# Field observations and laboratory experiments for evaluating the effectiveness of avalanche defence structures in Iceland : main results and future program

## *Observations de terrain et expérimentations de laboratoire pour évaluer l'efficacité de structures de protection contre les avalanches en Islande : résultats principaux et programme futur*

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ABSTRACT : Catastrophic avalanches in the villages Súðavík and Flateyri in 1995, which killed 34 people and caused extensive economic damage, have totally changed the view regarding avalanche safety in Iceland. The Icelandic government has drawn up a plan to construct avalanche protection measures for hazard areas and/or to purchase endangered property in order to reduce the death toll and the economic losses caused by avalanches in the future. Protection measures have up to now been constructed for three avalanche paths in north-western, northern and eastern Iceland and settlements in two villages have been relocated to safer areas. Deflecting dams in the villages Flateyri and Siglufjörður have already been hit by snow avalanches on four separate occasions since the construction of the dams in 1997–1999. The avalanches were in all cases successfully deflected away from the settlements. Data about these avalanches provide interesting information about the dynamics of snow avalanches that hit deflecting dams. Laboratory experiments, that were performed as a part of the design of retarding mounds and a catching dam for the village Neskaupstaður in eastern Iceland, have provided new insights into the dynamics of avalanches that hit retarding structures. Plans have been made for the installation of instrumentation to measure the speed of avalanches that hit the deflecting dams at Flateyri.

KEY WORDS : deflecting dams, catching dams, retarding mounds, laboratory experiments

RÉSUMÉ : *Les avalanches catastrophiques dans les villages de Súðavík et Flateyri en 1995, qui ont tué 34 personnes et causé d'importants dommages économiques, ont totalement changé le point de vue concernant la sécurité contre les avalanches en Islande. Le gouvernement islandais a élaboré un plan pour construire des structures de protection contre les avalanches dans les zones à risque et/ou pour acheter les biens soumis aux risques d'avalanches afin de réduire les coûts liés aux pertes humaines et économiques. Depuis, des structures de protection ont été construites pour trois couloirs d'avalanche dans le nord-ouest, le nord et l'est de l'Islande et des mesures ont été prises pour déplacer des habitations de deux villages vers des zones plus sûres. Les digues dans les villages de Flateyri et Siglufjörður ont fonctionné à quatre reprises depuis leur construction en 1997 –1999. Les avalanches ont été dans tous les cas déviées avec succès vers des zones non habitées. Les données* *concernant ces avalanches fournissent des informations intéressantes sur la dynamique des avalanches de neige interagissant avec une digue. Les expérimentations de laboratoire, menées pour aider à la conception des tas freineurs et d'une digue d'arrêt dans le village de Neskaupstaður dans l'est de l'Islande, ont fourni de nouvelles perspectives sur la dynamique des avalanches impactant des structures dissipatrices d'énergie. Un projet a été réalisé pour la mise en place de capteurs pour mesurer la vitesse des avalanches interagissant avec la digue de déviation de Flateyri.*

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## 1. Introduction

Dams and retarding structures are often used to protect settlements against dense-flow snow avalanches. The traditional design of such structures is based on simple physics that can only be considered to apply to real avalanches in a qualitative way. There are not many direct observations of the effectiveness of man-made structures that have been hit by snow avalanches. Each well-documented case, where avalanches have been observed to hit obstructions, therefore provides valuable insight into the dynamics of avalanches that hit dams or retarding structures.

Avalanche protection measures that have been constructed in Iceland since the catastrophic accidents in the villages Súðavík and Flateyri in 1995 provide a unique opportunity to study the interaction of avalanches with obstructions. The deflecting dams in the villages Flateyri and Siglufjörður have already been hit by snow avalanches on four separate occasions. The present paper summarises observations that were made of these avalanches, the results of laboratory experiments that were carried out as a part of the design of retarding mounds in Neskaupstaður in eastern Iceland, plans for instrumentation of avalanche paths and future laboratory experiments to study the effectiveness of dams and retarding structures. First, the avalanche situation in Iceland and the government programme for the build-up of avalanche protection measures, that was initiated after 1995, will be briefly described.

## 2. Accidents and economic loss

Snow avalanches and landslides have caused many catastrophic accidents and severe economical losses in Iceland since the country was settled in the ninth century. Figure 1 shows the main villages where avalanches and landslides threaten settled areas and Figure 2 shows locations where avalanches have been reported to cause damage or deaths since the settlement of Iceland (based on Figure 6 in [BJÖ 80]). Although the concentration of the accidents is highest in western, central northern and eastern Iceland, avalanche accidents


**Figure 1.** *The most important villages in Iceland that are threatened by avalanches and landslides.*

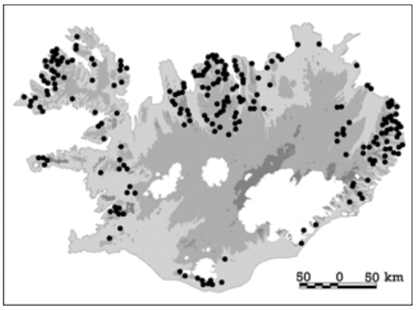


**Figure 2.** *Locations where avalanches have been reported to cause damage or deaths since the settlement of Iceland in the ninth century.*

have occurred at scattered locations all over the country. Clearly, the avalanche problem is relevant to most populated areas of Iceland, although the problem is by far most serious in the western, northern and eastern parts of the country.

A total of 193 people have been killed in snow avalanches, slush flows and landslides in Iceland since 1901 [JÓH 01a]. Of these people, 113 were killed in buildings, at work sites or within towns, and 80 were killed on roads or travelling in backcountry areas. Snow avalanches and slush flows caused the majority of the fatalities, but a total of 27 fatalities were caused by landslides (including debris flows and rock falls). Since the catastrophic avalanches in Neskaupstaður in 1974, altogether 69 people have been killed in avalanches, slush flows and landslides. Of these people, 52 were killed in buildings, at work sites or within towns, and 17 were killed on roads or travelling in backcountry areas. Rock falls caused 3 of the fatalities during this period. Figures 4 and 5 show the number of fatalities in snow avalanche accidents in Iceland in the last 200 years for populated areas and for unpopulated areas, respectively, grouped into 25-year intervals.

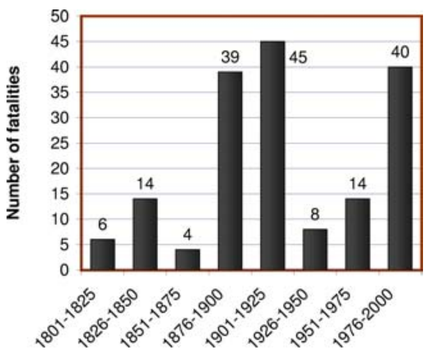


**Figure 3.** *Fatal snow avalanche accidents in populated areas 1801–2000.*

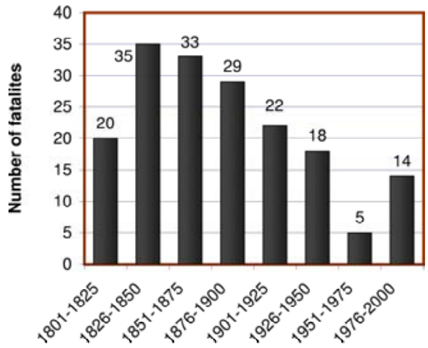


**Figure 4.** *Fatal snow avalanche accidents in unpopulated areas 1801–2000.*

The economic loss that has been inflicted by avalanches and landslides in Iceland has been enormous. The direct loss and the cost of rescue and relief operations since 1974 is summarised in Table 1 (August 2000 price levels) [JÓH 01a]. The bulk of the cost is caused by the three largest accidents; in Neskaupstaður 1974 (12.8 million USD), Súðavík 1995 (7.4 million USD) and Flateyri 1995 (9.1 million USD), which also caused the vast majority of the fatal accidents (46 of the 52 fatalities that have occurred in populated areas since 1974).

| **Type of accident** | **Amount (million USD)** |
|---|---|
| Snow avalanches, excl. ski areas | 37.4 |
| Damages in ski areas | 2.1 |
| Infrastructures such as power lines | 0.9 |
| Damage due to landslides | 1.1 |
| **Total** | **41.5** |

**Table 1.** *Direct loss and cost of rescue and relief operations 1974–2000.*

### 3. Protection measures

Following the catastrophic avalanches in 1995, a government fund that finances protection measures in threatened areas was strengthened considerably. A plan was made by the government to construct avalanche protection measures for hazard areas and/or to purchase property at risk in order to reduce the death toll and the economic losses caused by avalanches in the future. According to the plan, the construction of protection measures or relocation of settlements for the most dangerous areas shall be completed before the year 2010. Table 2 list the areas where protection measures have been constructed or settlements have been relocated since 1995 (August 2000 price levels) [JÓH 01a].

| Location | Cost (million USD) |
|---|---|
| Súðavík (relocation) | 10.1 |
| Hnífsdalur (purchasing of buildings) | 2.8 |
| Flateyri (dams [SIG 98], completed in 1998) | 5.5 |
| Siglufjörður (dams [VSN 97], completed in 1999) | 4.0 |
| Neskaupstaður (dams and supporting structures [TÓM 98]) | 6.8 |
| Various costs | 1.6 |
| **Total** | **30.8** |

**Table 2.** *Cost of relocation and avalanche defence structures 1995–2000.*

**4. Avalanches hitting deflecting dams**

The new defence structures at Flateyri and in Siglufjörður have already been hit by avalanches on four separate occasions since the deflecting dams were completed [JÓH 01a, JÓH 01b]. Figures 5 and 6 show outlines of the avalanches that hit the deflecting dams at Flateyri in 1999 and 2000 and in Siglufjörður in 1999 and 2001. All the avalanches were successfully deflected away from the settlements. Figure 5 also shows the outline of the catastrophic avalanche at Flateyri in 1995. The avalanche in 1999 from Skollahvilft above Flateyri was substantially smaller than the catastrophic avalanche in 1995. It would thus probably not have caused damage in the absence of the dams, because the avalanche in 1995 devastated buildings in this area of the village. It is possible, on the other hand, that the avalanches from Innra-Bæjargil in 2000 (Figure 5) or from Ytra-Strengsgil in 1999 (Figure 6) would have reached the current settlements and destroyed or damaged several domestic houses.

The estimated volume of the avalanches at Flateyri in 1999 and 2000 is on the order of 100 thousand $m^3$ and modelled speed at the location of the impact with the dams is about 30 m/s [JÓH 01b]. The highest run-up marks were 13 m above the base of the Skollahvilft dam for the 1999 avalanche and 12 m above the base of the Innra-Bæjargil dam for the 2000 avalanche (Figure 7). The minimum vertical distance from the highest marks to the top of the dam was about 4 and 6 m in the respective cases. The impact with the dams channelled a part of or the whole of the width of the avalanches into a stream of width 20–80 m where the thickness of the flowing avalanche seems to have been increased with respect to the thickness of the undisturbed flow (indicated with a dashed curve for the Skollahvilft avalanche in Figure 5). It is estimated that the deflection and channelling of the flow by the Skollahvilft dam in 2000 increased the run-out by over 100 m compared with the run-out of an undisturbed avalanche.

The flow of the avalanches outside of the streams that formed along the dams seems to have been to a large extent unaffected by the dams. East of the stream, which is indicated with the dashed curve in Figure 5, the tongue of the Skollahvilft avalanche in 1999, seems, in particular, unaffected by the presence of the dam. This shows that disturbances in the flow due to the impact with the dam are advected at high speed with the main avalanche flow along the dam and are therefore unable to reach further away from the dam than the

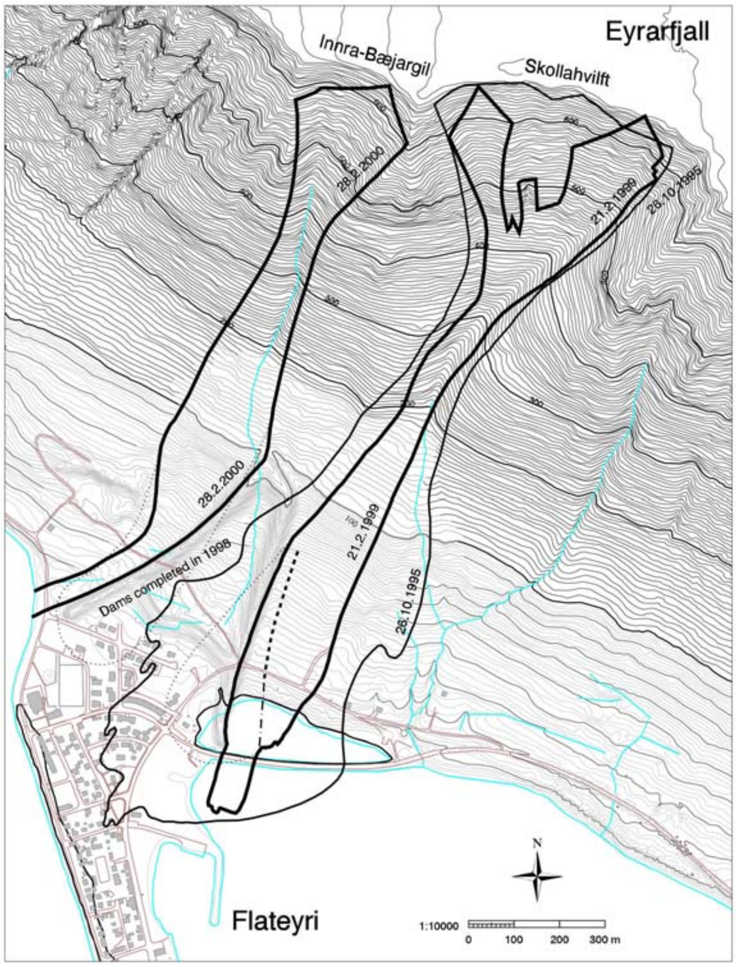


**Figure 5.** *The outlines of avalanches that were deflected by the deflecting dams at Flateyri in 1999 and 2000. The outline of the catastrophic avalanche in 1995 is also shown. The channelled flow of the 1999 avalanche from Skollahvilft along the deflecting dam is indicated with a dashed curve. Hypothetical outlines of the avalanches in 1999 and 2000 in the absence of the deflecting dams are shown as dotted curves.*

20–80 m indicated by the width of the streams. The apparently sharp boundary between the streaming flow along the dam and the undisturbed flow away from the dam indicates that the interaction between the supercritical avalanche flow and the dam may be interpreted as an oblique shock in a shallow layer gravitational granular flow.

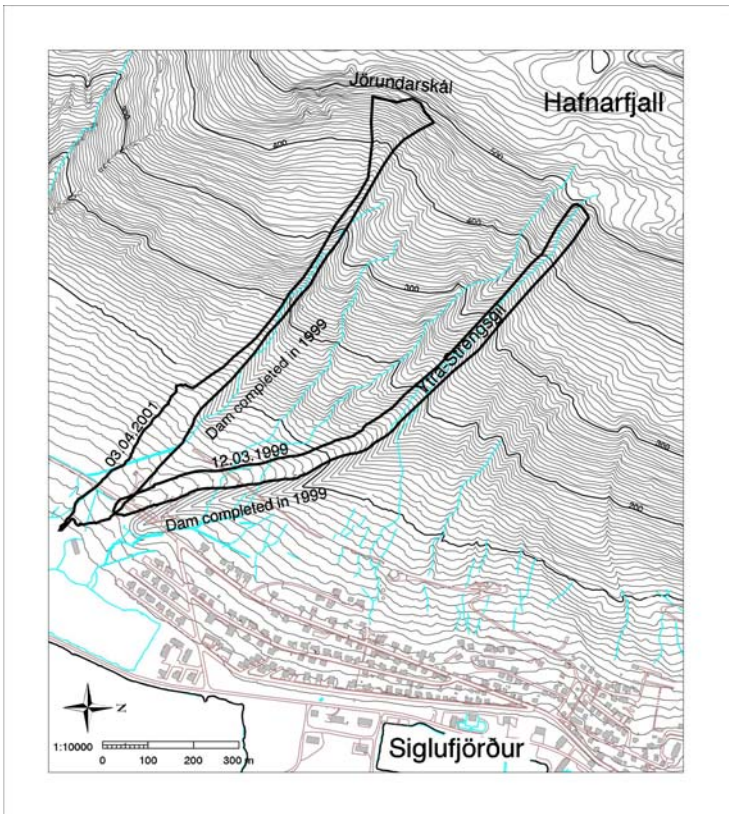


**Figure 6.** *The outlines of avalanches that were deflected by the deflecting dams below Ytra-Strengsgil and Jörundarskál in Siglufjörður in March 1999 and April 2001.*

## 5. Laboratory experiments

Braking mounds (or retarding mounds) are widely used for protection against dense, wet snow avalanches, but they are often thought to have little effect against rapidly moving, dry snow avalanches. The design of such mounds is in most cases based on the subjective judgement of avalanche experts as there exist no accepted design guidelines for braking mounds for retarding snow avalanches. There are, furthermore, no accepted methods for estimating the retarding effect of avalanche mounds in a quantitative way.

A number of chute experiments in 3, 6, 9 and 34 m long chutes with different types of granular materials have recently been performed in order to shed light on the dynamics of avalanche flow over and around braking mounds and to estimate the retarding effect of the mounds [HÁK 01, HÁK 02, HÁK subm.]. Some of these experiments were carried out as a

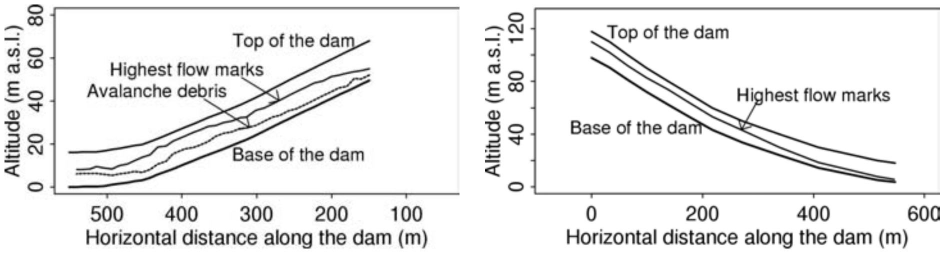


**Figure 7.** *Run-up of the avalanche from Skollahvilft on 21 February 1999 along the eastern deflecting dam (left) and the avalanche from Innra-Bæjargil on 28 February 2000 along the western deflecting dam. Maximum vertical run-up on the Skollahvilft dam is 13 m and 12 m on the Innra-Bæjargil dam.*

part of the design of avalanche protection measures for the town of Neskaupstaður in eastern Iceland (Figure 8) [TÓM 98].

The experiments showed that the collision of the flow with a row of steep mounds that are 2–3 times as high as the flow thickness leads to the formation of a jump or a jet, whereby a large fraction of the flow is launched from the top of the mounds and subsequently lands back on the chute. As the first front of the flow hits the obstacle, particles are launched from the top of the mound at an angle close to the slope of the upstream face. The jet rapidly adjusts to a new throw angle due to the formation of a wedge behind the upstream face of the mound. The

**Figure 8.** *The braking mounds and the catching dam in Neskaupstaður. Each mound is 10 m high and the catching dam has a height of 17 m. Photo: Tómas Jóhannesson.*

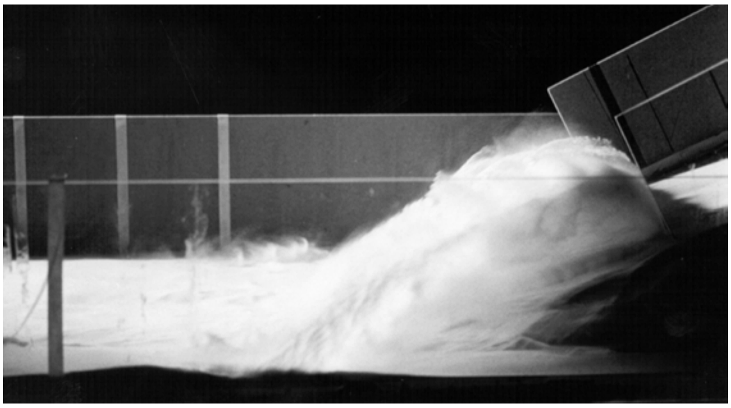

**Figure 9.** *The quasi-steady state jet formed by the collision of granular flow with a row of mounds in the 6 m long experimental chute at the University of Bristol. Photo: Kristín Martha Hákonardóttir.*

bulk of the current then passes over the barrier as a coherent quasi-steady state jet (Figure 9). This part of the jet lands furthest away from the mounds. After the main flow has passed over the mounds, the jet quickly dies out. Energy dissipation takes place in the impact of the avalanche with the mounds and also in the interaction of jets launched from adjacent mounds. Energy dissipation, furthermore, takes place in the landing of the jets on the chute and the subsequent mixing with snow flowing in between the mounds.

The chute experiments with granular materials and previously performed fluid experiments with baffle blocks, that are documented in scientific papers (see the list of references in [HÁK subm.]), lead to the following recommendations for the geometry of braking mounds for snow avalanches:

- The height of the mounds (above the snow cover) should be 2–3 times the thickness of the dense core of the avalanche.
- The upstream face of the mounds should be steep. An upstream slope of ≈60° is sufficient since a steeper upstream face only marginally improves the energy dissipation.
- The aspect ratio of the mounds above the snow cover, defined as the height to width ratio of the mounds, should be chosen close to 1.
- The mounds should be placed close together, so that jets launched sideways from adjacent mounds will interact. Many short mounds were found to be more effective than fewer and wider mounds for the same area of the flow path covered by mounds.

## 6. Plans for installation of measuring devices in avalanche paths

The information about the avalanches that have been deflected by the dams at Flateyri (Figures 5 and 7) is obtained by field observations after the avalanches have fallen. This limits the usefulness of the events for dynamical studies because only crude velocity estimates derived by modelling are available. In the summer of 2003, a continuously operating microwave CW Doppler radar will be installed at Flateyri as a part of the research project *Satsie* (Avalanche Studies and Model Validation in Europe), which is supported by the Fifth Framework Programme of the European Community. Two antennas will be installed on the dam below Skollahvilft (see Figure 5), one near the top of the dam and the other near the easternmost lower end. The data from future events at Flateyri and several other avalanche paths in Europe will be analysed in a collaboration between avalanche scientists from Norway, Austria, Switzerland, France, Spain and England that participate in Satsie. Chute experiments will also be used within Satsie to study the flow of granular materials against obstructions under more controlled and more easily reproducible circumstances than can be obtained in the field.

The simple geometry of the comparatively unconfined run-out areas at Flateyri and the regular form of the dams there make the Skollahvilft avalanche path a particularly suitable location for a study of the flow of avalanches hitting deflecting dams. The results from Flateyri, since the construction of the dams in 1998, indicate that more detailed observations and analysis of future events may lead to a substantial improvement in the understanding of the flow of avalanches that hit deflecting dams and other obstructions.

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