The total length of the lines between the aluminium smelter and the powerhouse of a hydropower plant is around 50 km for each transmission line. The elevation of the line is between 20 and 620 metres above sea level.

Such an aluminium smelter requires a reliable power supply, because outages longer than a few hours cause the aluminium to solidify. The failure of the transmission line for a few hours results in a calculated loss of approximately $US 1 billion. This enormous monetary loss is unacceptable for the company that owns the aluminium smelter.

Before the 420 kV line was built, a smaller (66 kV) transmission line had been impacted by avalanches. So the engineers had some historic experience for the new line in the same corridor.

Fig. 2: Parallel transmission lines with avalanche towers

Fig. 3: "Y" type single pole tower.

After a study of existing types of towers for electrical lines, a special type with a single tubular Y-shaped pole was developed.

A total of 83 towers with the special Y-form were built. Eighty-one of them were reinforced against avalanche pressures. The complete lines contain a total of 326 towers.

Statistical runout models (alpha/beta-model) and dynamic models (PCM and NIS) were used to calculate design loads. The design loads and avalanche risk were evaluated for each tower.

The definition of the avalanche loading was divided in three layers. A dense avalanche core located from 5.0 to 8.5 metres. A saltation layer with rolling particles on top of the dense core and the highest layer – the turbulent snow cloud (thickness of snow cloud = 15 – 35 m).

The avalanche velocity goes up to 50 m/s. The supposed density of the dense core was 300 kg/m³.This results maximum pressures in the lowest layer in a range of 350 to 400 kPa.

Additional to the avalanche pressures the load of stones with a diameter of 50 cm was calculated. Because of the rocky terrain it is possible that a tower could be hit by a stone carried in the avalanche.

To reduce the risk, two parallel transmission lines were built. The calculated exposure level for failure of both lines was, P = 6.5*10-4 (T≈1500 years).

Fig. 4: Tower in an avalanche path

Slush flows in Eskifjörður

Fig. 5: Eskifjörður with several gullies

The next short stop was in a little town in a fjord called Eskifjörður. This town with a small settlement near the seaside has some characteristic watercourses from the hillside straight to the sea, which flow down in small gullies. Four gullies go directly through the small settlements. Along these gullies, several slush flows have caused accidents and damages to homes and infrastructures. A wet and thick snow layer in combination with precipitation causes very spontaneous flows. Because of these accidents, a hazard map based on the Icelandic guidelines with three risk lines was also prepared for this area.

Neskaupstaður – Catching dam, Braking Mounds and Supporting Structures in the Drangagil Starting Zone

Next we visited Neskaupstaður and went to the Drangagil starting zone.

The town of Neskaupstaður is located in a fjord named Norðfjörður at the Island Eastfjords. After 1870, the fishing industry replaced agriculture as the main industry in Norðfjörður and became the basis of urbanisation. During the 1910s and 1920s there was great population growth in Norðfjörður and it became the authorized market town named Neskaupstaður in 1929.

The Eastfjords as well as the Westfjords are in the old basaltic rock formations, 3-20 million years old, and have been eroded by glaciers during the periods of glaciation. The fjords are embraced by steep mountains that reach a height of approximately 600-800 metres above sea level.

Although avalanches could start almost anywhere in the mountainside above the town, two gullies make the main threat to the inhabited area, i.e. Drangaskarð and Innra Tröllagil.

During the first years of urbanization in Nordfjördur, a few large avalanches fell in the area. In 1885, an avalanche destroyed two houses and killed three people in "Naustahvammur". In 1894, a large avalanche from the Drangagil avalanche path fell where the farm "biljuvellir" was located. It destroyed sheds and killed livestock. Two people were saved from a snow tunnel which had been dug between the houses and the river. The same year, a large avalanche from Tröllagil went to the sea in an area that was uninhabited at that time. It caused a minor damage to some houses.

The major avalanche accident in this century was in December 1974, when 15 big avalanches were recorded during a period of 2 days.

On December 20, 1974 two avalanches killed 12 people in Neskaupstaður. Avalanches fell from almost the entire mountainside above the town during a cycle of 2 days. The snowfall was very intensive; the wind was also strong offshore. The first avalanche struck on December 19, but no one saw it, due to low visibility in the heavy snowfall.

Shortly after the accidents in 1995 at Flateyri and Súðavík, preparations for protection measures for the settlement below the gully of Drangagil were started.

The design of avalanche defence structures for the Drangagil area was initiated in 1997 and these were built in 2002.

Defence structures in the Drangagil area are of three types, supporting structures, braking mounds and a catching dam.

Fig. 6: Three types of defence structures; supporting structures, braking mounds, catching dam

The supporting structures are located in the starting zone of Drangagil and include approximately 1000 m of 3.5-4.0 metre high avalanche nets.

The braking mounds are positioned in two rows above the residential area, a total of 13 mounds. The mounds have a steep front facing the mountain, are 10 metres high und each mound is approximately 10-12 metres wide at the top. The 400 metres long catching dam is located

Fig. 7: Supporting structures: type ISOFER ©

at a distance of 100 metres from the residential area. The dam is 17 metres high with a steep front facing the mountain. The total volume of earth fill comprising the catching dam and the braking mounds is approximately 260,000 m³. The steep dam fronts facing the mountain are built with earth reinforcement system made of steel. The avalanche defences were inducted in 2002.

Fig. 8: Braking mounds with 76° steep face, constructed in reinforced earth technology

The design avalanche had a return period of 1000 years with a 3 metre thick dense core, a speed of 38 m/s, and thus a Froude number of 7 upon hitting the upper row of mounds. The shallow-layer theory predicts that a dam with an effective height of 32 metre is needed such that a shock will form upstream of the mounds. The theory therefore predicts that the flow will be launched in a supercritical flow state over the mounds. Parts of the avalanche will be deflected between the mounds, also in a supercritical flow state. The two rows of mounds were therefore spaced such that an avalanche could be launched ballistically over the first row of mounds and would land upstream of the lower row and of the catching dam downstream of the mounds. With this design it is guaranteed that both rows of braking mounds will effectively participate in dissipating energy from the avalanche before it hits the downstream catching dam.

Fig. 9: Area of the avalanche deposition

Supporting structures in Innra-/Ytra-Tröllagil, Neskaupstaður

In the afternoon we visited the second starting zone of the Ytra -Tröllagil avalanche in Neskaupstaður. There is an installation of steel bridges in work as a part of the ongoing protection measurements for

Tröllagil. Because of the bad weather during the past days and the snowfall in the upper regions it wasn't possible to meet the installation workers on site.

Tröllagil in Neskaupstaður is located on the north side of the fjord Norðfjörður which is onan east to west axis from the bay Norðfjarðarflói. A south to southeast facing mountain rises above the settlement of Neskaupstaður up to between 700 and 900 metres above sea level.

The annual precipitation in Neskaupstaður is among the highest observed in the lowland in Iceland and varies greatly in magnitude from year to year. The maximum was observed in 1997 with 2183 mm and the minimum in 1983 with 1382 mm. The maximum vertical snow depth measured at the uppermost stakes by the local snow observers in the starting zones is typically in the range of 2 metres to more than 4 metres. The highest snow depths were reached in the winter 1994/1995.

The top of the mountain ridge is a sharp edge with the fjord Mjóifjörður on the other side. The Tröllagil avalanache is divided in two parts: Innra-/Ytra-Tröllagil belong to the main gullies where avalanches are expected from. The characteristic cliffbelts in the mountain between about 400 and 500 metres above sea level. mark the limit between the starting area and the track. The upper part of the mountain is found to be a characteristic bowl and is later transformed into a deep narrow gully by the cliff belt. The cliffs are considered the lower limit of the starting areas and therefore areas with inclination between 30° and 55° below the cliffs are not considered to be a part of the potential starting area.

The starting zone in Innra-Tröllagil ranges from 680 m to 380 metres above sea level with a maximum width of 250 metres. It is a bowl in the upper part and a gully in the lower part. It is oriented SSE to SSW. The area is 9.2 ha and inclines at 38°. The surface is composed of weathered rock interrupted by cliffs.

The starting zone above Ytra-Tröllagil ranges from 700 to 400 metres above sea level with a maximum width of 190 m. It is a 15 m deep gully that is oriented SSE to SSW. The area is 7.0 ha and inclines 34°–38°. The surface is similar to the Innra starting zone. Snow accumulation in both areas is high.

The altitude of the runout area in Tröllagil ranges from 30 metres above sea level to sea level. It is 200 to 270 m long and inclines at 7° to 8°. The slightly convex runout area has a high avalanche spreading potential.

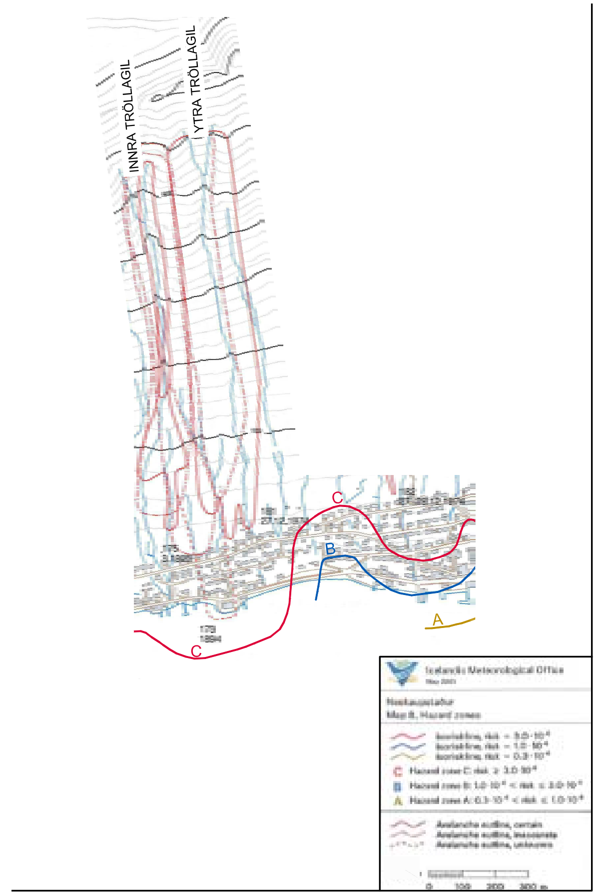

Fig. 10: Detail of the hazard zone Tröllagil

The area below Tröllagil has been settled for more than a century. In 1894 there are records of a large avalanche from one of the gullies down to the sea. But it didn't do much damage. In December 27th in 1974 long avalanches fell from most of the gullies above Neskaupstaður. A large wet slab avalanche fell from Ytra-Tröllagil and stopped 30 metres above sea level around 190 metres from the sea. The tongue was 210 metres at its widest. Only some fences were slightly damaged. The hazard map shows the highest risk (C-zone) already within the sea.

Currently in Neskaupstaður dams and supporting structures are implemented in the Tröllagil area. The measurements follow the same strategy as in Drangagil.

From 2010 until 2012 about 1,900 meters of snow bridges should be installed. The system comes from the South Tyrolean Company Mair Wilfried GmbH. All components are hot-dip galvanised for Icelandic conditions. Varying the distance of the bars and using uniform dimensions has the advantage of lower weights (up to 169 kg or 22% for DK 4.5).

The installation workers come from Estonia. They work 6 days per week and ten hours daily. During the week they stay in containers situated near the starting zone.

Special attention deserves to be paid to the organization because they normally only get a helicopter twice a year: in spring and autumn. Beyond that, everything has to be done by the cable railway.

The dams near the village were under construction when we visited Neskaupstaður. It is designed as a combination of a check dam with braking mounds in front of. At the western side there is also a deflecting dam to prevent from side effects from avalanches in the neighbourhood.

Fig. 11: Steel bridges under construction at the Tröllagil starting zone (Copyrigt Mair Wilfried GmbH)

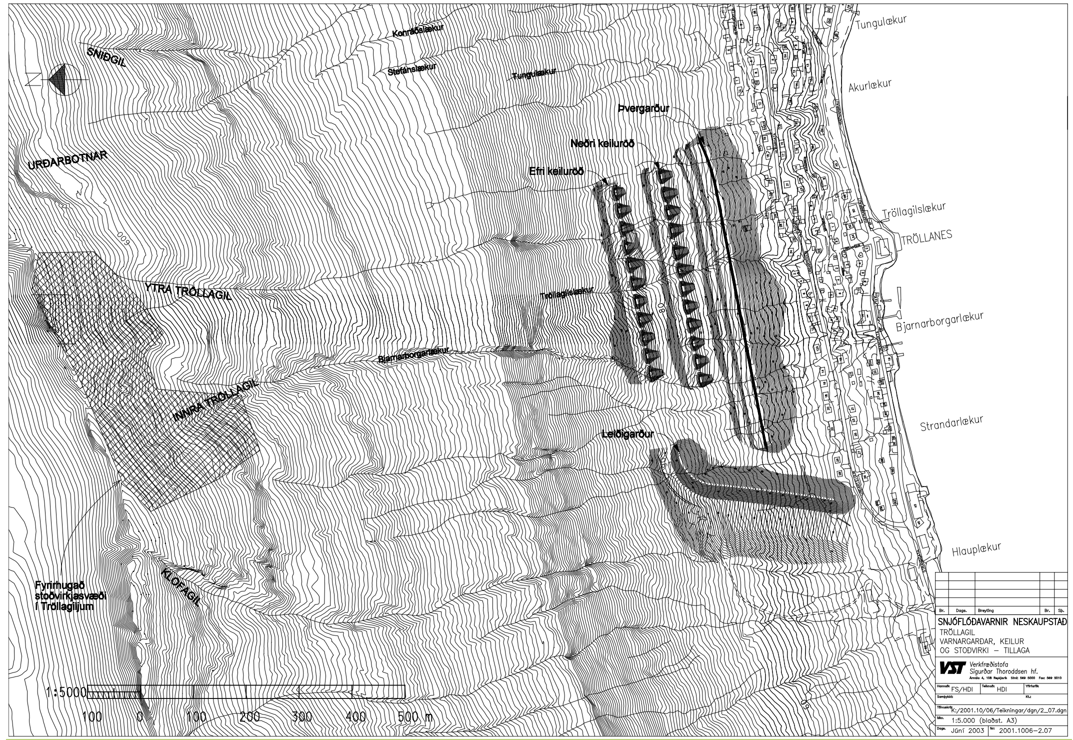

Fig. 12: Overview of the planned measurements in Tröllagil

Summary of the Presentation about Avalanche Conditions in Iceland

In the evening of June 20th we joined a presentation in Neskaupstaður about Avalanche risk assessment, adaptation and mitigation in Iceland prepared by Tómas Jóhannesson:

Since 1901, 169 fatal accidents caused by avalanches have been recorded in Iceland. After accidents at sea and storm catastrophes, this is the third most number of fatal accidents caused by natural catastrophes in Iceland between 1901 and 2009. From outside one expects that volcanic eruption and earthquake should cause much more injuries. But due to the low populated regions endangered by volcanic eruption and earthquake, the number of fatal accidents is not more than 2%

Fig. 13: Main villages with avalanche and landslide problems in Iceland

of the number caused by fatal avalanche accidents inside of inhabited areas. The direct economic loss due to the largest natural catastrophes in

Iceland caused by avalanches in settlements can be quantified by 36.4 million US dollars.

Date	Location	Fatalities
20.12.1974	Neskauptstaður	12
22.01.1983	Patreksfjörður	4
05.04.1994	Tungudalur, Skutulsfjörður	1
16.01.1995	Súðavik	14
18.01.1995	Grund, Reykhólahreppur	1
26.10.1995	Flateyri	20
14.01.2004	Bakki, Ólafsfirði	1
Total		**53**

The catastrophic avalanches in Súðavík and Flateyri in 1995 gave need to review the whole approach to avalanche safety in Iceland. Until then there had been almost no mitigation measurements. Complex administration and unclear areas of responsibility didn't allow useful requirements for municipalities to secure protection from avalanches and landslides.

After 1995 the government reviewed the legal framework for avalanche mitagation and established financial support for the endangered municipalities. Furthermore, a new Avalanche and Landslide Committee was established. The Committee organised public meetings in the relevant communities and established monitoring and evacuation schemes. Permanent protection structures were built. The funding was provided through the Avalanche and Landslide Fund. The fund income is endowed by a levy amounting to 0.3‰ of property insured value in Iceland.

The fund assets are defined by:

- Hazard zoning
- Equipment for research and surveillance
- 90% of preparation, design and construction of protection structures or purchasing of residential houses (the rest comes from the relevant municipalities)
- 60% of maintenance of protection structures

The cost of avalanche protection measures and relocation of settlements between 1995 and 2010 amounted to 67.8 million US dollars.

The government assigned the Icelandic Meteorological Office (IMO) to conduct research on avalanches and landslides, to provide advice on preventative measures, hazard zoning and snow observations. The avalanche and landslide work at IMO can be defined as following:

- Monitoring of avalanche danger
  - o Local snow observers
  - o Decisions about evacuations in collaboration with local authorities
- Database of avalanches
- Hazard zoning
- Advisor to the government regarding to avalanche protection measures
- Scientific search on avalanches and landslides

IMO collects data from 5 main snow observers in Neskaupstaður, Seyðisfjörður, Siglufjörður, Ísafjörður, Bolungavík. Assistant observers are employed in 9 other villages. Their main job is to collect data (snow height, Evaluation of snowpack stability) outside in representative areas near the starting zones of the relevant avalanches. Their work is supported by automatic weather stations, which are located especially in the north-west or north-east of Iceland.

The adaptation and mitigation strategies can be defined as following:

- Adaptation
  - o Regular real-time observations
  - o Evacuation plans
  - o Improved preparedness for rescue operations
- Mitigation
  - o Relocation of settlements
  - o Purchase of endangered buildings
  - o Permanent protection measures
- Precondition for both: hazard zoning

The evacuation plans are made in collaboration with the civil defence division of the National Commissioner of the Icelandic Police in Reykjavík. Plans are executed by the local civil defence authorities according to an evacuation map with evacuation areas on different levels (I, II and III). An accompanying report from IMO about avalanche conditions ist added.

In the construction of protection structures the following types of action are distinguished:

- Dams
  - o Deflecting dams and wedges
  - o Catching dams
  - o Breaking mounds
- Supporting structures
- Relocation

Total effort for construction of protection structures might be in the range of 16 to 20 billion ISK or 130 to 170 million USD. The conclusion of construction is planed for 2013-2015. Recess in

Fig. 14: Evacuation plan Bolungarvik

Fig. 15: Deflecting dams in Flateyri
Photo: Oddur Sigurðsson

construction was recorded in 2004 to 2007 due to economic expansion and problems following the economic collapse. More towns and villages were identified to be threatened than in the initial plans.

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Presentation Avalanche risk assessment, adaptation and mitigation in Iceland

MARGARETE WÖHRER-ALGE, GERHARD PRENNER

Report on Tuesday, June 21st
Hydrological and Geological Situation and Forestry of Iceland

Bericht Dienstag, 21. 06.
Hydrologische, geologische und forstliche Situation in Island

Summary:
Due to the unfavourable snow situation, an inspection of the catching dam in Seyðisfjörður was not possible. Our guide Eiríkur Gíslason from IMO made use of the second day of our study tour to give us a comprehensive introduction to the geological and the hydrological situation and the forest cover of Iceland. The excursion route passed by the glacial rivers Jökulsá á Bru, Jökulsá á Fjöllum und Skjálfandafljót, the waterfalls Dettifoss and Goðafoss, the geothermal area Námaskarð, the geothermal power plant Krafla and the unique and impressing Lake Mývatn

Zusammenfassung:
Da die Besichtigung des Auffangdammes in Seyðisfjörður am zweiten Tag unserer Studienreise aufgrund der Schneesituation nicht möglich war, gab uns unser Begleiter und Führer Eiríkur Gíslason (IMO) einen umfassenden Einblick in die geologischen, hydrologischen und forstlichen Verhältnisse Islands. Die Exkursionsroute führte uns zu den Gletscherbächen Jökulsá á Bru, Jökulsá á Fjöllum und Skjálfandafljót, zu den Wasserfällen Dettifoss and Goðafoss, zum geothermischen Gebiet Námaskarð beim Berg Namafjall, zum geothermischen Kraftwerk Krafla und zu dem einzigartigen See Mývatn.

On the second day of our study tour we travelled from Neskaupstaður at the far east of Iceland to Akureyri in the north. On our way to Akureyri our excellent guide Eiríkur Gíslason from IMO gave us an introduction into the hydrological and the geological situation of Iceland. At Akureyri, the company Sandblástur og Málmhúðun invited our group to a barbeque in the premises of the new Motorcycle museum.

Forestry in Iceland (www.skogur.is/english)

Near Egilsstadir we passed birch woodlands, a rare site in Iceland. Hallormsstadarskogur in the vicinity of Egilsstadir is Iceland's largest forest and the centre of Iceland's forestry. The first trees were planted at Hallormsstadarskogur in 1903 but most of the planting has taken place in the past 50-60 years.
At the time of settlement (in the 9th century), 25 – 40% of the country was covered by birch forests (up to 15 metres high) in sheltered valleys and low-growing woodlands on unfavourable sites (birch and willow shrub toward the coast, on exposed sites and on wetland areas and willow tundra at high elevations), whereas today forests only cover about 2% of the country. The greatest losses result from the extensive sheep grazing which prevented regeneration of the birch wood after cutting and therefore the area of woodland declined steadily.

Nowadays birch woods are recognized as being important from an ecological point of view and some birch forests are popular recreation areas.

Organised forestry is considered to have started in Iceland in 1899 with the planting of the "Pine Stand" at Thingvellir. After an early phase of experiments with exotic tree species, forestry efforts largely focused on protecting birch forest remnants during the first half of the 20th century. Since about 1950, the emphasis has been on afforestation through planting trees. The principal species planted were exotic conifers: Picea abies, Picea sitchensis, Pinus sylvestris, Pinus contorta and Larix sibirica. Larix sukaczewii)(syn. L. sibirica var. sukaczewii) is planted to roughly the same extent as native birch and picea sitchensis has recently gained a similar status.

Today about 80% are state-supported afforestations on farms. Originally the only afforestation goal was wood production, but today

Fig. 1: Birch forest near Egilsstadir

Fig. 2: Afforestation with spruce near Neskaupstaður

the most important aim is to afforest eroded or degraded land. According to our colleagues from IMO, afforestation is not possible in avalanche starting zones because of severe climatic conditions. Rising temperatures due to climate change could give afforestations in those areas a chance in the future.

The legal basis for the protection of existing forests and the afforestation of treeless land in Iceland is the Forestry Law (1955) and three Afforestation Laws. In the Regional Afforestation Projects Act of 2006 a concrete goal of 5% forest and woodland cover of lowlands was set.

Hydrology

Icelandic rivers are of three general types:

Glacial rivers (jökulsá): Their runoff is mainly influenced by ice melt and is high in the summer and low in the winter, reaching a peak in July and August with daily variations during the warm season. Apart from regular variations in discharge, glacial lake outburst floods (GLOF, isl. jökulhlaup) are known from ancient times. The temperature is low and close to freezing (1-4°C) at the source. Due to a high sediment load (fine silt and clay) they are typically brown in colour and their flow velocity is high. They typically divide into many interlinked distributaries which constantly change course on the progclacial outwash plain.

On our journey to Akureyri we stopped at the concrete bridge over the river **Jökulsá á Bru**. The Jökulsá á Bru is the longest river of Eastern Iceland (about 150 km), with a catchment area of about 2610 km² and a discharge rate of 152 m³/ sec. It deposits about 120 tons of silt in the delta area per hour. The main source of its discharge, Bruarjökull, is the largest glacier tongue of the icecap Vatnajökull.

Twenty-five kilometres the river have been dammed by the 193 m high and 730 m long Kárahnjúkar concrete-face rockfill dam and the discharge rate is reduced to 95 m³/sec. The Kárahnjúka Dam is the largest of 5 dams which create the Hálsalón reservoir and the largest of its type in Europe as well. The water from Hálsalón reservoir is channelled through a network of underground tunnels feeding into a 450 metre deep vertical steel-lined penstock, then into a turbine hall for the underground power station. **The hydro-power plant Kárahnjúkar (690 MW)** was completed in 2009 and is designed to produce 4,600 GWh annually for an aluminium smelter 75 kilometres to the east in Reyðarfjörður.

Fig. 3: The canyon of J the river Jökulsá á Fjöllum

The second river, which has its source at the Vatnajökull glacier and which we passed on our route, is **Jökulsá á Fjöllum** west of Jökulsá á Bru. It is the second longest river of Iceland (206 km). Jökulsá á Fjöllum has the largest catchment area of all Icelandic rivers (7.380 km²). The average discharge rate at the Dettifoss waterfalls is 183m³/ sec.

On the first 150 km from the glacier, the bottom slope is very low (0.5 ‰). Downstream the river plunges over the waterfalls **Selfoss** and **Dettifoss** to the canyon at Jökulsárgljúfur National Park, which was formed by Jökulhlaups (glacial

Fig. 4: Dettifoss

floods). The largest Jökulhlaups in Iceland are known to have occurred along **Jökulsá á Fjöllum** approximately 7,100 to 2,000 years ago. At Dettifoss the glacial waters drop over the 100 m wide and 45 m high waterfall. During the summer time the river has a discharge of 1500 m³/sec and is thus the most powerful waterfall in Europe. Every day the river transports 120,000 tonnes of sediment load. The erosive power of the water and the debris is responsible for the deepening of the canyon and the migration of the edge of the falls (several cm/year upstream).

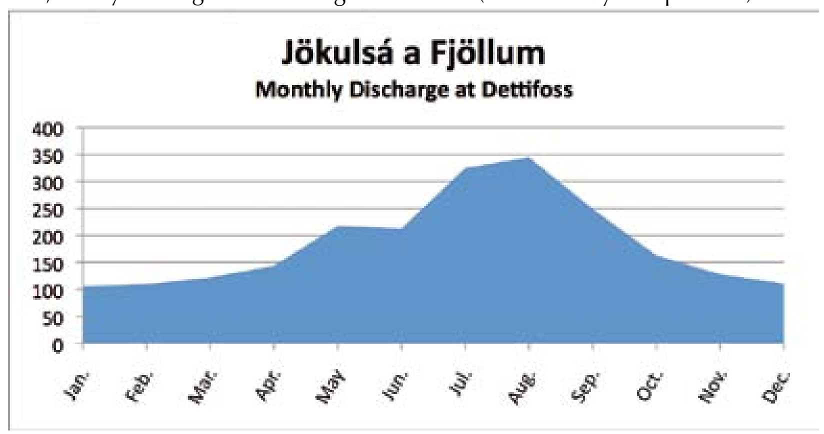

Fig. 5: Discharge of Jökulsá a Fjöllum at Dettifoss waterfalls (Source: UNESCO, 1969).

Fig. 6: Goðafoss

The **Goðafoss (waterfall of the gods)** is located halfway between Lake Myvatn and Akureyri. The water from the river Skjálfandafljót falls from a height of 12 metres over a width of 30 metres. It divides into two horseshoe-shaped falls that developed at the border of an 8,000 year-old lava flow from the volcano Trölladyngja, north of Vatnajökull. This waterfall played an important role in Iceland's history. In the year 999 or 1000 the Lawspeaker Þorgeir Ljósvetningagoði decided at the Alþingi (Parliament of Iceland) to make Christianity the official religion of Iceland. After his conversion to Christianity it is said that Þorgeir threw his statues of the Norse gods into the waterfall.

Direct runoff rivers (dragár) are relatively clear and are characteristic of old basaltic areas where the bedrock is relatively impermeable. They have a variable discharge with maximum flow in late spring during snowmelt and in autumn following heavy rains. The smallest discharge is during winter but there is a secondary minimum during the summer. Floods may occur at any season and drifting snow may also affect the flow of small streams.

The river **Eyvindara**, a tributary to the glacial river Lagarfljót, belongs to this river type. It is the only river in Iceland with a significant risk of flooding for settled areas. The confluence of Eyvindara and Lagarfljót is near the town Egilsstadir (north of the airport).

Spring-fed rivers (lindár) drain areas covered by permeable postglacial lava fields. In these neo-volcanic zones where the ground

is more porous, subsurface drainage is common and the water emerges in springs at lower levels to supply the rivers with an almost constant flow of generally clear water. These spring-fed rivers have a water temperature of 3–5°C at source and never freeze over at that point. Their beds and banks are usually stable and therefore they transport a low sediment load.

Fig. 7: Lake Mývatn

The river **Laxá** is the second greatest spring-fed river in Iceland. It is the outflow (in three channels) from **Lake Mývatn** and it is among the best trout and salmon fishing rivers in the world (laxá means salmon). Mývatn is a shallow lake (3 – 5 m deep) situated in an area of active volcanism not far from Krafla volcano (see Geology). During the Ice Age, the Mývatn basin was covered by a glacier, whose huge end moraines can still be seen at the north end of the lake. At the end of the Ice Age a glacial lake was dammed up in the Mývatn depression until the glacier retreated. Lake Mývatn was created about 3,000 years ago by a large fissure eruption of the Mid-Atlantic Ridge pouring out basaltic

Fig. 8: The river Laxá, outflow of Lake Mývatn

lava which dammed up the lake. Another huge eruption (the so called Mývatn fires) shaped the present lake 2,300 years ago. Repeated explosions built up groups of craters which now dominate the landscape on the shore of Lake Mývatn and also form some of the islands in the lake. This type of lava formation is called pseudocraters.

Fig. 9: Basaltic rocks near Dettifoss

Its water originates from a number of springs welling up on the lake shore.

The lake **Mývatn** and the river Laxá form the most fertile freshwater system in Iceland. The bird and fish life is extremely rich. Thirteen duck species of Eurasian and American origin nest here. This mixture of species is unique.

Geology (http://earthice.hi.is)

Iceland is part of the ocean floor which has been forced up above sea level by special geological conditions. The island owes its existence to the coincidence of the spreading boundary of the North American and European plates (Mid-Atlantic-Ridge) and a so-called hotspot or mantle plume. **Hot spots** are volcanic regions which are fed by the underlying mantle that is anomalously hot compared with the mantle elsewhere. As the plates moved apart, excessive eruptions of lava constructed volcanoes and filled rift valleys. Subsequent movement rifted these later lava fields, causing long, linear valleys bounded by parallel faults. The divergence of the ridge started in the north about 150 million years ago and 90 million years ago in the south. These movements continue today, accompanied by earthquakes, the reactivation of old volcanoes and the creation of new ones. Iceland is the largest island on the ridge because of the additional volcanism caused by the hot spot under the country, which moves slowly towards the northwest across it.

Iceland can be divided into three zones based on the age of the basaltic rocks. Tertiary flood basalts make up most of the northwest quadrant of the island. This stack of lava flows is at least 3,000 metres thick. Quaternary flood basalts and hyaloclastites are exposed in the central, southwest and east parts of the island. The Quaternary rocks are cut by the neovolcanic zone areas of active rifting that contain most of the active volcanoes. The rifts are topographic depressions bordered by and containing many faults. Fissure swarms make up most of the neovolcanic zone. The swarms are 5-10 km wide and 30-100 km long. The rift zones have opened about 30 metres in the last 3,000-5,000 years, that means an average annual rate of 1 – 2 cm. The neovolcanic zone is about one-third

of the area of Iceland and the Krafla region east of Akureyri belongs to this zone. This neovolcanic zone is dominated by large swarms of faults and fissures (80 km long and 4-10 km wide, with over 1000 tectonic fractures) which pass through the central volcano Krafla forming together a volcanic system.

Volcanic area of Krafla

The Krafla central volcano in the Mývatn region forms a low, broad shield some 25 km in diameter, with a caldera (a cauldron-shaped volcanic feature usually formed by the collapse of land following a volcanic eruption) of about 10 km in diameter in its centre. A high temperature geothermal field lies within the caldera. Drilling has revealed temperatures in excess of 340°C at 2 km. Fissure eruptions called Mývatn fires occurred between 1724 and 1729. The youngest volcanic episode within the Krafla volcano occurred between 1975 and 1984. It involved nine volcanic eruptions and fifteen uplift and subsidence events. This interrupted some of the Krafla drillfields. During these events a large magma chamber emerged.

Exploitation of geothermal energy at Krafla started in 1974 with trial boreholes. In summer 1975 production wells were drilled and the construction of the 60 MW power station and a 132 kV transmission line to the town of Akureyri started. The powerhouse was designed to match two 30 MW turbine units.

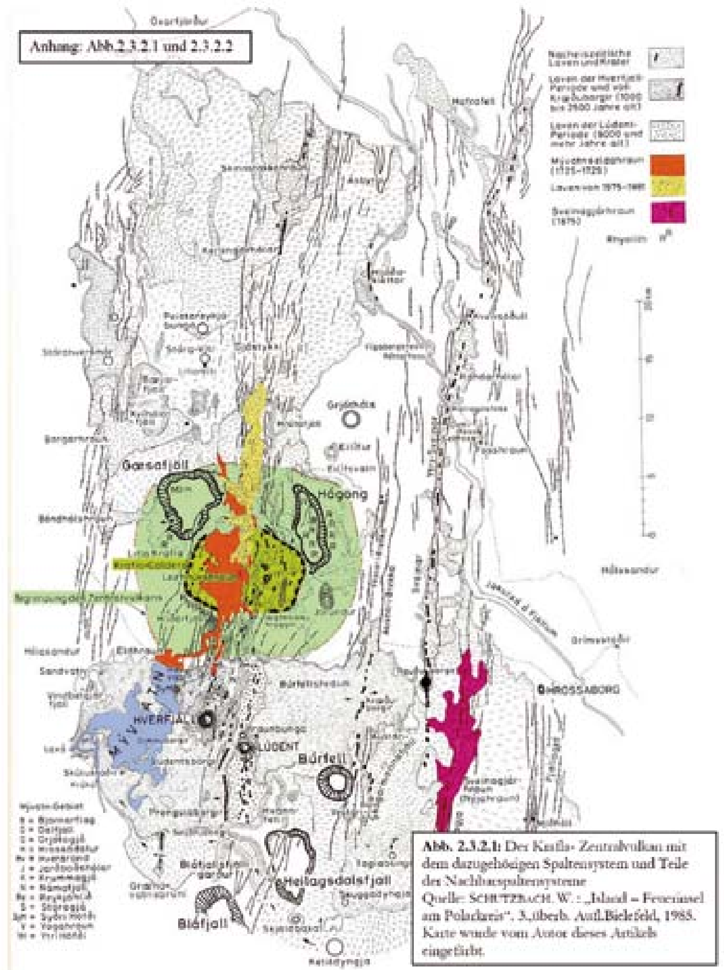

Fig. 10: Volcanic area of Krafla (http://home.arcor.de/andrew_steiner/2_3_2_Vulkansimus_Krafla.pdf)

The first turbine started up in August 1977, but electricity production did not begin until February 1978 due to inadequate steam supply. Various initial difficulties had to be managed largely due to seismic activity, which caused corrosive volcanic gasses to enter the geothermal system, destroying the borehole linings. A series of nine volcanic eruptions began near

Fig. 11: Fissure east of Lake Mývatn

the station on December 20, 1975 and lasted until September 1984. Since then, seismic and volcanic impacts on operations have greatly diminished.

In 1996, the second turbine was installed and new boreholes were drilled. Electricity production using the second turbine unit began in November 1997 and Krafla Station has been operating at its full installed capacity of 60 MW since 1999.

Geothermal power plants generate 25% of Iceland's total electricity and about 90% of the

Fig. 12: Production well of Krafla geothermal power plant

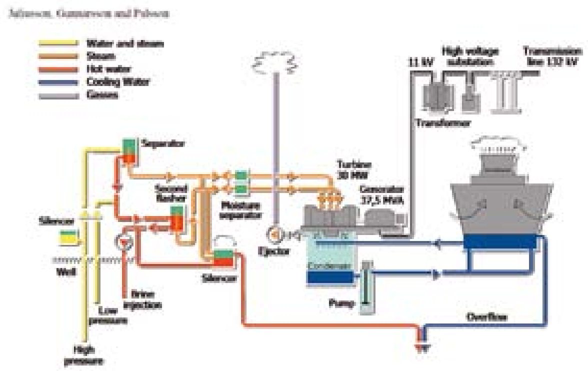

Fig. 13: An overview of the Krafla power station (Bjarni Már Júlíusson, Bjarni Pálsson, Árni Gunnarsson, 2005)

houses and buildings are heated with geothermal hot water (direct use of geothermal energy).

Hverir is an active solfatara (=sulfurous mud springs) field in the Krafla volcano area east of the mountain Námafjall near lake Myvatn. Groundwater seeps down to a depth of 1000 metres, where its temperature rises to above 200°C and it finds its way upwards as hot steam. Along with the steam come volcanic gases such as hydrogen sulphide which is responsible for the characteristic smell.

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Fig. 14:
Mudpots in
Hverir/ Námaskarð

Fig. 15:
Geothermal area at
Mt. Námafjall

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http://www.skogur.is/english

MATTHIAS GRANIG, CHRISTIAN IHRENBERGER, INGO SCHNETZER

Report on Wednesday, June 22nd
From Olafsfjörður to Siglufjörður

Bericht Mittwoch, 22.06.
Von Ólafsjörður nach Siglufjörður

Summary:
The north western part of Iceland is dominated by its fjords, which were formerly populated by many fishing villages and single farms. Since the beginning of rural settlements the threats from avalanches have always restricted development in this area. At least after the catastrophic avalanche events in Súðavík and Flateyri in 1995, an effective protection of the settlements and the maintenance of a secure transportation infrastructure have become a central priority for the responsible authorities. It is based on consequent risk management and focused on sustainable preservation and development of the region.

The traditional fishing town Siglufjörður is situated between the sea and steep avalanche prone slopes in the very north of Iceland. Until 1968 it was one of the main harbours for herring processing. Nowadays the town can be reached safely through an avalanche tunnel. Avalanches were always a threat for the town. Therefore in 1996 they began to construct protection measurements in cooperation with Austrian experts. Since then, supporting structures in the release zones and a series of avalanche dams in the run out zones were installed in Siglufjörður.

Zusammenfassung:
Die Nordwestküste Islands ist landschaftlich geprägt durch seine Fjorde, welche ursprünglich von einer Vielzahl von Fischerdörfern und Einzelgehöften besiedelt waren. Seit jeher stellte jedoch die Bedrohung der Siedlungen und essenziellen Verbindungswege durch Lawinen eine maßgebliche Einschränkung in der Region dar. Spätestens seit den fatalen Lawinenereignissen in Súðavík und Flateyri 1995 hat die Sicherung und Aufrechterhaltung der Siedlungs- und Infrastruktur auf Basis eines konsequenten Risikomanagements auch für diese Bereiche eine zentrale Bedeutung für die Gewährleistung einer nachhaltigen Entwicklung in dieser Region.

Der Ort Siglufjörður im Norden von Island war bis 1968 einer der wichtigsten Heringshafen, eingebettet zwischen dem Meer und den steil abfallenden Hängen im Westen. Durch Lawinentunnels gelangt man heutzutage in den Ort. Lawinen reichten immer wieder an den Ort heran, daher wurde im Jahr 1996 ein Pilotprojekt für umfangreiche Verbauungen mit Unterstützung aus Österreich gestartet. Seither wurde in mehreren Phasen eine Reihe von Verbauungsmaßnahmen mit Anbruchverbauungen, Leitdämmen und Lawinenauffangdämmen umgesetzt.

Introduction

The study tour on Wednesday, June 22nd, led from Akureyri in the north of Iceland along the coastal road to Sauðárkrókur. Along this trip the central thematic points were the replacement of parts of the old ring road by tunnels in the areas of Héðinsfjörður and Olafsfjörður and the avalanche protection measures that have taken place since 1996 in Siglufjörður.

Starting from Akureyri, this part of the "Ring Road" leads along the west coast of the Eyjafjörður (as one of the biggest outgoing glacier fjords in the north). Starting in the north of Dalvik to Olafsfjörður, the distance between the mountainside and the cost line where the road is situated becomes narrow. This leads to a big problem of being endangered by avalanches during the wintertime. As orientation and warning signs and at least as marked observation points, small boards were put up in the avalanche paths at the cross sections to the road to show the number of the each path as it is documented in the avalanche maps.

Risk analyses along threatened roads

As the central connecting road in this part of the island, the usability and safety of the infrastructure was always essential for the inhabitants. In the beginning of 2000, the Icelandic authorities initiated several studies about the risk situation along this part of the road by adapting the use of approved risk analyses methods like the Avalanche Index Methode (Jónsson et al 2008). For risked-based analyses of endangered roads, not only doest the characteristic and recurrence of the avalanche have to be considered, but elements like probable effects of measures, aspect of the starting zone or the usability of alternative detours were also included in an adapted indexing valuation scheme.

Tunnel system to Siglufjörður

As result of these studies and as consequence of the frequent threats on the road, it was considered that the endangerment by avalanches and rockfall could not be controlled by local counter measures only. So the building of a tunnelling system that drives around the most endangered parts was decided upon. At this time this tunnelling system consists of 3 tunnels which lead from the north of Dalvik to Olafsfjörður, from the west part of Olafsfjörður to the valley of Héðinsfjörður (which is a currently uninhabited fjord where snow avalanches were a constant threat to the past rural settlement) and at least from this valley to the valley of Siglufjörður.

Avalanche dams in Siglufjörður

The fishing town Siglufjörður is situated between the sea and steep mountain slopes. Especially the southern part of the town has repeatedly been endangered by avalanches starting from the Strengsgili and the Jorundarskal ravines. Since 1939, in total 37 avalanches were recorded in this area. After the tragic avalanche disasters in Flateyri and Súðavik in 1995, the preparations for defence structures in Siglufjörður began in 1996 (Johannesson et al. 2008). Further details are described by Kleemayr and Unterweger in their contribution about the pilot project in Siglufjörður. At the southern end of the town, two deflecting dams were built to protect the settlement. The dimensions of the big deflection dam (Stori boli (big bull)) are 700 metres in length with a height of 18 metres. The smaller one (Litli-boli (little bull)) is 200 metres long and 15 metres high.

Fig. 1: The Strengsgili and the Jorundarskal avalanche deflection dams in the southern end of Siglufjörður

During the winter 1998/99 and after finishing the construction in 1999, several avalanche events happened and the avalanches were successfully deflected as designed.

In the second phase from 2002 to 2008, a series of avalanche dams was built above the settlement (see Fig. 2). From the southern to the northern end of the town, 5 catching dams were constructed with earthworks and strengthened geo textiles. At the northern end of Siglufjörður another deflection dam protects the houses now.

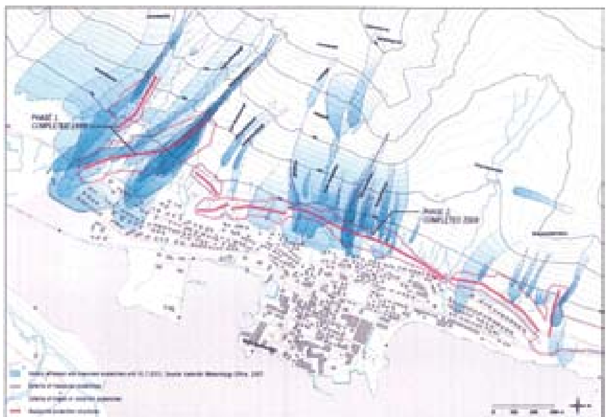

Fig 2: Map of the avalanche events between 1939 and 2001; avalanche dams (red lines)

Fig 3: Avalanche catching dam above the town with a viewpoint

The catching dams add up to 2000 metres in length with a height of about 14 metres. In total 750,000 m³ earth material was moved to fill the dams. The basis of the avalanche dams is a compacted earth filling following the steeper section with reinforced earth and geo textiles. During the construction, the lose earth material was too problematic to build a steep dam face on the avalanche side.

The community of Siglufjörður put not only a lot of effort in the construction of the protection measurement itself, but also in keeping the impact on the natural landscape on a lower level. Therefore the dams were fitted into the surrounding landscape to mimic the natural forms that are found in the natural setting around the dams (see Fig.1). A landscape architect brought into the project planning presented his ideas for the alteration of the terrain to minimise the visual impact. By using local materials for the construction and the re-growing vegetation, the

Fig 4: The longest avalanche catching dam in Siglufjörður

local landscape character could be retained. Furthermore the layout of hiking trails, viewpoints (Fig. 3) and recreational areas enhanced the acceptance of the population for the measurements (Vilhjalmsson et al. 2008). Today the avalanche protection dams are well integrated into the landscape and the daily life of the town.

Supporting structures in Siglufjörður

In the north of Siglufjörður, the avalanche path from Grouskardshnjukur endangers the settlement area of Hvanneyrarkrokur. To improve the safety of people it was decided to combine a catching dam near the houses with about 620 metres of supporting structures in the main release zone. The starting zone begins at 300 metres above sea level and ends at a height lower than 150 metres above sea level.

Based on the experiences made at the pilot project in Grindagil, it appeared feasible to use snow bridges to stabilize the snowpack in the steep slope. This type of construction has greater reserve strength to withstand overloading and has no problems with corrosion under Icelandic meteorological conditions. The snow bridges at Siglufjörður

Fig. 5: Avalanche path north of Siglufjörður

Fig. 6: Drilling the upper anchor

are very similar to the type used by the Austrian service for avalanche and torrent control. The only important difference is to galvanize all parts of the steel bridges. The foundation is done with a split upper anchor and a base plate for the posts.

The base plate has to be fixed with an anchor to prevent heavy storms from lifting the footplate. Footplates are covered with loose material for the same effect. The length of the upper anchor is about 5 metres to 6 metres.

The construction site is covered by loose rocks and so it was possible to build an access road from the settlement to the upper end of the release zone at

Fig. 7: Snow bridges north of Siglufjörður

300 metres above sea level. The defense area ends at a height of 150 metres above sea level. Under the instruction of Austrian workers 106 steel bridges were installed in 2003 and 2004. One steel bridge has a length of 4,0 m and is designed for the snow thickness Dk = 3.5 metres. The gaps between the bridges were closed with steel beams to achieve the most effective stabilization of the snowpack. The use of caterpillars for transporting the steel bridges and doing the ground work made the work easier und caused a good performance.

After the installation of the supporting structures, the access roads were removed and now most of the construction area is covered with lupine.

Conclusion of Wednesday

On this part of the study trip the principle views in the mitigating strategy against natural risks in Iceland could be seen and discussed:

It could be shown that the few viable rural areas in this northern part of Iceland were heavily threatened by avalanches (as the catastrophic avalanche events in Súðavík and Flateyri in 1995 that caused 34 fatalities and extensive economic damage). With this, the inhabitants had to deal with decreasing economical income by agricultural use and fishing especially in circumstances of actual economical crisis. This leads more and more to a rural exodus which will never make a sustainable development of a region possible.

To strongly act against such negative trends and to save the population in these sensitive areas, a bulk of activities were initiated by the officials. These activities led to a comprehensive elaboration of hazard maps for the most endangered cities based on a consequent risk management. According to this, massive protection measures such as tunnels, dams and counter measures in the release zones of avalanches were planed and rapidly build up in the last years. In addition, the buildings were purchased from the concerned inhabitants where no protection or reinforcement was possible or acceptable in terms of technical and economical costs.

All these investments show that, for Iceland, there is a very high importance in mitigation measures against avalanches to secure a sustainable preservation and development in the formerly rural areas.

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MICHAEL BOTTHOF, CHRISTOF SEYMANN, HANNES BURGER

Report on Thursday, June 23rd
On the road from Sauðarkrokur to Ísafjörður

Bericht Donnerstag, 23.06.
Am Weg von Sauðárkrókur nach Ísafjörður

Summary:
On Thursday, June 23rd, 2011 our schedule led us from Sauðarkrokur past Holmavik and Súðavik to Ísafjörður in the Northwest of Iceland. A long bus trip of more than 400 km showed us the marvellous landscape of this region characterized by fjords, little villages and isolated farms. So we had plenty of time to regard the sights and soak in the impressions of this unknown country we got in the previous days. During the bus trip, Tomas Johannesson gave us an introduction of the culture and history of Iceland. In the afternoon we relaxed with a short break at the hot spring in Reykjanes before we were kept busy again with avalanche issues in Súðavik and the visit of IMO at Ísafjörður.

Zusammenfassung
Am Donnerstag, den 23. 6. 2011 führte uns unsere Reise von Sauðárkrókur über Hólmavik und Súðavík nach Ìsafjörður im Nordwesten Islands. Eine lange Busreise über mehr als 400 km zeigte uns die eindrucksvolle Landschaft dieser Region, geprägt durch Fjorde, kleine Dörfer und abgelegene Gehöfte. Daher hatten wir Zeit in den Reiseführern zu schmökern bzw. den Ausführungen von Tomas Johannesson, der uns die historischen und kulturellen Hintergründe über sein Land näherbrachte, zu folgen. Darüber hinaus konnten wir die vorbeiziehende Landschaft betrachten und die bisherigen Eindrücke eines uns bisher unbekannten Landes auf uns wirken lassen. Ein kurzer „Wellnessaufenthalt“ am Nachmittag in der Freilufttherme von Reykjanes verkürzte die Reise bevor wir uns wieder in fachliche Themen in Súðavík (Lawinenunglück 1995) und Ìsafjörður (Besuch des IMO) vertieften.

Historical and cultural aspects of Iceland

For centuries Iceland was one of the poorest countries of Europe. In the meantime – even considering the economic crisis of the last years – that has changed fundamentally. Although the question remains how the people's life looked in the middle ages and the following periods under these difficult climatic conditions in the geographic outskirts of Europe. No cities appeared like they were developed in Central Europe. The cultural development was very small with the exception of literature, which was recognized at the Book Fair at Frankfurt this year.

Within the 13th und 14th centuries Icelandic literature reached its height. Most of the sagas were written during this period. Even today the Icelandic identity is connected with the stories of the sagas. Because the Icelandic language has not changed too much since the middle age, like the most European languages did, the sagas are still readable for the modern Icelandic readers.

These and other facts about Iceland's culture and history were presented by Tomas Johannesson during the long bus ride this day. Meanwhile we enjoyed the marvellous country of the Icelandic northwest through the window of the bus: sheep, Iceland horses, fjords lit by the midnight sun, landscape with all kinds of green colours, endless roads without traffic, waterfalls and rivers - finally not enough time to concentrate on details. Everything passed by like a movie. The untouched nature reminded us being in a kind of national park.

Fig. 1: Travelling through the western highlands

Busstop in Reykjanes in the afternoon

As Iceland's geology is based on volcanic activity. It is a fact that the island is geologically very young The eastern and Westfjords and some smaller parts in the north and the west are the oldest parts of the island, and they are only about 20 million years old. Due to the distance of the Westfjords to Iceland's hotspot they do not have any volcanic activity like eruptions, solfataras and fumaroles, yet. The only witnesses of their volcanic history are, next to the layered structure of the mountains, hot springs (called laugar or hverir). In the Westfjords there are some of these hot springs.

Concerning the hot springs of the Westfjords

In the Western Fjords of Iceland you can find more than 20 hot spots as a last stadium of volcanic activity. They all vary concerning temperature, content of minerals and amount of flow depending on the ground water, the hydrostatic pressure and the chemical characteristics of the geological materials, which the water flows through to its way up and the distance to the magma cells. There are many hot springs along the Ísafjarðardjúp, and its side fjords like in Strandasýsla.

In the region of the Western fjords there are 8 geothermal outdoor spas. Often there was a recently built pool where somebody can swim and enjoy the marvellous view over the fjords to the mountains. In the afternoon we stopped at Reykjanes to take a bath in such a geothermal

Fig. 2: Relaxing in the pool of Reykjanes

spa, where the water reaches the surface at 96° C. In the pool, there are zones with different temperatures like a scale of temperature.

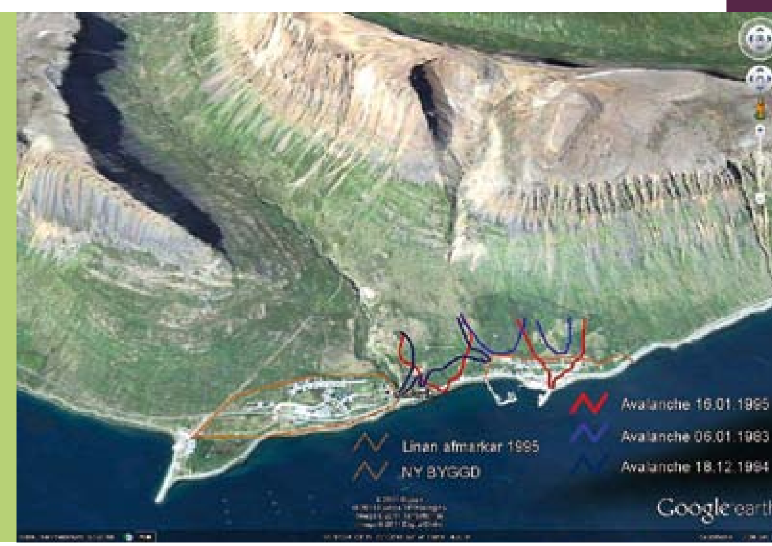
Súðavik - The making of a fishing village

Relaxed from swimming in the geothermal bath we reached the village Súðavik in the late afternoon. The first settlers here, Eyvindur kné and his wife Puriður rymgylta, claimed land in Àlftafjörður and Seyðisfjörður in the 10th century after arriving from Agder from Norway. For centuries thereafter farmers lived in Àlftafjörður, raising animals and fishing. As the small land area limited possibilities to increase the size of herds, fishing was an essential supplement to raising cattle and sheep. Small rowboats were used for fishing, most of them launched from Súðavik. From there it was a relatively short distance to the fishing grounds and local beach conditions were also good for landing. Other farmers in Àlftafjörður spent the fishing season in huts near Arnarneshamar, where there is an ancient fishing station called Hafnir. A hamlet started forming in Àlftafjörður around the middle of the 19th century, and Súðavik is first called a village in the 1880 census. The population of the district increased considerably between the years 1835 – 1870, and there was not enough work for everyone on the farms. People therefore tried their luck on the coast. Súðavik was a favourable site, as there was more land there and it was close to the fishing grounds. The first villagers followed their ancestors´ example, both fishing and raising livestock. But there was a significant change: fishing now became the main source of livelihood and livestock-raising a supplement. In 1883, Norwegians built a whaling station at Langeyri, which operated for two decades, along with a whaling station in Dvergasteinseyri. The Norwegians also maintained operations at Hattareyri in Àlftafjörður and Uppsalaeyri in Seyðisfjörður. These businesses attracted people who were looking for work and the population of Àlftafjörður increased considerably during the time the whaling stations were in operation. But despite expanding commercial activity at Langeyri, based first on whaling and then on the fishing done from there during the first decades of the 20th century, people continued to maintain permanent homes in Súðavik. The village had become established and it was easiest to make a living there given the work methods prevailing at the time.

An Avalanche hit Súðavik

On January 16, 1995, at about 6:20 in the morning, a 400-metre wide snow avalanche fell on the

Fig. 3: Map of avalaches of the years 1983, 1994 and 1995 of Súðavik



centre of the town of Súðavík. Fourteen people were killed. Among these were eight children, while twelve people were rescued. Sixteen houses were hit by the huge snow slide, and most of them were destroyed. The snow also demolished a kindergarten and damaged a building complex with the municipal offices, various workshops, the local post office and residential housing. There had been a furious storm the day before the avalanche, with winds from the northeast bringing a lot of snow. The wind direction changed to north/northwest during the night, and gale-force winds and heavy precipitation caused a rapid accumulation of snow lower down on the side of the mountain. Overhanging snow is then believed to have fallen from a mountain ridge above the town, setting a large area of snow farther down the mountainside in motion.

Local residents began rescue operations immediately after the avalanche fell. The first outside assistance came shortly before ten o'clock, when dozens of rescue workers with search dogs, doctors and nurses arrived from Ísafjörður. An emergency centre was set up in the Frosti ltd. fish-freezing plant and town residents gathered there. By all accounts, the specially trained search dogs from Ísafjörður were vital to the rescue operation,

Fig. 4: Visiting the memorial of the avalanche desaster of 1995 in Súðavik

saving several lives. A twelve year old boy was the last person found alive some 24 hours after the avalanche fell. The search ended on the evening of January 17, when the last victim of the avalanche was found. In the evening of January 16, a large avalanche fell on the town from Traðargil, demolishing three houses in the street Aðalgata. Earlier this same winter, on Sunday, December 18, a snow slide had come down to Traðargil, hitting the farm Saurar and completely destroying the house and two sheepcotes there. An elderly resident was rescued from the avalanche, which killed five sheep. Most of the houses on which the avalanche fell in January 1995 were located outside the limits of established danger zones. The boundaries had been set according to two snow slides that had fallen in similar areas in 1983. The first had hit the farm Ytri-Höfði, located above Túngata, and the second Innri-Höfði above Nesvegur. These snow slides destroyed two sheepcotes, killing several sheep.

Town relocated

After the avalanches, the inhabitants of Súðavík had to confront the issue of whether the town should be rebuilt. At a town meeting held in Ísafjörður on January 23, 1995, a majority of residents expressed a definite wish to move back to their home area, provided the town could be relocated in a safe location on the other side of Eyrardalsá. The same month, the head of the local authority was asked to seek planning proposals for a new town in the Eyrardalur area. The Súðavíkurhreppur council asked the Avalanche Prevention Fund and the National Civil Defence Agency to arrange the purchase of townspeople's property in areas at risk from avalanches rather than build a protective wall against snow slides. Buying up this property and rebuilding the village in a safe place would cost much less than a structure of this kind. The first task was to find temporary housing for those who lost their homes in the avalanche while reconstruction took place. Eighteen summerhouses were transported to Súðavík, and about 70 people moved into them in March. Ground was broken for the new town of Súðavík on April 30, 1995, and on August 23rd the foundations were laid for the first new house in the Eyrardalur area. One year later, construction was fully underway. By the autumn of 1996 the foundations had been completed during the winter. Nine houses were moved from their former locations, including five older structures and four that had only recently been finished when the avalanches occurred. A total of 54 houses remained on the town's former site. They were offered for sale, and many people used the opportunity to by a summer house. In 1998, the corporation Sumarbyggð was founded to maintain vacation homes in Súðavík, and the first holiday guests arrived in May 1999.

In the evening of this long day we visited the office of IMO in Ísafjörður and we were introduced to the main purposes of this organization by Harpa Grimsdóttir. It should also be mentioned that IMO also developed the ideas to build constructive measures in combination with hazard zoning for sheltering the settlement areas and the infrastructure after the avalanche disasters in Iceland in the 90ies of the last century.

The Icelandic Meteorological Office (IMO) is a public institution, historically based on the Icelandic Meteorological Office (1920) and the Icelandic Hydrological Survey (1948). The two institutions merged in 2009, with the responsibility of monitoring natural hazards in Iceland and conducting research in related fields, as well as participating in international monitoring and research. IMO has a staff of 270 people, of which 60 staff members work on research-related activities.

The main purpose of IMO is to contribute towards increased security and efficiency in society by:

- monitoring, analyzing, interpreting, informing, giving advice and counsel, providing warnings and forecasts and where possible, predicting natural processes and natural hazards;
- issuing public and aviation alerts about impending natural hazards, such as volcanic ash, extreme weather and flooding;
- conducting research on the physics of air, land and sea, specifically in the fields of hydrology, glaciology, climatology, seismology and volcanology;

- maintaining high quality service and efficiency in providing information in the interest of economy, of security affairs, of sustainable usage of natural resources and with regard to other needs of the public;
- ensuring the accumulation and preservation of data and knowledge regarding the long-term development of natural processes such as climate, glacier changes, crustal movements and other environmental matters that fall under IMO's responsibility.

IMO's nationwide monitoring systems consist of 115 automatic and 100 manned weather stations, a network of 170 hydrological gauges in rivers, a 55-station seismic network (SIL) with automatic, real-time data acquisition and earthquake location, a continuous GPS (ISGPS) network of 70 stations, some with high sample rate, a 5-station borehole strain metre network is operated in southern Iceland, and a weather radar, which can also monitor volcanic plumes, is located in south-western Iceland. In addition, IMO conducts extensive manned monitoring of glacial rivers and sub-glacial floods (jökulhlaup), of glacier mass balance and margin positions and participates in nationwide GPS campaign measurements.

IMO has a long-term advisory role with the Icelandic Civil Defence and issues public alerts about impending natural hazards. The institute participates in international weather and aviation alert systems, such as London Volcanic Ash Advisory Centre (VAAC), the Icelandic Aviation Oceanic Area Control Center (OAC Reykjavík) and the European alarm system for extreme weather, Meteoalarm.

IMO has participated in several European and Nordic funded research projects, having the role of lead partner in some of them. This includes, for example, the "Climate and Energy Systems" project whose goal is to look at climate impacts closer in time and assess the development of the Nordic electricity system for the next 20-30 years.

The main research focus of IMO is on earthquake and volcanic processes and hazards, glacial studies, ice-volcano interaction and climate change. IMO also focuses on research in multiparameter geophysical monitoring to develop better forecasts of hazardous events.

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PETER GOTTHALMSEDER

Report on Friday, June 24th
Westfjords of Iceland, previous and current avalanche protection

Bericht Freitag, 24.06.
Islands Westfjorde, bisheriger und derzeitiger Schutz vor Lawinen

Summary:

On the fifth day of our journey we remained in the Westfjords of Iceland and visited the northernmost villages, such as Flateyri and Hnífsdalur, where in the past many people were buried and killed by avalanches. The first deflecting dam of Iceland, built in 1996, was introduced and we visited the newest catching dam construction in progress in Bolungarvík.

During this day we got a view of concrete methods of avalanche protection, up to concepts for permanent and temporary evacuation of the people. We went through small tunnels with passing points for two way traffic that were built so that rescue teams would be able to respond to the areas by road, even when weather conditions are horrible.

Interest was attracted by the detailed extents of known avalanches, collected by the snow observers of IMO and by the different combination of measures against avalanches.

At the end of the day we had dinner at Tjöruhúsið. This is a wonderful restaurant in Isafjordur, a “must do”-visit for those traveling to Iceland. Fish smells wonderful and it just seemed sinful to leave any of it uneaten. The mind of fishery gets clear – even for continental people.

Zusammenfassung:

Tag 5 der Studienreise führte uns in den äußersten Nordwesten Islands, an die Stätten historischer Lawinenkatastrophen, wie Flateyri und Hnífsdalur. Der Bogen spannte sich von den ersten Dammprojekten aus dem Jahr 1996 bis zu einer aktuellen Großbaustelle in Bolungarvík, von harten Verbauungskonzepten zum Schutz der Unterlieger über Aussiedelungen von Gefahrenbereichen (Ísafjörður) bis hin zu temporären Evakuierungsplänen und zu Straßen- und Tunnelbauten, um im Katastrophenfall auch bei extremen Wetterbedingungen einen raschen und effektiven Einsatz von Rettungsteams zu ermöglichen.

Interessant waren die detaillierten Aufzeichnungen der Mitarbeiter des Meteorologischen Instituts (IMO) bezüglich der Auslauflängen beobachteter Lawinengänge, die verschiedenartigsten Maßnahmenkombinationen von Bremselementen, Lawinenleitdämmen und Lawinenauffangdämmen, die Diskussionen über deren Wirkung auf Extremereignisse sowie deren konkrete Auswirkung auf die Gefahrenzonenplanung und Siedlungspolitik in Island.

Einen unvergesslichen Eindruck machte das abschließende Abendessen im Fischrestaurant Tjöruhúsið in Ísafjörður, bei dem jedem Skeptiker der Wert einer unter harten Lebensbedingungen ausgeübten Fischereiwirtschaft verständlich wurde.

Introduction

Before starting the report it is very important to acquaint you with the basic conditions in the background of Iceland:

The Westfjords of Iceland is a very rough country with horrible weather conditions during the wintertime, it is sparsely populated and with large uninhabitated areas. The Icelander survived by fishing, cultivation of land and sheep farming is not successful, even in some favoured areas in the south.

Fishery is very efficient, but it is also very dangerous because of the cold water, the rough sea and the riffs that cannot be seen in fog and during the nights.

Other important factors in the economy are tourism, skiing and golf, but skiing does not have the same importance as in Austria.

Fig.1: General map of the Westfjords, containing the villages Ísafjörður, Hnífsdalur, Bolungarvík and Flateyri

Topographic conditions, climate

Fjords are formed when a glacier cuts a U shaped valley by abrasion of the surrounding bedrock. After the melting of the glacier and the comeback of the sea there mostly remains only small band of coast for settlement. Above this area, mountain slopes rise to between 400 and 700 metres above sea level and usually the mountain tops are flat and formed as large plateaux - terrible catching areas for snow drift. You can hardly imagine the circumstances in the starting zones of avalanches if there are high winds reaching above 45 m/s for a few days.

Cold temperatures and large amounts of drifting snow cause catastrophic avalanches with surprisingly long runout areas.

Forestry and Avalanches

The timber limit would be reached at a height of about 300 to 400 metres above sea level, but usually you will not see any trees on the mountain slopes. People in the Westfjords never needed sustainable forestry because they were supported with drift wood from Siberia. (The Viking name "Bolongarvík" means "woodpile-bay", due to lots of drift wood usually being there.)

Apart from that geothermical energy is used for heating houses in Iceland. Also therefore sustainable forestry was never established in Iceland during the past.

Extreme snow accumulation in the avalanche starting zones were built by heavy snowfalls combined with very low temperatures and storms from the Northeast with wind speeds up to 200 km/h. As a result of these factors dry snow avalanches with huge powder layers and extraordinary run out zones could be observed.

Fig. 2: The Ósvör museum, a fascinating replica of an old fishing outpost. There, the museum curator greets visitors wearing a skin suit similar to these Icelandic sailors have worn in the 19th century.

Traditional way of life – fishery-museum in Osvör

In the Ósvör museum a fascinating replica of an old fishing outpost was built in remembrance of the foundation of Bolungarvik in 1890. First settlers wore watertight skin suits in their hard everyday life.

Fig. 3: Old fisherman gears on the basement of an old hut.

Fig. 4: Fish drying platform in the salt-shed.

Fig. 5: The salt shed in the front, and the fisherman shed.

Hard living conditions till today

During the polar night the people near the polar circle don't see the sun for more than three months. They live in the knowledge of an imminent risk of avalanches and they already know about the happenings in the recent past. From 1901 to 2000, all together 166 people were killed in avalanches. Of these people, 107 were killed in buildings, the rest of them on roads or travelling in background areas.

One of the last accidents in Súðavík took the life of 14 people. The weather conditions were horrible and it was impossible for the rescue teams from the nearest towns to reach to the area by road. In the end they had to sail by ship, even though velocity of wind was up to 90 knots (180 kilometer per hour).

One of the greatest problems is the depopulation of the Westfjords, on the one hand by death (in Flateyri the avalanche killed about 5% of the inhabitants), and on the other hand because of migration. Especially young women migrate to Reykjavik for the temperate climate, theatres and coffeehouses. And that's why actually about 70% men and only 30% women live in the Westfjords.

The political priority is to preserve cultural sites of Iceland's past and to avoid migration by providing infrastructural facilities to the economically weaker regions.

Some areas in the northeast of Bolongarvík have been deserted since 1950. Every year some polar bears from Greenland strand on this part of the coast. These dangerous animals are usually quickly shot by hunters.

Rescue operations and alarm plans

The avalanche events that have occurred have also demonstrated the problem of quickly deploying well-equipped rescue teams. The roads often run above cliffs and are closed due to avalanche danger and snow chaos, the ocean routes are extremely dangerous due to waves, polar storms, poor visibility, dangerous reefs and the ice cold water. Due to storms, fog and avalanche dangers, an approach with snow mobiles or skis over the 600 meter high mountains is also not advisable, and flights to the few airports in the region are also impossible if the weather is poor. Furthermore, the runways are generally also threatened by avalanches.

The people in the scattered villages are left to their own devices for 6 to 12 hours after a catastrophe until help arrives from the neighbouring villages or from Reykjavik. And for just this reason it appears that at least the knowledge of a secure village centre as a place of refuge as well as a half-way secure transportation network can be of the highest practical and psychological importance.

Therefore, regardless of all cost-benefit analysis, relatively high amounts of money have been invested in the construction of dams and braking elements to protect a few homes, just as considerable financial amounts are directed to tunnel projects that ensure safe traffic connections to very remote villages in which often - as in Flateyri - only 237 people live.

WESTFJORDS – Ísafjörður

Ísafjörður, with 2,636 inhabitants, is the largest port town in the Westfjords and has an airport, a ski area and a golf course as well as an excellent fish restaurant. The ski season runs from January until April, ski tours are possible starting in November.
Ísafjörður is surrounded by steep mountain walls so that, due to avalanches, larger settlements have formed under the relatively safe south-east

Fig. 6: Isafjörður with threatening, south-east facing slopes towering above the town centre, where previously no major avalanches had been observed.

slopes. But a sword of Damocles hangs over the inhabitants here as well: The 700 ha large slopes are only interrupted by around 150-200 metre wide flat area at 450 metres above sea-level before they break steeply down over 380-400 ha to the densely populated coast. Due to the winds mainly coming from the north and north-east and blowing parallel across these slopes, the centre of Ísafjörður has been spared from larger avalanche events in the recent past.

The south-facing slopes tower 600-700 ha over the coastal areas and are - as can be seen in the records by the "snow observers" from the Icelandic Meteorological Office (IMO) - more often hit by avalanches than the terrain would suggest. A clear increase in avalanches also occurs under pronounced summit plateaus.

The first documented avalanche occurred on March 24, 1947. This reached the coast and damaged a farmhouse (figure 8, right). Additional large avalanches followed on the south slopes in the years 1994 (figure 7 and figure 8) as well as 1999 and 2005.

The event of September 5, 1994 (Figure 7/8):

The snow masses from heavy snow falls with drifts from a summit plateau dropped 300 metres in elevation before crossing around 300 to 350 m^3 and 4-6° slope shoulder and penetrating settled area on the other side of the flat area.

A ski lift running across the break surface was destroyed and the ski run along the slope shoulder was covered by the avalanche.

Spatial planning consequences:

The red avalanche danger zone (C-Zone) was placed above the scattered settlement within the deposit limits of the major avalanches (Figure 7).

Fig. 7: South to south-west facing slopes above Ísafjörður, where large avalanches penetrated over a flattened slope into the valley.

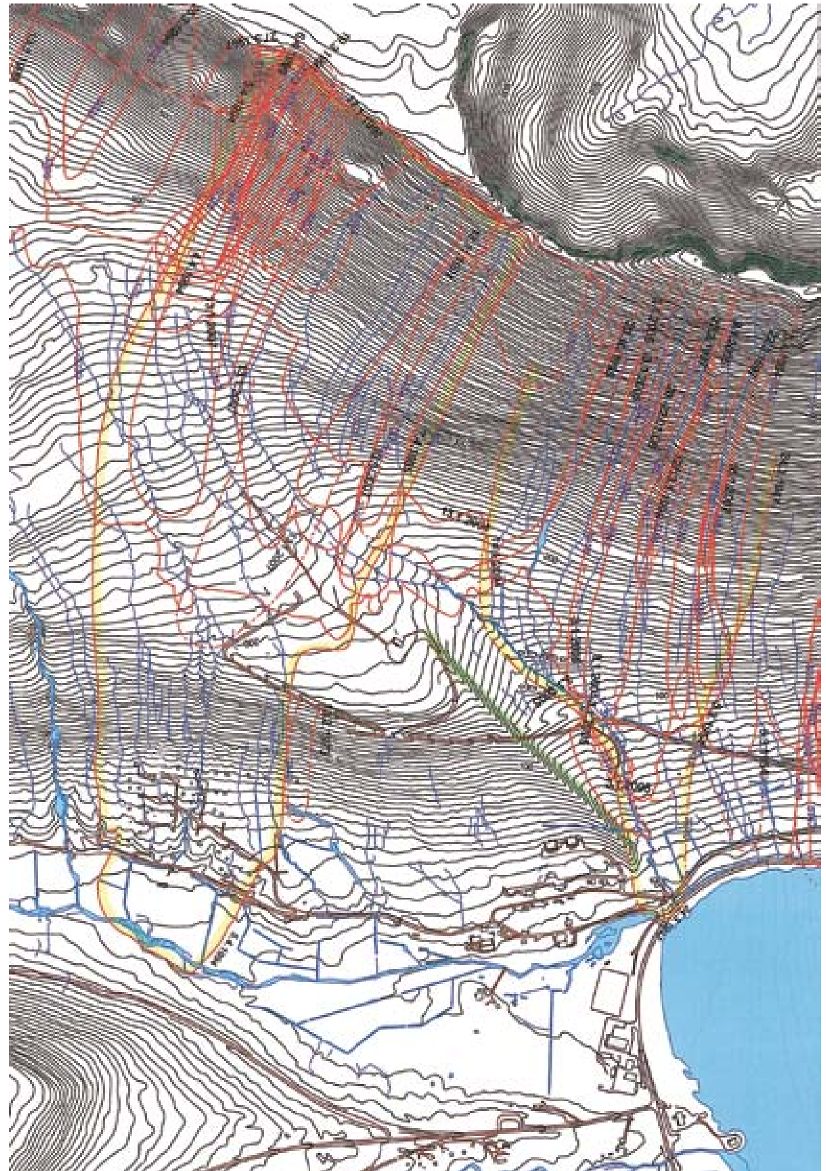

Fig. 8: Mapped run out distance of avalanches (Ísafjörður)

This resulted in a ban on new buildings, limiting the existing homes to summer occupation only and in the government taking measures to protect the population.

The ski area at the foot of the dangerous south slopes was also blocked off and moved to safer terrain.

In Austria in cases with similar conditions, the slopes would also generally be subject to closure, however it was then the responsibility of the avalanche commission in the community or the lift owner to ensure the daily evaluation of the slopes and determine whether they would open. For the safety of the ski lifts, the lift owners would most likely also built permanent protective constructions.

Measures taken:

In 2004, a combined avalanche catchment and guide dam was built on the valley-side edge of the flat terrain where the break off and fall zones reach thicknesses of 550 to 650 metres above sea-level. The dam project protects a section of land at the foot of the fjord that has not yet been hit by avalanches but has been evaluated as dangerous by the Icelandic hazard zone planning so that along with the land tongue that projects into the fjord like a horseshoe (centre of the settlement) now also has a second avalanche safe area for new construction of the homes destroyed in the 1994 avalanche and which

Fig. 9: Ísafjörður: Braking elements before the avalanche deflecting dam.

Fig. 10: Ísafjörður: The avalanche deflecting dam constructed in 2004 with a building in the middle of the run off zone.

can also be used if needed for the evacuation of the scattered population settled around the neighbourhood of Holtahverfi.

A standard procedure for the Icelandic government is to purchase highly endangered residential objects and then sell them again with a legal stipulation that the use is limited to the time period between the 15th of April and the 30th of October. This procedure was also applied for the home visible in Figure 10. This had already been damaged by an avalanche in 1947 and is now located directly in the push direction of the avalanche flows to be deflected by the dam.

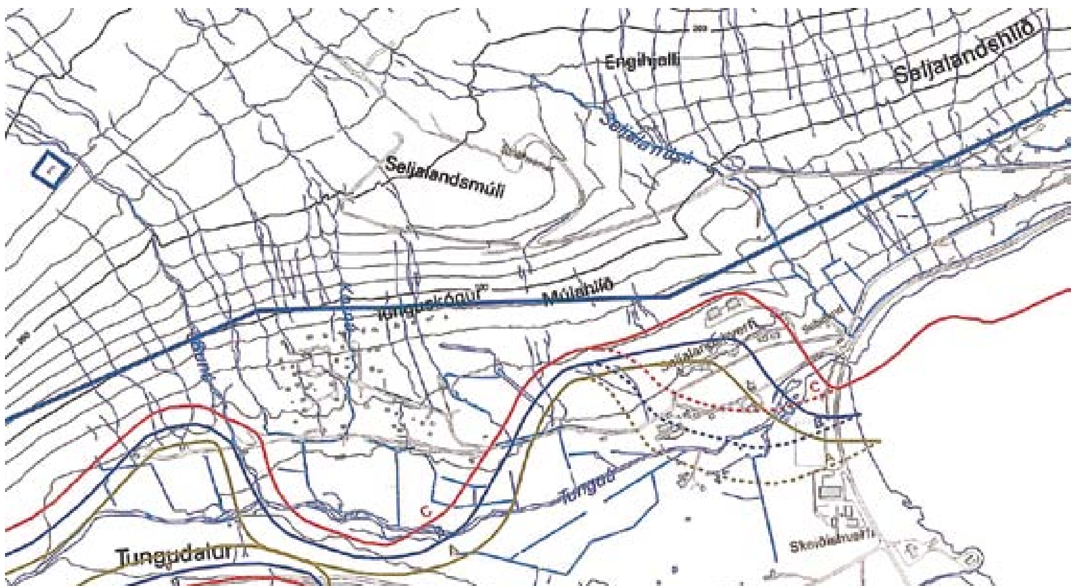

Fig. 11: Effects of the dam body on hazard zone planning (Ísafjörður).

Technical considerations:

In the area of the avalanche flow dam, where the deflection angles for the falling avalanche flows are more than 30°, two rows of alternating braking elements were positioned facing each other (Figure 9).

The break surfaces for the avalanches that could hit the dam are located below the gratschneide plateaus (not directly below a summit plateau), which is why the amount of snow can be estimated and the dam offers a higher level of safety. On January 3, 2005 a first avalanche ran in to the retarding mounds and was deflected to the left by the dam; however it did not reach the coast.

The avalanches have once again demonstrated that flattened surfaces do offer protection from repetitive small events, but however the major events in the hazard zone plans are able to cross over these flat areas.

No construction or braking measures have yet been taken for the areas affected by the event on April 5, 1994. A guard wall should be able to deflect the avalanche to the west but also have openings for several mountain torrents (see figure 7) - therefore this would not be easy to implement. Furthermore, the relevant break off areas for this area are again under a larger summit plateaus which would increase the vulnerability of this type of dam project.

Therefore, the purchase of the houses with a limited use permit for the summer months only and the relocation of the population were given priority over the construction of the dam. The people in Iceland cannot be forced to leave their homes, but the government's offer has only been refused in a very few cases.

Fig. 12: Tómas Jóhannesson, from the Icelandic Meteorological Office (IMO) in Reykjavík at the start of the mountain run over the crown of the dam.

WESTFJORDS – Hnífsdalur

Hnífsdalur is a small village with 231 inhabitants located at the foot of 600 meter high slopes with a south to south-east exposure. Contrary to the avalanches that generally occur in Iceland, these are basin-shaped breaks that are generally channelled into a gully.

The break basins have the disadvantage that even storms blowing across them can result in a very large accumulation of drifting snow. The exposition is only slightly different than the simple slopes above Ísafjörður located 4 km to the south. However, it appears as if the snow settles here instead of on the slopes above Ísafjörður and this is why the port town in the Westfjords has been saved avalanches so far.

Since these avalanches do not correspond

Fig. 13: Hnífsdalur: Above the settlement, contrary to the normal slope avalanches in Iceland, there are three arrow-shaped avalanche ravines.

Fig. 14: Highly endangered homes with the collection of stones in the foreground that is typical for avalanche deposit zones.

to the standard type of Icelandic slope avalanche that are found on most slopes above the fjords, the "SAMOS" avalanche model was tested on them and the Icelandic parameters were calibrated.

Measures:

The road north of Hnífsdalur that had a high risk of avalanches was then moved from the toe of the slope so that it is now at least outside of the reach of the most common events. Temporary measures (evacuation) are used for individual threatened objects.

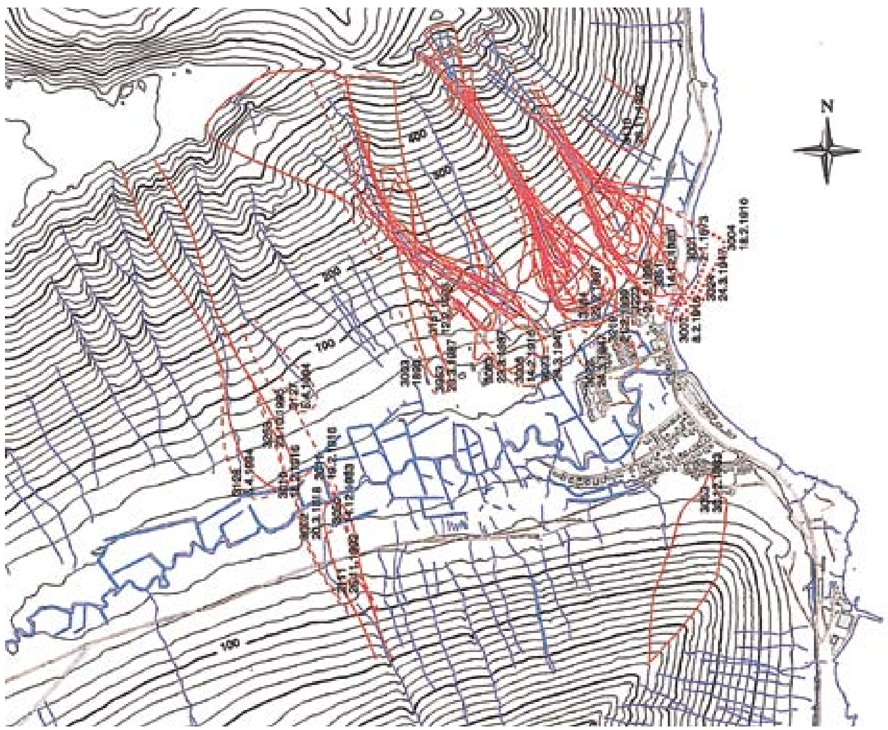

Fig. 15: Mapped avalanche run outs in the Hnífsdalur settlement.

Events:

On February 18, 1920, twenty people were killed by an avalanche here; there were also more encroachments from avalanches in 1916, 1947, 1973 and 1983 that reached past the connecting road to Bolungarvík. The last major avalanche was observed in 2005 when it completely destroyed a farmhouse and broke the windows in a block of flats.

Avalanches, which present a hazard for roads, are increasingly seen as a problem in Iceland since generally there is only one road that is not easy to close and the usability of the roads can be extremely important for a quick rescue team response.

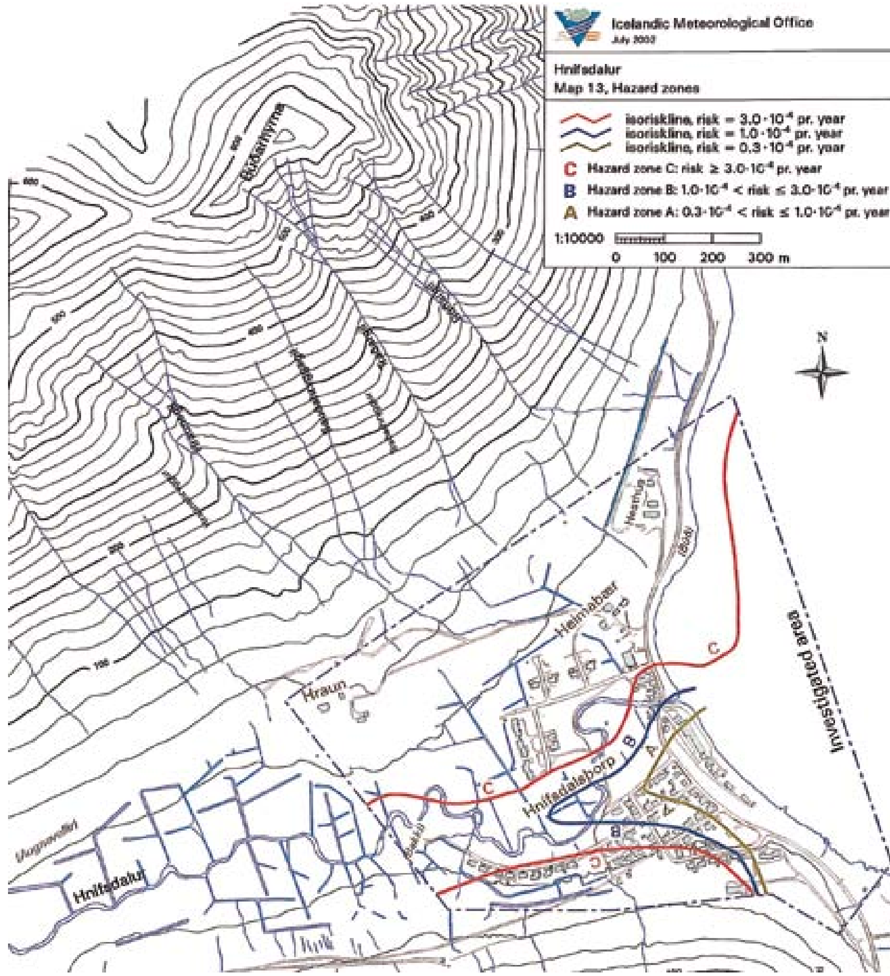

Fig. 16: Hazard-zone map for Hnífsdalur.

A-Zone	No new constructions possible; existing homes are, ideally, purchased and re-sold with limited time period use restrictions
B-Zone	Measures to protect property must be made on all homes.
C-Zone	Recommendation to equip private homes with reinforced outer walls; public buildings must be designed to be stronger.

By constantly evaluating the individual risk (the probability of death) the protection of roads has a higher priority due to the larger numbers of people using them as compared to, for example, a runway. The Ísafjörður airport, on the other hand, was given low priority since there is a relatively low number of flights and in the winter, when avalanches are a hazard, there are not any flights if the visibility is low and the runway is iced over.

The mountain torrents are also given low priority since the observations of the past have clearly shown that people generally have enough time to move away from the hazard zone. The most likely reason for this: In Iceland most of the valleys are very wide so that during high runoff periods the streams flood at mid run and deposit the sediment there; furthermore there is no wood and therefore no log jams and mud piles.

For the Icelander, only unpredictable glacier floods are really dangerous (volcanic eruptions under the glacial ice), the ocean (spring tides and tsunamis), explosive volcanic eruptions and avalanches that surprise one in bed and against which there is no finding protection during periods of bad weather.

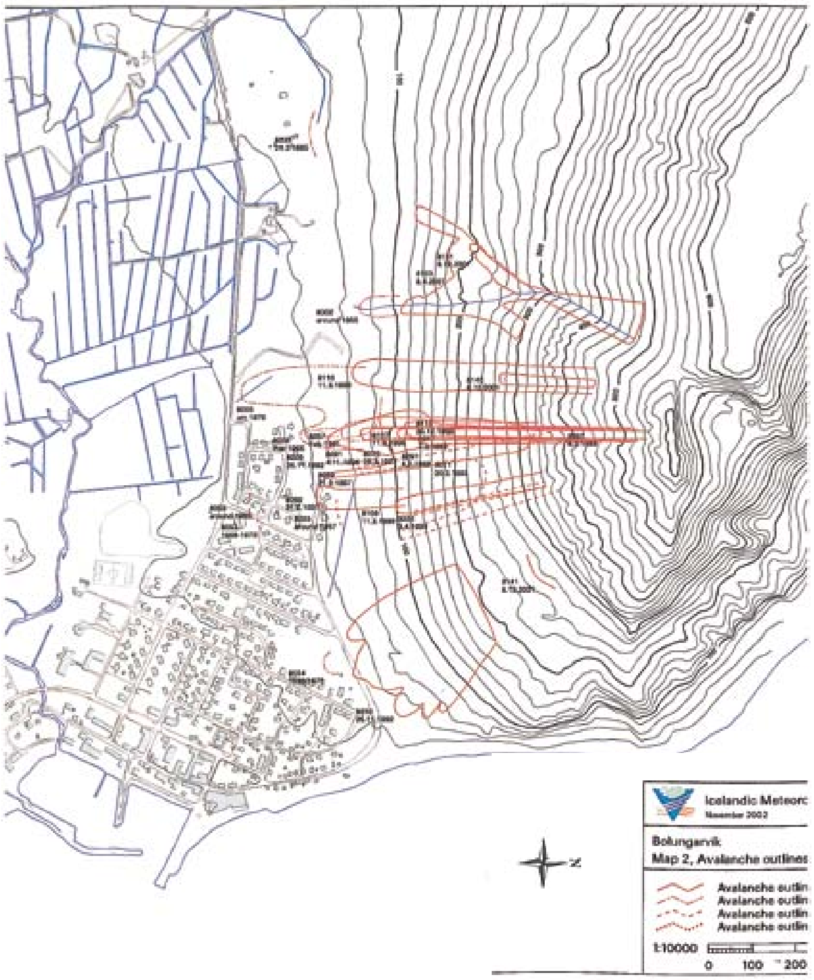

Fig. 17: Mapped avalanche run outs in the Bolungarvík settlement.

WESTFJORDS – Bolungarvík

The village of Bolungarvík has 970 inhabitants and is the northern most settlement in the Westfjords. In the years 1970, 1992 and 1997 avalanches penetrated deeply into the settled areas, as a result the red hazard zone (C-Zone) was charted deeply into the settlement area.

Due to the endangerment of a large number of people, measured are being planned here for massive avalanche control: The avalanche proneness comes from the 560 ha sized south slopes of the Bolafjalls, a very smoothly designed ridgeback without pronounced summit plateaus. The largest avalanches result from the kettle-shaped break areas under the peak.

Since the village is exposed to the avalanche hazard along 1100 linear metres, an avalanche deflecting dam could not be designed, but only an avalanche catching dam. A supplementary break off construction is not possible due to the high risk of damage from falling rocks. Due to the steepness of the terrain, only a row of break constructions could be planned ahead of the dam. Locally, discussions were held as to which effects avalanche-retarding mounds have above the avalanche barrier on a powder avalanche. In the best case they will disperse energy and reduce speed, in the worst case they will act as a jump ramp.

Fig. 18: Hazard-zone map for Bolungarvík.

However, to still achieve a high degree of safety from powder avalanches, the highest avalanche dam in Iceland is being built here with a height of 22 metres. The length of the first dam body is 700 linear metres; to the east of this a second dam body 15 metres high and with 250 linear metres will be constructed.

Viewing a professional earthwork project with stone crushers, dumpers, compactors, reinforced earth (plastic net) and sectional steel to pave the surface.

Planned construction time from 2008 to 2012; cost estimate 900 mill IK. (Icelandic crowns, €5.5 mill.)

Calculation:

- Material requirements of 400.000 m³ for the main dam (w = 52, h = 22, l = 700 linear metres)
- with expected installation costs between 12 and 15 €/m³

Fig. 19: Bolungarvík at the foot of the south-east facing slope on the 600 metre high Bolafjall. The current avalanche dam construction site can be seen in the photo.

However, these prices may vary since the economic crises in 2008 resulted in the value of the Icelandic crown dropping by more than half as compared to the euro. This also led to problems for the companies participating in the tender.

Noteworthy:

Although Iceland is a highly developed country, a large majority of the population believe in elves and trolls.

Fig. 20: Bolungarvík construction site: Construction of a 22 metre high avalanche catchment dam

Fig. 21: Compactors (left), reinforced earth and stone crushers (right) during the processing of the autochthonous material.

Fig. 22: Well-organized use of heavy equipment on the 700 linear metre long dam construction.

The enormous trolls turn to stone in the sunlight and turn into the cliffs and rock towers in the ocean. According to our tour guide at the Golden Circle - the elves are the children that Eve hid when God visited because they were unwashed and uncombed. Then - in a punishment typical of our "righteous God" - they had to live as a hidden people.

Everywhere on the island, but mainly on the Westfjords, there are symbols of these beliefs that grew in long polar nights, adverse weather conditions and strangely shaped volcanic rock, as well as on "elf hills" and artificial homes of the "hidden people".

It may be surprising, but there is actually an Elf commissioner in the Icelandic government who contacts the elves when there are problems (sick workers, accidents, etc.) and negotiates with them to that roads are diverted around any "elf hills" or - as on the building site in Bolungarvík – when elves disturbed by blasting had to be reassured so that calmness could return to the building site.

This happened - two days after our visit to the site.

This might be a blame ideology, but perhaps there is a bit more going on than we are prepared to admit - at least in Iceland.

Fig. 23: Elf hill in the settlement of Hólmavík (Westfjords).

Fig. 24: A small house for the "hidden people" – also in the Westfjords.

Fig. 25: Tourism uses: A witches house in Hólmavík in which one can purchase herbs as well as all sorts of symbolic objects.

WESTFJORDS –

The "most dangerous road" in Iceland

The connecting road from Ísafjörður via Hnífsdalur to Bolungarvík was constructed in the 50s and for a long time was considered the most dangerous road on the island. The road required cutting massively through moraine deposits and only a makeshift protection from falling rocks was constructed with wire mesh gabions.

During the journey over the closed road, there were a few worried glances cast up to the cliffs towering over our heads.

There is an extremely high danger of falling rocks throughout the entire summer season; the warmer weather in the last decade has also increased the frequency of falling rock events. There is a considerable danger of avalanches during the winter. It must be noted that even a small snow slide can push a car over the cliff and into the ocean, resulting in certain death. The road transverses a total of 20 avalanche stretches.

However, the highly endangered coastal road is still cleared and used; this is a service for everyone who is willing to take the risk. The goal is to keep the road open for tourists during

Fig. 26: The impressive landscape, but also highly dangerous coastal road from Hnífsdalur to Bolungarvík.

Fig. 27: Glacier layers and slope rubble bodies thoughtlessly cut during road construction in the 60s.

the summer as part of the scenery. However, officially the road remains closed.

Due to the extremely hazardous situation, in 2010 a 5.4 km tunnel was constructed to ensure a secure connection from Bolungarvík to Ísafjörður (Fig. 29). There are cavities throughout the natural volcanic rock, during the tunnel work from Ísafjörður to Flateyri a powerful water vein was hit which is now used and tapped as a source of drinking water.

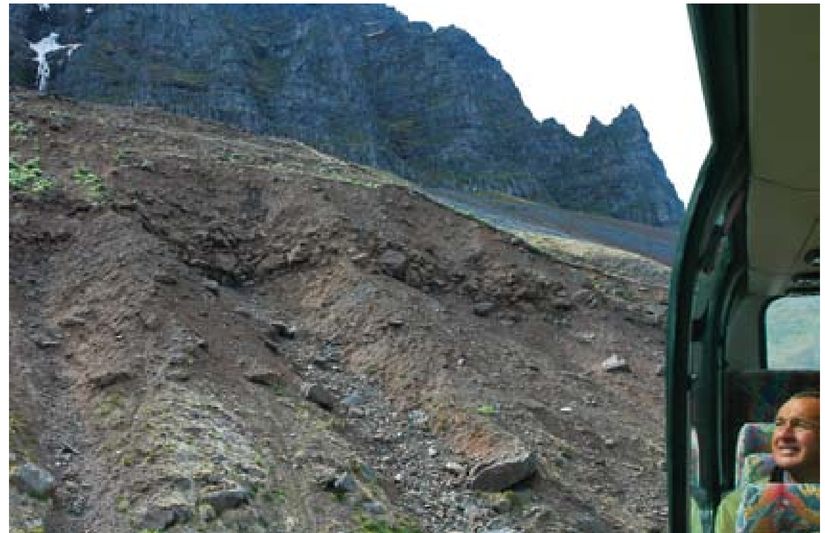

Fig. 28: Under this mass of rubble, this feeling of claustrophobia cannot be hidden - at least among the specialists.

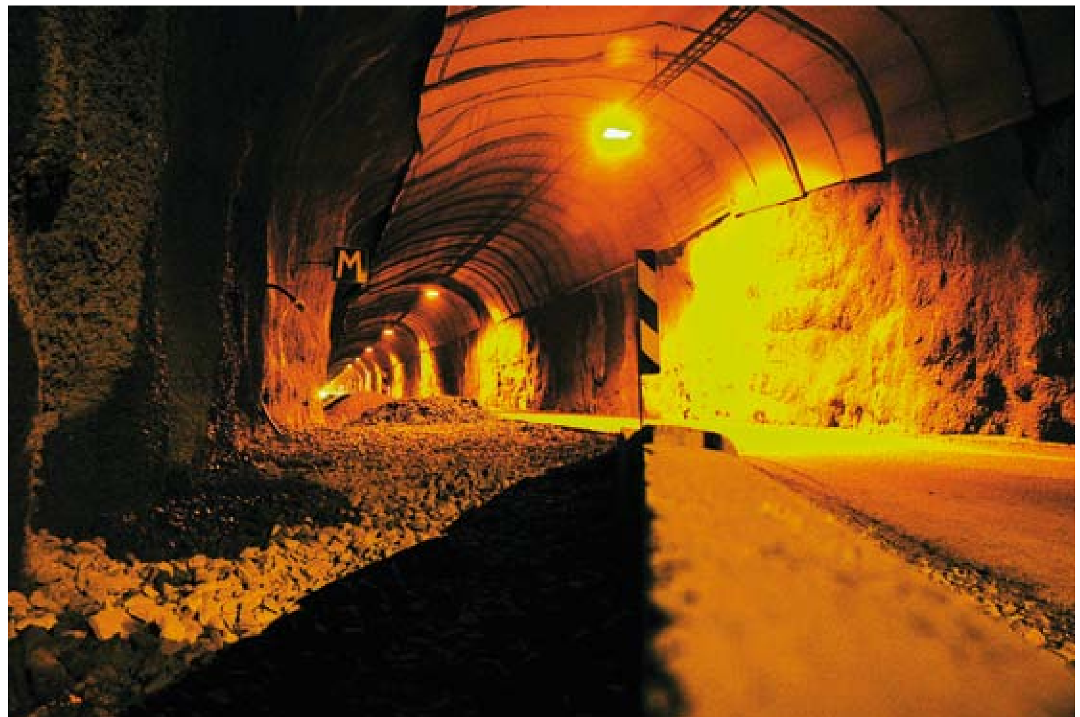

Fig. 29: The only alternative: construct a tunnel

WESTFJORDS – Flateyri

Flateyri was founded as a founded as a trade post and during the 19th century it developed into

Fig. 30: Flateyri, at the foot of a 660 metre high mesa with a large summit plateau.

Fig. 31: Flateyri: Memorial plaque for the 20 victims of the avalanche of 1995.

the regional shark and whale culling centre for the region. Today (2011) more than 237 people live in this settlement.

Above Flateyri there is a 660 metre high mesa with a 1.2 km wide summit plateau, a rich breeding ground for avalanches. The hitches are oriented to the south west, which is extremely unfavourable for the Icelandic situation and the predominant north-east weather conditions. Two break basins and the hitches located underneath them point exactly to the settled headland on which the settlement was founded.

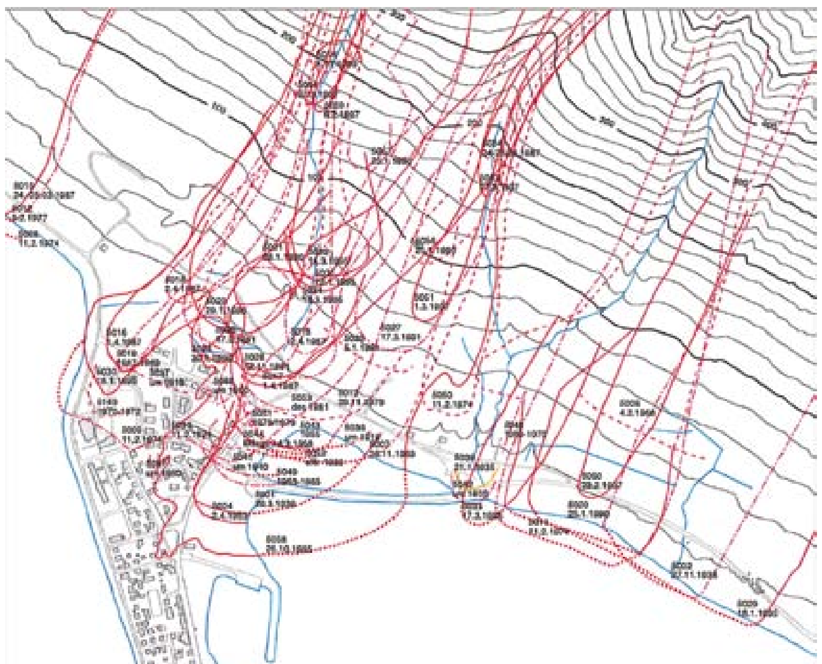

Fig. 32: Mapped avalanche run outs in the Flateyri settlement.

After several avalanches in 1936, 1953, 1963, 1972, 1974 in as in January 1995, which almost reached the existing settlements, on October 26 (!) after three days of snow accompanied by a strong wind that reached speeds of 160 km/h in the night before the avalanche, a catastrophic avalanche happened at 6:15. 430,000 m³ snow broke off of the east of the two basins; Off shoots of the avalanche penetrated deep into the headland, burying 32 homes and 54 people. Twenty people could only be found dead, 34 people survived, of these 5 were injured.

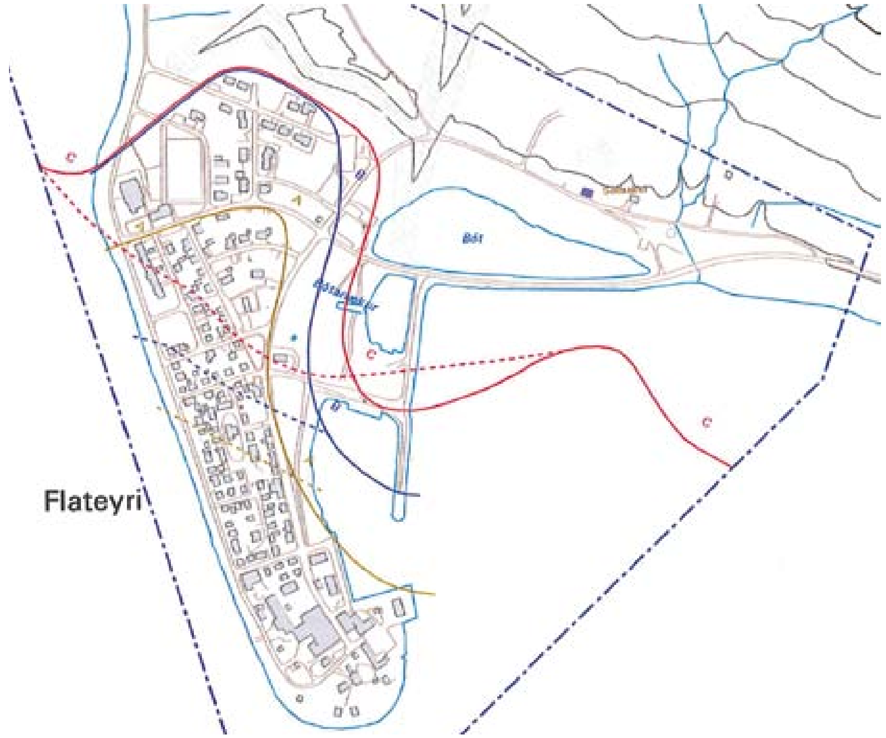

Fig. 33: Hazard-zone map for Flateyri including the protective effect of the A-shaped dams built in 1995.

Fig. 34: Eirikkur Finnur Ereigsson, the president of the community, who together with daughter and teddy bear, welcomed us to Flateyri.

Fig. 35: Emotional eye-witness report from Daniel Jakobsson, the mayor of Flateyri, who was also among the buried in 1995.

Fig. 36: The guide dam and the avalanche barrier from a bird's eye view.

During our visit in 2011, we were greeted by the mayor, Daniel Jakobsson, and the president of the community, Eirikkur Finnur Ereigsson. We heard a very emotional eye-witness report from the mayor, who had been buried himself in 1995 and only his head and one hand remained above the snow. He had to wait for rescue for over an hour in this position under a clear sky - because the roof of his house had been torn away by the avalanche.

Measures:

After the avalanche on October 26, 1995, in 1996 a tunnel was built with two lanes with passing bays in the middle, to connect Flateyri and the adjacent Fjord since the road over the pass is extremely prone to avalanches and falling rocks.

Fig. 37: The memorial with the list of deaths, the break zone of the avalanche in the back-ground.

From 1996-1998, 650,000 m³ of material was taken from above the settlement of Flateyri to build the first two large avalanche deflecting dames in Iceland. This is an A-shaped dam body, existing of two 15-20 metre high guide dams of 600 linear metres each and a catchment dam that is 10 metres high and 350 linear metres long to hold back or brake the overflowing avalanche flows.

According to the model calculations, a flowing avalanche with a speed of 15 metres per second will flow to the orographic right over the deflecting dam, be stopped by the catchment dam, but still reach almost to the church.

An avalanche of the dimension of about 100,000 m³ was held back by the dam in 1999; this had 13 metres of flow depth - there was only 5 metre reserve to the edge of the dam.

The majority of the population places a lot of trust in the barriers and accepted this with pleasure. There were differences in opinion regarding the Siberian lupin used for pavement which continues its march over the entire island.

Point of discussion:

The crown of the eastern deflecting dam appears to be a bit too deep at the critical collision location (Figure 38); this is also true for the crown of the avalanche barrier (Figure 39).

The long excursion day was completed in the "light of night" with a visit to a wonderful fish restaurant in historical Tjöruhúsið (the oldest building in Iceland) in Ísafjörður where the "Icelandic Governmental Construction Agency" invited us to dinner.

For anyone near Ísafjörður, we highly recommend this unbelievable place where ever fish offered on the buffet is better than the last.

Fig. 38: A weak point crest of the guard wall.

Fig. 39: A weak point in the catching dam – probability due to a culvert that was too short; the sea level clarifies the horizontal levels

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KARL KLEEMAYR, OTTO UNTERWEGER, TOMAS JOHANNESSON, JOSEF HOPF

Feasibility of supporting structures for avalanche protection in Iceland - Siglufjörður pilot project

Machbarkeit von Stützverbauungen zum Lawinenschutz in Island – Das Pilotprojekt in Siglufjörður

Summary:
The use of supporting structures and their design parameters under Icelandic conditions were investigated in an experimental installation of steel bridges and snow nets within a pilot project, started in the autumn 1996 above the village of Siglufjörður in northern Iceland. The maximum tension measured in upper anchors of the snow nets was approximately 350 kN while the maximum compressive force and moment in the snow net post was approximately 150 kN and 15 kNm, respectively. The maximum snow pressure on the steel bridges averaged over the whole construction was inferred to be approximately 30 kPa. The observations have been used to formulate requirements for supporting structures under Icelandic conditions based on the Swiss guidelines for supporting structures from 1990. Lessons regarding the use of snow bridges and/or nets under Icelandic conditions derived from more than a decade of observations and experience in this project are described in this paper.

Zusammenfassung:
Ab Herbst 1996 wurde in der Gemeinde Siglufjörður in Nordisland die Verwendung von Lawinenstützverbauungen und deren Design unter den lokalen Bedingungen getestet. Neben Stahlschneebrücken wurden auch Schneenetze installiert. An den oberen Ankern betrugen die maximal gemessenen Zugspannungen 350 kNm, während die max. Druckkräfte in den Stützen ca. 150 kN betrugen. Der maximale Schneedruck auf den Stahlschneebrücken betrug im Mittel über die gesamte Konstruktion 30 kPa. Die Beobachtungen dienten – neben den Schweizer Richtlinien für den Stützverbau - als Grundlage für die Ableitung der notwendigen Anforderungen. Die Erfahrungen bezüglich der Verwendung von Stahlschneebrücken und Schneenetzen unter isländischen Bedingungen nach zehnjähriger Beobachtung werden in dem Bericht zusammengefasst.

Introduction

In 1996, the Icelandic Meteorological Office (IMO) implemented a pilot project for testing the feasibility of supporting structures for avalanche protection in Iceland and for obtaining data which will be used to define an optimal setup of such structures under Icelandic conditions. About 200 metres of supporting structures, both stiff steel constructions and snow nets, were installed for experimental purposes in Hafnarfjall, above the village Siglufjörður in northern Iceland. The project is financed by the Icelandic Avalanche Fund.

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

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

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

Guidelines for supporting structures in Alpine countries specify different snow loading on the structures depending on height above sea level and aspect of the slope through a so-called height factor and a higher value of the gliding factor in ENE-S-WNW exposed slopes compared with WNW-N-ENE exposed slopes (cf. EISLF, 1990). Wet snow metamorphosis and wind packing in the wet and windy Icelandic climate may be expected to lead to more uniform densification of the snow pack in Iceland compared with the continental climate of Alpine countries. Starting zones of avalanches that threaten inhabited areas in Iceland are, furthermore, in the narrow altitude range 300-700 metres above sea level and there are no indications of a variation in density, gliding or snow loading with height above sea level or aspect of the slope in Iceland. Strength requirements for supporting structures in Iceland should be such that irrelevant variations with height above sea level and aspect of the slope are not imposed. Apart from this, traditional formulations for snow loading of supporting structures, which are used in Alpine countries, appear to be adequate for Icelandic conditions when proper account has been taken of the higher snow density and the lower gliding in Iceland, as will be further described below. In addition to the different conditions with regard to snow density and gliding described above, extreme snow depths in many starting zones in Iceland may be expected to pose serious problems for supporting structures under Icelandic conditions. As a consequence of frequent snow drift in the windy Icelandic climate, snow depth in starting zones in Iceland is often quite non-uniform. The snow accumulates preferentially in depressions and gullies, where vertical snow heights in excess of 6 metres are common, even in average winters, whereas the snow depth on ridges and concave parts of the starting zones remains low throughout the winter. One may expect that supporting structures are impractical due to extreme snow depths in many important starting zones above inhabited areas in Iceland for this reason. This problem is not unique to Iceland, as similar problems are sometimes encountered in high altitude avalanche starting zones in Alpine countries.

Another problem in connection with the snow depth in starting zones in Iceland is that it is in general difficult to estimate an appropriate design snow depth for supporting structures due to lack of long term snow depth measurements. Snow depth measurements in starting zones of avalanches in Iceland have only recently been started (Sigfússon and Jóhannesson, 1997; Kiernan and others, 1998), and it will take some time before estimates of long term maximum snow depths in the relevant starting zones become available. Corrosion conditions in Iceland are more severe than in Alpine countries and supporting structures for Icelandic conditions must be designed with due regard to these conditions. Observations of supporting structures in Audbjargarstadabrekka, Ólafsvík and Siglufjörður in Iceland and a compilation of relevant information about corrosion protection of steel structures in Iceland is described in the report by Sigurdsson, Jóhannesson and Sigurjónsson (1998).

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

The following report describes observations of snow height, snow density, gliding and the loading of the supporting structures in

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

Supporting structures in Siglufjörður

The supporting structures of Siglufjörður are located at 490-530 metres above sea level. The structures are arranged in four rows which are labeled I, II, III and IV from above (Figure 1).
The types of structures in each row are given in Table 1:

Installation

Between August 21 the and September 26 the 201.5-metre supporting structures were installed. The main part of anchor drilling was rock drilling under varying conditions and only 15% had to be carried out in loose material. A part of the snow bridges from Martin was damaged in a storm shortly after the installation of the structures in the fall of 1996. This was repaired by drilling anchors through the ground plates of all the posts that are mounted on ground plates. Mistakes were made in the installation of 5 posts in the Geobrugg net line, which are founded on micropiles in loose material, and these posts failed during the first winter. This was repaired in the fall of 1997

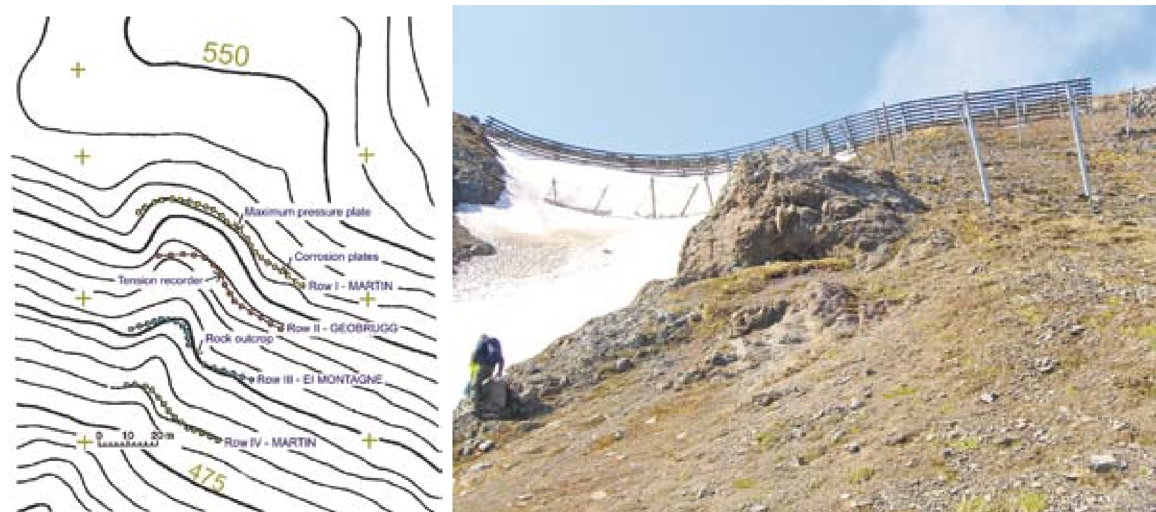

Fig. 1: Location map of the supporting structures in Siglufjörður showing the location of the upper anchors in each row together with the placement of measuring instruments in the rows.

Row	Type	Producer	Length (m)	Number of posts	Heigth Dk (m)	Cost (kIKR/m)
I and IV	bridges	J. Martin	110	38=24+14	3-5	161
II	nets	Geobrugg	50	14	3-4	156
III	nets	El Montagne	41.5	15	3-5	158

Tab. 1: Types of structures

Fig. 2: Uppermost row of J. Martin snow bridges. The line is adapted to the curved terrain. Plates for measuring maximum snow pressure are seen on the left side.

by replacing the micropiles of these posts with ground plates. No damages of the structures occurred during the following winters.

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

Load Measurements

Tension in three upper anchors of the snow nets, and compressive forces and moment loads in one net post have been measured with continuously recording instruments. Maximum pressure at different height levels in the steel bridges has been measured with maximum pressure plates with an area of 0.5 m^2 (Fig. 2). Snow thickness in the test

Fig. 3: The snow bridges are designed for snow heights up to 7 metres

Fig. 4: An instrument for measuring tension in the Geobrugg net row (left) and a broken top loop in a wire rope anchor from the same row (right).

area, snow density and gliding of the snow pack, as well as corrosion of the structures, have also been monitored.

The height of the highest steel structures in a part of row I is up to Dk = 5 m, which corresponds to a vertical snow depth of more than 7 metres (Fig. 3). This part of the row has been overfilled several times by up to more than 2 metres (!) without this leading to any detectable damage of the structures. Figure 4 (left) shows

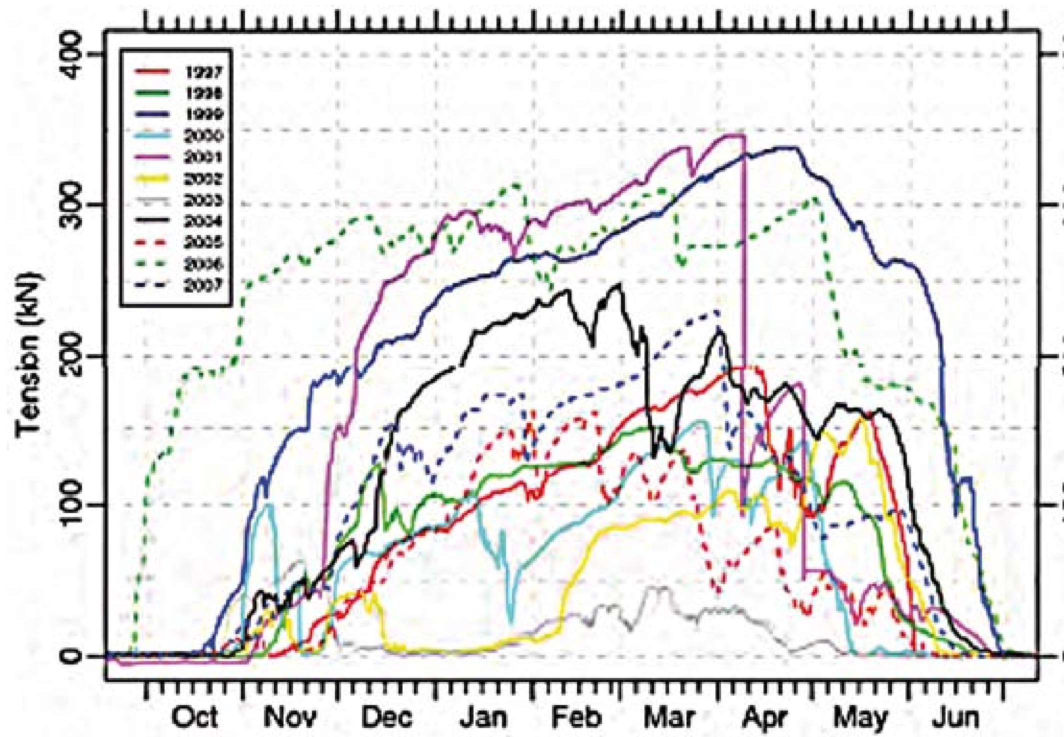

Fig. 5: Measured tension in an uphill anchor in the Geobrugg and El nets in Siglufjörður from eleven winters, 1996/1997 to 2006/2007. Note that a d-link shackle connecting the instrument to the anchor broke in the winter 2000/2001 resulting in the abrupt drops in the tension for the curve from that winter.

a part of the Geobrugg net line with a tension instrument in one of the upper anchors. Strain recording instruments are located in one of the posts below. This part of the nets has also been repeatedly overfilled by up to 2 metres, which in the end led to a break of one of the upper anchor wire ropes as seen in Figure 4 (right). The experience with the overloading of the structure indicates that the steel bridges have greater reserve strength to withstand local overloading without damage. The flexible net structures have not withstood the overloading as well.

Figure 5 shows the tension recorded by one of the two instruments in rows II for the eleven winters since the start of the experiment. The tension increases with increasing snow depth in the early part of the winter and typically reaches a maximum between 150 and 350 kN in March to April. The maximum tension varies from year to year, depending mainly on the maximum snow depth of the winter. The onset of melting, typically in the beginning of May, leads to a sharp decrease in the tension. There are no indications of an increase in the loading due to deformation or gliding introduced by melting.

Figure 6 shows the compressive force and the moment from the winter 1997/1998 computed from the strain recorded by four vibrating wire sensors that are mounted about 1 metre above the ground on a post in the Geobrugg nets in row II. The maximum force and moment of the winter are found to be 160 kN and 19 kNm, respectively.

The measured tension in the upper anchors of the nets appears to be within the design assumptions of the Swiss Guidelines. The moment load is, however, considerably higher than assumed in the guidelines. The guidelines give a design moment load of only 5.7 kNm when allowance has been made for the high density of the Icelandic snow. This is less than one third of the measured maximum moment in Siglufjörður. The guidelines are based on the assumption that the snow pressure on the post is given by the depth-averaged snow pressure on the construction applied over the width and length of the post. In practice, the effective width of the post may be expected to be substantially larger than this because the post will support more snow than corresponds to its width.

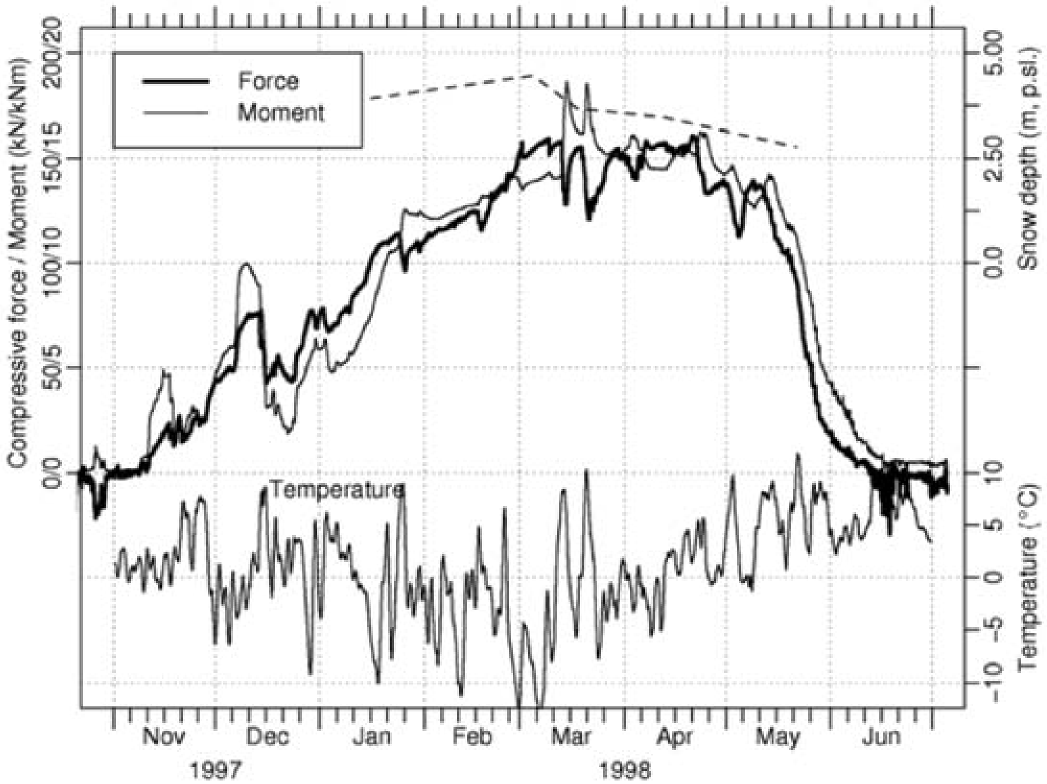

Fig. 6: Compressive force (kN) and moment (kNm) in a post in the Geobrugg nets in row II in Siglufjörður. Wiggles in the force curve near the beginning and end of the record are due to differential heating of the post by the sun on clear days.

Conclusions

The pilot experiment in Siglufjörður has provided many lessons for the design of supporting structures for Icelandic conditions after more than a decade of observations. The main conclusions may be summarized as follows.

Snow properties

The gliding of the snow pack along the slope was found to be low, only several cm during the winter. Reference values for snow density during maximum snow pack thickness (400–450 kg/m^3) and for spring loading with a higher density (500 kg/m^3) were determined.

Loading

Measured loads on the structures were, in general, within the corresponding design loads of the Swiss guidelines from 1990, with the exception of the moment load on net posts which turned out to be substantially larger than assumed. The maximum loading of the structures occurred around the time of maximum snow depth. The onset of melting led to a sharp decrease in the loading. There were no indications of an increase in the loading due to deformation or gliding introduced by melting.

Reliability and performance under overloading

There have been much more damages in the rows of the snow nets than the steel bridges due to overloading of a similar magnitude as described above. The continuous rows of the steel bridges with a varying structure height were better adapted to the terrain and to local variations in snow depth than the snow nets. Furthermore, the continuous rows of the steel bridges provide much better lateral stability than the snow nets. Lack of lateral stability appears to be an important failure mechanism for some of the damages that have been observed in the snow nets. For this reason, the stiff steel constructions appear to be able to survive more overloading than the nets without damage. Failure of net posts with micropile foundations in loose materials and of snow nets with narrow post spacing has provided valuable experience about the proper design of supporting structures for the heavy loads experienced in Iceland. This experience indicates that the steel bridges have greater reserve strength to withstand local overloading without damage and that maintenance costs due to failure will in general be higher for snow nets than for steel bridges.

Corrosion

Serious corrosion problems have been encountered in all wire ropes in the Geobrugg and EI nets, indicating that corrosion protection of wire ropes traditionally used in Alpine snow nets are unsuitable for Icelandic conditions. These problems are very serious and hard to solve. It is recommended that steel bridges be generally

Fig. 7: Comparison of galvanized and black type of snow bridges in the lowest row of the J. Martin snow bridges (left). The row with El snow nets was deformed by the heavy snow loads, partly due to lack of lateral stability.

hot-dip galvanised for Icelandic conditions. The experience in the test area indicates that, with that type of protection, corrosion is not a problem for steel bridges.

Environmental

Undoubtedly the landscape is less interfered with using nets than when using snow bridges, especially if those are not galvanized. In time the galvanization leads to a gentle grey colour, well adapted to the Nordic environment, especially during winter, as can be seen after ten years in the test area. Also for that reason the use of black steel should not be an option for supporting structures in Iceland.

Recommendations

An important result of the pilot project is that traditional formulations for snow loading of supporting structures, which are used in Alpine countries, appear to be adequate for Icelandic conditions with relatively small modifications when proper account has been taken of the higher snow density and the lower gliding in Iceland. An adaptation of the Swiss Guidelines for Icelandic conditions has thus been formulated (Jóhannesson and Margreth, 1999; Jóhannesson, 2003). As a consequence of the problems that have been encountered with snow nets, a formal recommendation has been made to communities in avalanche-prone areas in Iceland that steel bridges are in general a more suitable type of construction unless special circumstances need to be taken into account (Jóhannesson, 2004).

The pilot project is showing us in a very clear way that the rest risk of the snow nets is too high. It is not possible to predict how long the snow nets are static in good condition. The possibility of a sudden break down will always exist. And this is - in our opinion – too much risk for the security of the inhabitants below the supporting structures. Controlling the static stability of steel bridges is comparatively simple. The Austrian experiences (more than 5 decades) in building snow bridges with little damages confirm our opinion to recommend this system. We have only poor knowledge about the durability of snow nets and the costs of both systems are nearly the same. Especially for the Icelandic conditions the odds are on side of the snow bridges.

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Hazard mapping in Iceland and Austria - a comparison

Gefahrenzonenplanung in Island und Österreich – Ein Vergleich

Summary:
Both in Iceland and in Austria, hazard mapping represents an important instrument for the preventive protection of gravity-caused natural hazards. In the course of the study trip in Iceland we got a detailed view of risk assessment in hazard zoning mapping for avalanches in Iceland. We discussed the differences from Austrian hazard zoning mapping, which is referred by probabilities of return periods.

In this report the basic intention and differences of Austrian and Icelandic avalanche hazard mapping will be presented.

Zusammenfassung:
Sowohl in Island als auch in Österreich stellt die Gefahrenzonenplanung ein wichtiges Instrument zum vorbeugenden Schutz vor gravitativen Naturgefahren dar. Im Zuge der Studienreise in Island konnten wir einen detaillierten Einblick in die risikobezogene Gefahrenzonenplanung in Island für den Bereich Lawinen gewinnen und die Unterschiede zur österreichischen, auf Wiederkehrwahrscheinlichkeiten bezogenen Gefahrenzonenplanung diskutieren.

In diesem Bericht werden die Grundzüge der österreichischen und isländischen Lawinengefahrenzonenplanung dargestellt und deren Unterschiede gegenübergestellt.

Hazard mapping in Iceland based on individual risk

Introduction

Iceland is located in the North Atlantic Ocean in an area of high cyclone activity. The climate and the mountainous landscape are the cause of frequent avalanches in many areas of the country. BJÖRNSSON (1980) describes the general avalanche situation in Iceland.

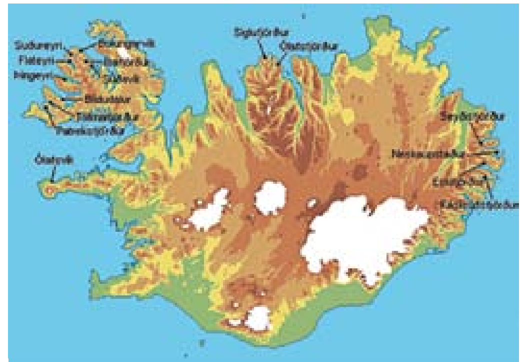

Fig. 1: The most important villages in Iceland, which are threatened by avalanches

Since Iceland was settled in the 9th century many fatal accidents caused by avalanches and landslide have taken place. The first chronicled accident was 1118 when an avalanche killed 5 people in western Iceland. Since the year 1851 a total of 307 persons were killed by avalanches and landslide accidents. A total of 90 of these fatalities occurred in 5 accidents in small villages where 12 or more people were killed in each accident (ARNALDS et al., 2004).

Fig. 2: On October 26, 1995 an avalanche from Skollahvilft pushed far into the residential area where 29 houses were damaged or destroyed and 20 people killed. The church was not damaged.

Two fatal accidents in Icelandic villages caused 34 fatalities in 1995. This catastrophe led to a discussion of what is acceptable in terms of avalanche risk in homes. A new method for risk-based hazard mapping was developed in the following years, and new laws and regulations were enacted.

Acceptable level of avalanche risk in Iceland

Following the 1995 accidents there was a discussion in Iceland about what is acceptable in terms of avalanche risk in settled areas. Although the economic loss due to avalanches in Iceland has

Fig. 3: Flateyri in 2011, with the two big deflecting dams and the catching dam in the background.

been significant (JOHANNESSON and ARNALDS, 2001), it was decided that the loss of human lives should be a dominant factor when considering the acceptability of risk for the society. The criterion in the hazard mapping regulation is individual risk, measured as the annual probability of being killed in an avalanche if one lives or works in a building under a hazardous hillside. The building is assumed to be a fairly weak timber or concrete house with relatively large windows facing the mountainside. The reference value of exposure is 75% for living houses but 30% for work places. One of the advantages of using individual risk as criterion is that the avalanche risk can then be compared to other sources of risk such as traffic or diseases. In Austria or in other European countries, return periods of avalanches are traditionally used as a criterion for hazard mapping. In Iceland it is not possible to discuss what is acceptable in terms of return periods without thinking in terms of risk. "At a first sight, it may seem that a place where the return period of avalanches is on the order of 150 years is acceptable for building a house. However, living in a house in such a place would cause the avalanche risk to be by far the greatest source of risk in life, especially for children and younger people. The annual probability of death due to avalanches would, for many people, greatly exceed the annual probability of dying in a traffic accident or dying from common diseases such as cancer or cardiovascular diseases" (GRIMSDOTTIR, 2008).

The Icelandic regulation states that for living houses, a (nominal) risk level of $0.3*10^{-4}$ is acceptable assuming 100% exposure and $1*10^{-4}$ is acceptable for work places (ICELANDIC MINISTRY FOR THE ENVIRONMENT, 2000). Assuming 75% exposure, the avalanche hazard on the acceptable risk line will add $\sim 0.2*10^{-4}$ or 11% to the death rate of children. Thus, it has been formally decided that it is not politically acceptable to have avalanche risk in houses as one of the main sources of risk in people's lives.

According to WILHELM (1997) it can be assumed that risk due to avalanches is mostly voluntary during activities such as backcountry skiing or ice climbing, and it is mostly involuntary for residential areas. Research indicates that the acceptable risk in society is low for involuntary and uncontrollable risks (FELL, 1994), which supports the decision of a low level of acceptable risk in the Icelandic hazard mapping regulation.

Hazard mapping criteria

Three different hazard zones are defined on hazard maps according to the regulation (ICELANDIC MINISTRY FOR THE ENVIRONMENT, 2000). Isorisk lines mark the boundary between the zones:

Zone	Lower level of local risk	Upper level of local risk	Buildings restrictions
A	$0,3*10^{-4}$ per year	$1*10^{-4}$ per year	Houses where large gatherings are expected, such as schools, hospitals etc., have to be reinforced.
B	$1*10^{-4}$ per year	$3*10^{-4}$ per year	Industrial buildings may be built without reinforcements. Homes have to be reinforced and hospitals, schools etc. can only be enlarged and have be reinforced. The planning of new housing areas is prohibited.
C	$3*10^{-4}$ per year	-	No new buildings, except for summer houses (if the risk is less than $5*10^{-4}$ per year), and buildings where people are seldom present.

Tab. 1: Iceland hazard zone definition

A- Zone:

The local risk assuming 100% exposure is 0.3-1.0 of 10,000. Note that the lower limit is the boundary of acceptable risk when assuming 75% exposure. Therefore, the risk below the A-zone is considered acceptable, even though it is not zero and should therefore not be referred to as a "safe zone". In areas that are previously unsettled, buildings should only be constructed where the risk is acceptable. In already settled areas, single houses and work places can be built in A-zones. Schools, hospitals, apartment buildings and other such buildings should be reinforced.

Fig. 4: Several recorded avalanches from Flateyri and their dates (solid line: certain, dashed-and-dotted line: inaccurate, dashed line: unknown, dotted line: sea).

B- Zone:

The local risk is 1.0-3.0 of 10,000. Working places can be built, but living houses should be reinforced. Schools and such buildings are not allowed.

C-Zone:

The local risk is higher than 3.0 of 10,000. It is only possible to build structures were people are not living or working. Where existing houses are in C-zones, the local authorities are required to make plans for permanent defence measures with the aim of reducing the avalanche risk to near the acceptable level. During the last 10 years, dams, breaking mounds and supporting structures have been installed above many avalanche prone villages in Iceland. In some areas, houses have been relocated. However, there is still a long way to go to complete the project to protect all settlements in C-Zones.

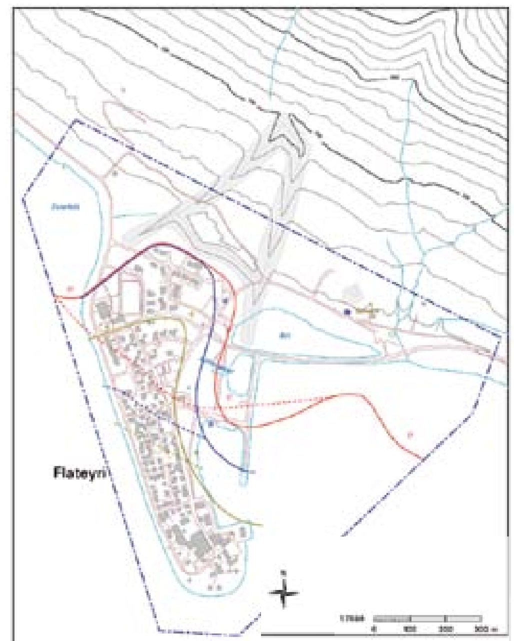

Fig. 5: The hazard map for Flateyri before and after the construction of two deflecting dams.

The ideology behind the Icelandic risk method

In order to estimate avalanche risk, both hazard potential and vulnerability should be taken into account as well as the exposure of the individual. In the Icelandic risk model, the frequency of avalanches is estimated as along with the run-out distribution of avalanches. Vulnerability is represented by the probability of being killed if staying in a house that is hit by an avalanche. This was estimated using data from the avalanches of Súðavík and Flateyri, comparing the calculated speed of the avalanche to the survival rate. The exposure is the proportion of the time that a person is expected to spend within the hazard-prone area (ARNALDS et al., 2004; JONASSON et al., 1999). If acceptable risk as defined by Icelandic regulation is to be reached, the return period of avalanches has to be on the order of several thousand years. Since the known avalanche history of each avalanche path does usually not reach far back, it is impossible to base the frequency estimation of long avalanches on local history alone. By combining the avalanche history of many paths with comparable terrain and weather conditions, one may, however, imagine that one path has been observed for a long time rather than many paths for a short time (JONASSON and others, 1999). To make this possible, one must be able to tell how far an avalanche that has fallen in a given path would reach in another path. Different models could be used for this purpose, for example topographical models such as the Norwegian alpha-beta model (LIED and BAKKEHOI, 1980) as well as the run-out ratio method of MCCLUNG and MEARS (1991). For hazard mapping in Iceland, physical models have been used for transferring avalanches between paths, which is a concept developed in SIGURDSSON et al. (1998). By transferring avalanches in a data set to a standard path with the PCM model (PERLA et al., 1980), the statistical distribution of avalanche run-out has been estimated. Run-out indices have been defined based on the horizontal distance in the standard path. The run-out indices have proven to be a useful tool in hazard mapping. For details regarding the methodology refer to JONASSON et al. (1999), and ARNALDS et al. (2004). The newest development of the Icelandic hazard mapping methods includes the utilization of 2D avalanche models, which have been developed in recent years. The Austrian SamosAT model has been in use at IMO for some years and systematic methods for using it as one of the tools for hazard mapping are being developed. A 2D standard path has been defined and the concept of run-out indices has been expanded to two dimensions (GISLASON, 2008).

Hazard mapping in Austria

Legal Basis

Hazard zoning was started in Austria around 1970 by the Austrian Forest Technical Service for Torrent and Avalanche Control and regulated officially in the Forest Law in 1975. The details concerning Hazard Zone Plans were settled in a decree by the Federal Minister of Agriculture and Forestry in 1976.

Beyond these federal regulations, executive rules concerning hazard zones are held in provincial laws for land use planning. These laws generally state that areas at risk from natural hazards like floods, avalanches, debris flows, rock falls or landslides cannot be defined as development areas.

The hazard zone maps have to be observed by local authorities in the relevant decisions.

Fig. 6: Section of a hazard map in Austria

Hazard Map Content

Under the 1976 decree, the Hazard Zone Plans for avalanches and torrents have to be prepared by the Federal Forest Technical Service for Torrent and Avalanches Control and are available free of charge to the communities.

A Hazard Zone Plan is worked out normally for an area of one community and consists of a cartographic and a textual part.

The cartographic part includes two types of maps, the hazard maps (scale of 1:10.000 – 1:50.000) with all relevant catchments, an overview of the whole community area, important details, … and the hazard zone maps (scale: 1:2.000), showing the results of investigated and evaluated data for each hazard in the form of "Hazard Zones" on the basis of a return period of approximately 150 years for torrential floods and avalanches. The map also includes the land register and often aerial images of the surface.

The textual part consists of description of the basic data, the arguments of valuation and arguments for the hazard zoning.

In the hazard zone maps, there are two different hazard zones for torrential floods, debris flow and avalanches:

The Red Hazard Zone

This includes areas at risk from torrential floods or avalanches to such an extent that their permanent use for settlements, infrastructures or traffic facilities is not possible. The red hazard zones also include less, but more frequently, endangered areas. The criterion for the delimitation of a red avalanche hazard zone is a pressure criterion. When an avalanche pressure of over 10 kN/m² is to be expected from an avalanche with a return period of approximately 150 years or less, the criteria for a red avalanche hazard zone has been met.

The Yellow Hazard Zone

This hazard zone covers areas with reduced danger between the red zone and the boundaries where the damaging effects of the design event with a return period of approximately 150 or 100 years come to an end. This means an avalanche pressure between 10 kN/m² and 1 kN/m².

In the yellow zone buildings and infrastructures are allowed to be built but they must be protected by reinforcements and special architectural design. People in new buildings should be safe, but outside they are still at risk.

Protection woods, that need special treatment to sustain the protection function, areas for flood retention, etc. and areas that are needed for future protection work, are summarized in blue areas

For rock fall or landslide hazard, a brown indication area is delineated.

Violet indication areas have special morphological protective effects.

Procedure of the Hazard Zoning

There are some methods in use for hazard zoning:

(1) Historical method

This means that all data from historical events has to be collected and evaluated. This would be written in old newspapers or historical archives as well as "silent witnesses" along an avalanche path or the experiences of old people in the locality such as on farms, foresters, etc. Hazard indicators, also known as "silent witnesses", are for example the pattern of vegetation, damage to houses and so on.

(2) Run out calculation (in the past)

When avalanche hazard mapping started in the seventies, the use of avalanche run-out models was limited to the analytic VOELLMY-SALM model. This model was widely used in alpine countries but the use was restricted to the flowing part of avalanches.

(3) Computational models in use (in present)

- First is the Topographical landscape model (LIED, BAKKEHOI, WEILER, HOPF, 1995) – the α/β-model is based on the Norwegian model developed by LIED and BAKKEHOI (1980). It is adapted to an Austrian dataset consisting of well-documented maximum run out distances in 80 avalanche paths.
- One-dimensional numerical dense snow avalanche dynamic model, called AVAL-1D (CHRISTEN, BARTELT, GRUBER, ISSLER 1999). This model was developed in Switzerland and it follows the classical analytical Voellmy-Salm model which has been applied for several years in Austria in the setting Salm, Burkhard, Gubler (1990) .
- Two-dimensional numeric dense-snow avalanche dynamic model ELBA+ (VOLK, KLEEMAYR 1999, 2005). The avalanche simulation model ELBA+ was developed in the initial form at the University of Natural Resources and Applied Life Sciences in Vienna and it is mainly designed for application in risk analysis.
- Three-dimensional powder snow-dense snow model SAMOS AT (SAMPL, ZWINGER, KLUWICK 1999, HAGEN, HEUMADER 2000, SAMPL 2007). The computer grogram SAMOS was developed in the first form by AVL in cooperation with the Austrian Service for Torrent and Avalanche Control, the Austrian Institute for Avalanche and Torrent Research and the University of Technology in Vienna. The model can describe the formation of powder snow avalanches from the dense flow part of dry avalanches and hence is able to capture the whole range of mixed dry avalanches from pure dense flow to pure powder snow avalanches.

There are also some models in use for torrential floods and rockfall. The determination of run-out distances and forces of debris flows is presently done by subjective judgement based on historical data and personal experience.

Comparison of the different hazard zoning approaches

In Iceland, as in Austria, hazard mapping started after big avalanche accidents in the last century. The first avalanche hazard maps in Iceland were made shortly after the avalanche accidents in Neskaupstaður in 1974 by local governments. Hazard zoning started in Austria around 1970

by the Austrian Forest Technical Service for Torrent and Avalanche Control and after a view years it was regulated with the new Forest Law of 1975. The first hazard maps in Iceland, based on legislation, were made in 1985.

In Iceland and in Austria, hazard zone maps were mainly made for settlement areas. In both countries the hazard maps are used for land use regulation and the planning of protection measures. The common intention is to protect human settlement and lives.

A major difference between Iceland's and Austra's avalanche hazard maps lies in the planning criteria.

In Austria the delineation of hazard zones is based on the avalanche pressure. The size of the event is based on the estimated frequency of snow accumulation in starting areas in a special return period (of 150 years). This can be calculated approximately using data from meteorological stations. The second step is to calculate the velocity, the run-out area and other criteria using physical models and finally to fix the pressure zone of the design event for a 150-year return period.

The red zone in the Austrian hazard maps indicates an avalanche pressure over 10 kN/m², and the yellow zone shows the area with avalanche pressures from 1 to 10 kN/m². New houses may not be built in the red zone, houses in the yellow zone houses must be reinforced.

In Iceland it was decided that the loss of human lives should be a dominant factor. Therefore it was decided to base the Icelandic hazard zoning regulation on individual risk. The annual probability of dying in a house due an avalanche must be not higher than that of dying in a car accident. Hazard potential and vulnerability

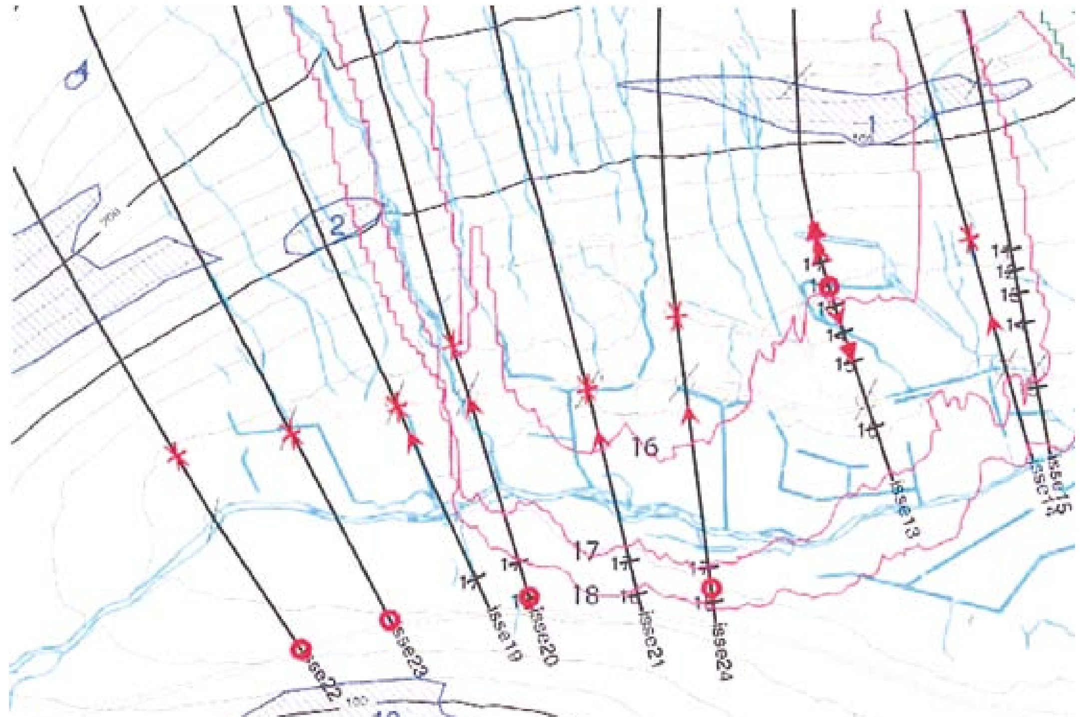

Fig. 7: Comparison of 1d and 2d run-out indices based on simulations with a modified PCM Flow-line model and SAMOS AT (GISLASON, 2008)

should be taken into account as well as the exposure of the individual. The frequency of the avalanche is estimated as the run-out distribution of avalanches, the vulnerability is represented by the probability of being killed if staying in a standard house that is hit by an avalanche. The death probability depends on the avalanche speed.

The C-ZONE in the Icelandic hazard maps represents a risk higher than 3.0 of 10000, in the B-ZONE it is 1-3 and in the A-ZONE 0.3-1 of 10000. New houses may not be built in the C-ZONE, houses in the A-ZONE and B-ZONE must be reinforced.

Although the criteria are quite different, the methods to get the danger-zones are to a degree nearly similar.

The historical method is used in Austria as well as in Iceland. In many cases there are not enough historical events or in some cases no avalanche events are documented.

Geomorphological analysis of the avalanche path is another factor in the investigation of the danger zones. In many cases the topography of the avalanche paths in Iceland is a little bit easier than in Austria. The Icelandic system uses a standard avalanche path and run-out index concept. The flow-line models consider the geometry of the path in the downstream direction. This might be sufficient in an unconfined mountainside, but topographical features such as gullies and ridges have an influence on the avalanche ranges.

Computational models for run-out calculation are used in Austria as well as in Iceland to estimate the range and the shape of avalanches. Since the year 2000, two-dimensional models have been used in Iceland to calculate the run-out ranges. Two-dimensional models do not rely on a single longitudinal profile but simulate the flow on a three-dimensional surface, representing the actual landscape. The result is a two-dimensional run-out distance, which is more precise than interpolated points of individual flow-line-models.

In Iceland the alpha-beta model (LIED and BAKKEHOI, 1980), the run-out ration method of MCCLUNG and MEARS (1991), the PCM model (PERLA et al. 1980) and the SamosAT model (SAMPL, ZWINGER, KLUWICK, 1999, HAGEN, HEUMADER, 2000) are used now, to abstract the complex dynamic of the avalanches.

In Austria the AVAL1d-Model (CHRISTEN, BARTELT, GRUBER, ISSLER 1999), the alpha-beta model (LIED and BAKKEHOI, 1980) modified by (WEILER and HOPF, 1995), the ELBA model (VOLK, KLEEMAYR, 1999), the SamosAT model (SAMPL, ZWINGER, KLUWICK, 1999, HAGEN, HEUMADER, 2000) are used and the RAMMS model (SLF, CHRISTEN et al. 2010) is being tested.

2d-models can provide a good overview in rural areas without historical data and comparison of avalanche conditions from one place to another. Erikur GISLASON (2008) believes these models are good for studying the avalanche motion and the effect of deflecting dams can be assessed with 2d-avalanche models.

After all, the experience of experts is essential for interpreting the results of all models, geomorphological and historical data. In Iceland, the IMO (Icelandic Meteorological Office) is responsible for the hazard zoning and most aspects of avalanche works. In Austria, the Austrian Forest Technical Service for Torrent and Avalanche Control creates the hazard maps.

It was a great pleasure for us to meet the Icelandic colleagues and to see the very interesting Icelandic avalanche path in a great landscape.

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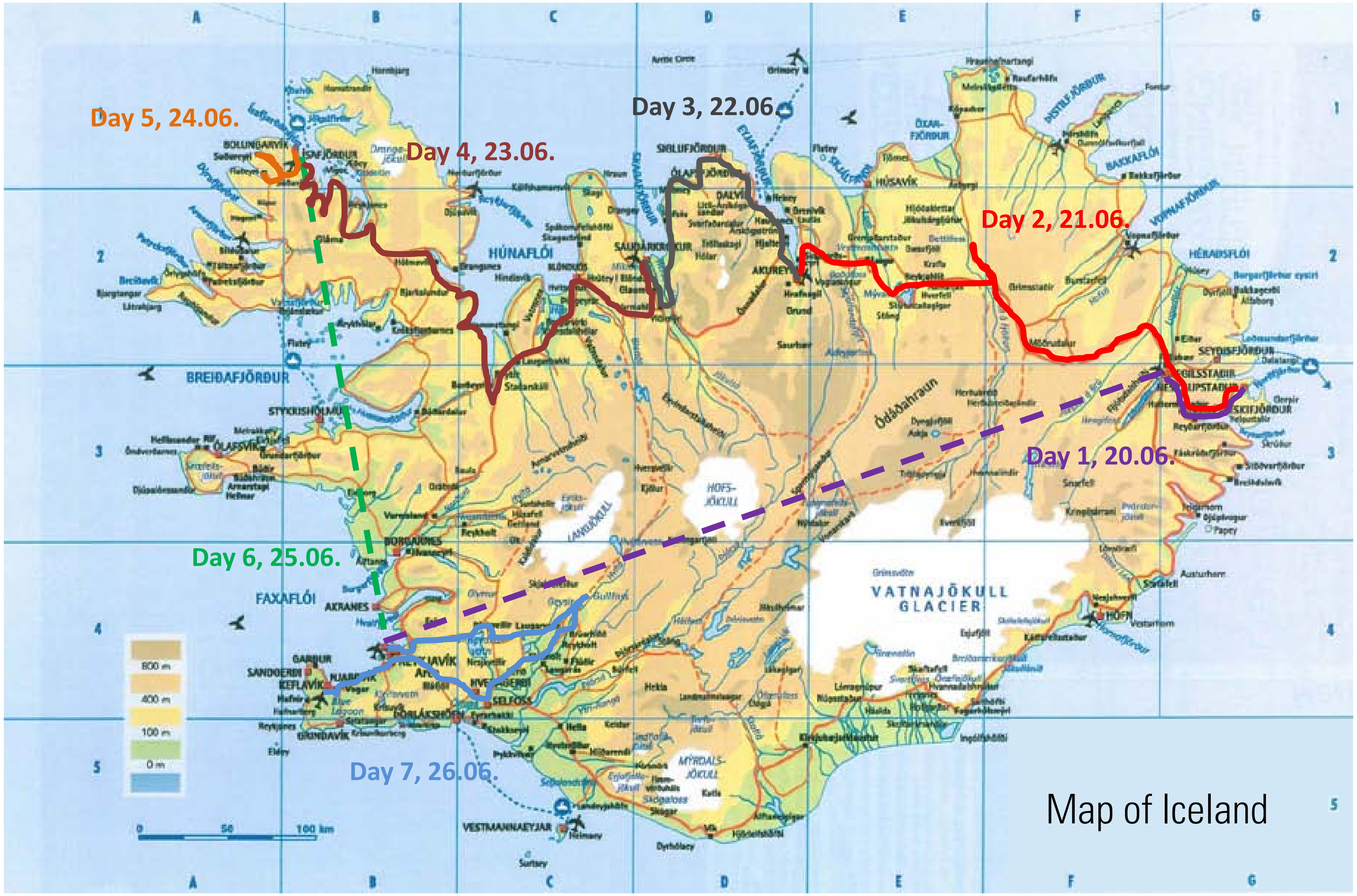
Route of field trip



Monday, June 20, 2011

Reykjavik – Egilsstaðir (flight), Egilsstaðir – Areyjardalur – Eskifjörður - Neskaupstaður

Tuesday, June 21, 2011

Neskaupstaður – Egilsstaðir – River Jökulsa – Dettifoss- Krafla (Geothermical Powerplant) – Namafjall – Lake Myvatn –Godafoss - Akureyri

Wednesday, June 22, 2011

Akureyri – Olafsfjörður – Siglufjörður – Sauðarkrokur

Thursday, June 23, 2011

Saudarkrokur – Blönduos – Holmavik – Reykjanes – Súðavik - Ísafjörður

Friday, June 24, 2011

Ísafjörður –Hnifsdalur – Bolungarvik – Osvör museum – Flateyri - Ísafjörður

Saturday, June 25, 2011

Ísafjörður – Reykjavik (flight)

Sunday, June 26, 2011

Reykjavik – Thingvellir – Geysir – Gullfoss – Skalholt – Blue Lagoon - Keflavik

Iceland – A journey in pictures

Fig. 01:
Volcanoes created by a single eruption located west of Vatnajökull, Iceland's and Europe's biggest glacier.

Fig. 02: Dettifoss – one of Icelands biggest waterfalls on the glacial river Jökulsa a Fjöllum originated in the Vatnajökull glacier. The average discharge rate is 183 m³/sec while the discharge during summer times is up to 1500 m³/sec transporting 120,000 m³ of bedload every day.

Fig. 03: Geothermical area at Mt. Namafjall called Hveraröndl. Groundwater seeps down to a depth of 1000 metres where its temperature rises up to 200°C and find its way upward as hot steam. Along with the steam come volcanic gases such as hydrogen sulfide which is responsible for the characteristic smell.

Fig. 04: Iceland is part of the ocean floor which has been forced up above sea level by special geological conditions. The island owes its existence to the coincidence of the spreading boundary of the North American and European plates (Mid-Atlantic-Ridge). Fissure east of lake Myvatn in the volcanic area of Krafla.

Fig. 05: Deflection and catching dams above the settlements in Siglufjörður in front of the panoramic view. In 1996 a testing area was established in the mountains above Siglufjörður to carry out the feasibility of supporting structures for avalanche protection under Icelandic conditiones.

Fig. 06: Serious corrosion problems have been encountered with all wire ropes at the testing site in Siglufjörður indicating that corrosion protection of wire ropes used in Alpine snow nets are unsuitable for Icelandic conditiones. Therefore IMO requests the use of hot-dip galvanised steel bridges.

Fig. 07: Typical Icelandic summer houses in Siglufjörður.

Fig. 08: More than half of the population of Iceland believes in elves and trolls and more than 90% think their existence is possible.

Fig. 09: Wood from the Barents sea which has been drifted several thousand kilometres by easterly winds can be found on the north-shores in the Westfjords.

Fig. 10: Cloth made of skin typically worn by Icelandic fishermen during the 19th century. A replica of an old fishing settlement was built in the Ösvor museum near Bolungarvik.

Fig. 11: On October 26, 1995 a big avalanche killed 20 people in the community of Flateyri in the Westfjords. An A-shaped combination of two 15-20 metre high deflecting dams and one app. 10 metre high catching-dam was built in 1996-1998. These were the first of their kind in Iceland and was considered to be very large even on a global scale.

Fig. 12: Lupine together with hawkbit nowadays covers most of the areas affected by supporting structures or avalanche dams and therefore reduces soil-erosion significantly.

Fig. 13: Wooden building in Ísafjörður's old fishery harbour close to Tjöruhusid – one of the best fish restaurants in Iceland. The former trade house now hosts concerts during Ísafjörður's concert week.

Fig. 14a and 14b: Midnight sun in Iceland on June 22 at 11 pm on the way from Siglufjörður to Sauðarkrokur.

Fig. 15: The concert and conference hall Harpa designed by Copenhagen's architect Henning Larsen is probably the most spectacular building in Reykjavik. During the financial crisis in 2008 completion was at risk and is therefore finished nowadays.

Fig. 16: Reykjavik's famous Hallgrimskirkja – a church built of concrete and finished after more than 40 years of construction. In front of the church a statue reminds people of Icelandic discoverer Leifur Eiriksson, who is said to have discovered America before Christopher Columbus.

Fig. 17: View from the plattform in the church tower of Hallgrimskirkja to Reykjavik downtown with its shops, restaurants and famous night life.

Fig. 18: Gullfoss, the so-called "golden waterfall", northeast of Reykjavik on the Golden Circle tourist route. It is said to be the most powerful waterfall in Iceland with the water falling down on two cascades 32 metres deep in a 2.5 km long canyon.

Fig. 19a and 19b: The gush spring Strokkur shoots hot water every 5 to 10 minutes up to 15 metres in the sky. Its bigger brother "Great Geyser", located a few meters to the east, is inactive nowadays.

Fig. 20:
Geothermal Spa Blue Lagoon located on the peninsula Reykjanes southwest of Reykjavik. The water temperature is 37-39°C. The lagoon holds six million liters of geothermal seawater, which is renewed every 40 hours. The seawater originates 2000 metres beneath the ground where it is heated by the earth's natural forces. At this depth the temperature is 240°C and the pressure is 36 times the pressure on the earth's surface.

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