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

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ABSTRACT

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

1. INTRODUCTION

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

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

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

2. SNOW AVALANCHES HITTING DAMS

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

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

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

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

2.1 Deflecting dams at Flateyri

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

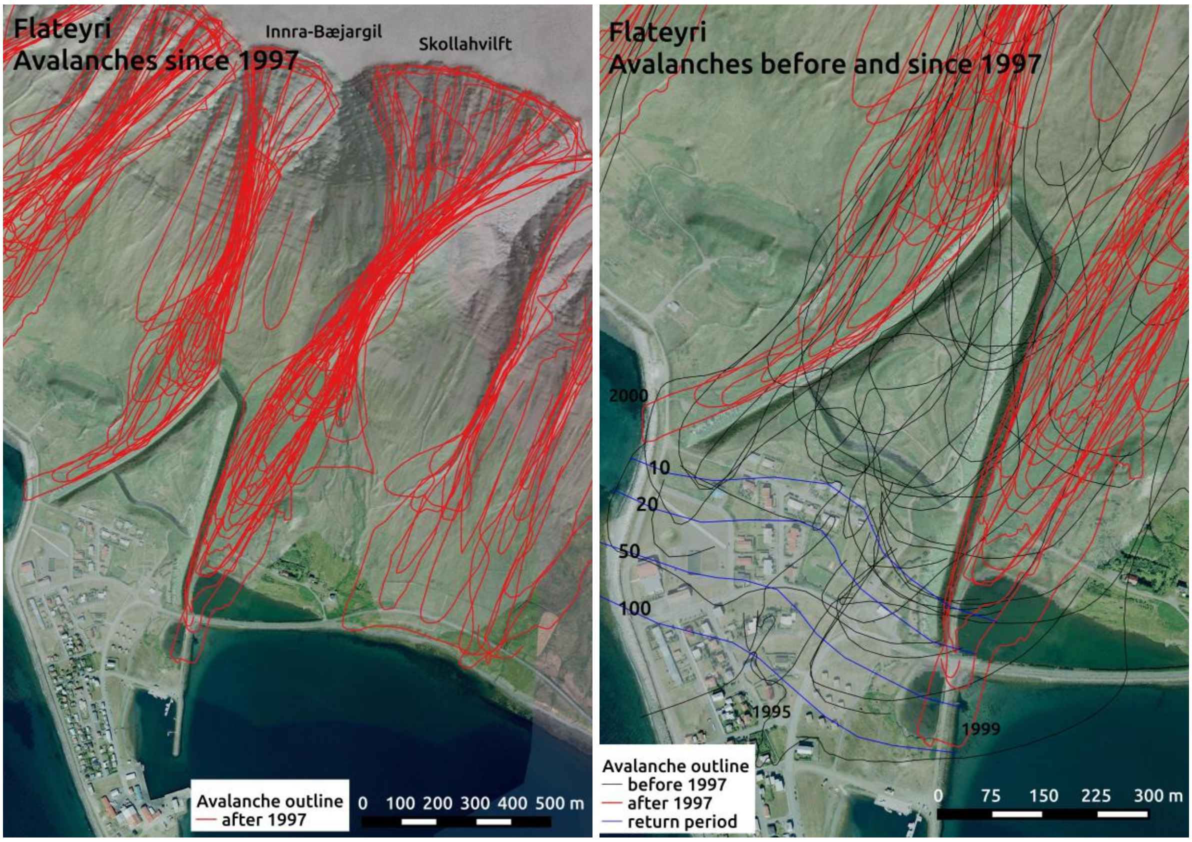

Figure 1 Outlines of snow avalanches at Flateyri, NW-Iceland since the construction of deflecting dams above the village in 1997. The background is a transparent shading of a lidar DEM from 2009 superimposed on an orthophoto from Loftmyndir ehf (©). The figure to the right shows a zoom-in of the dams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

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

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

2.2 Deflecting dam at Seljalandsmúli, Ísafjörður, NW-Iceland

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

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

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

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

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

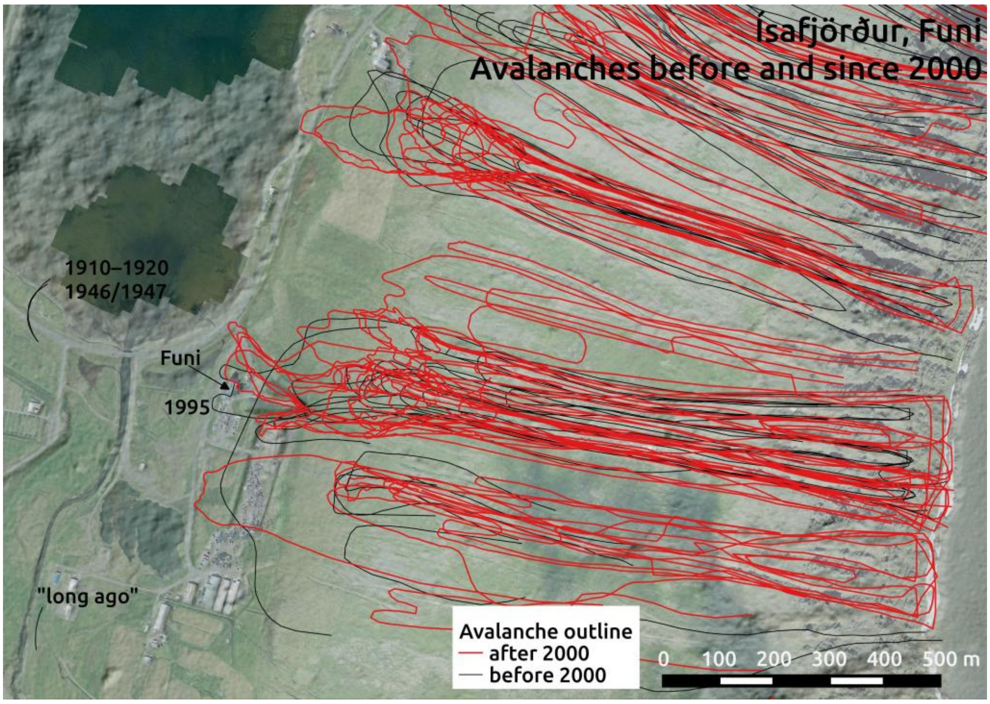

Figure 2 Outlines of snow avalanches at the Funi industrial building below the Innri-Kirkjubólshlíð mountainside in Ísafjörður, NW-Iceland, since the construction of a deflecting wedge above the building in 2000 (red curves), as well as all recorded avalanches before this time (black curves). The background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

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

2.5 Deflecting and catching dams at Siglufjörður, N-Iceland

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

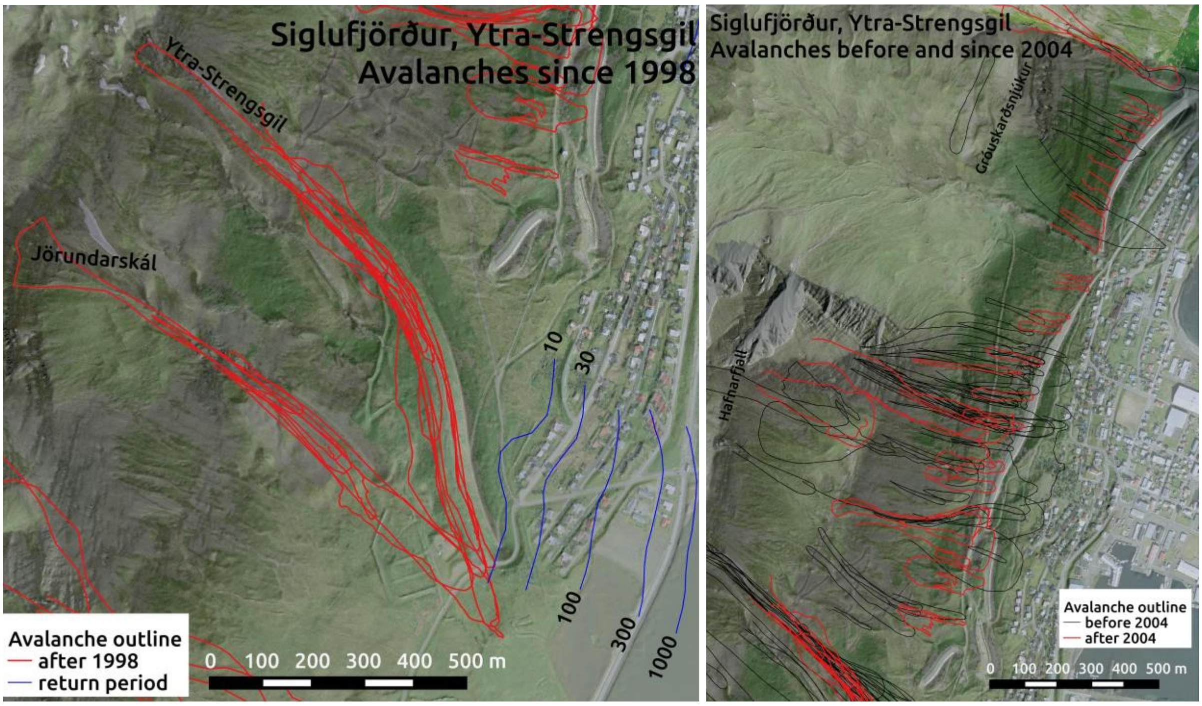

Figure 3 Left: Outlines of snow avalanches from the Ytra-Strengsgil and Jörundarskál avalanche paths at the southern end of the town of Siglufjörður, N-Iceland, since the construction of deflecting dams above the settlement in 1998 (red curves), as well as an estimate of the return period of snow avalanches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

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

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

2.6 Catching dam at Seyðisfjörður, E-Iceland

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

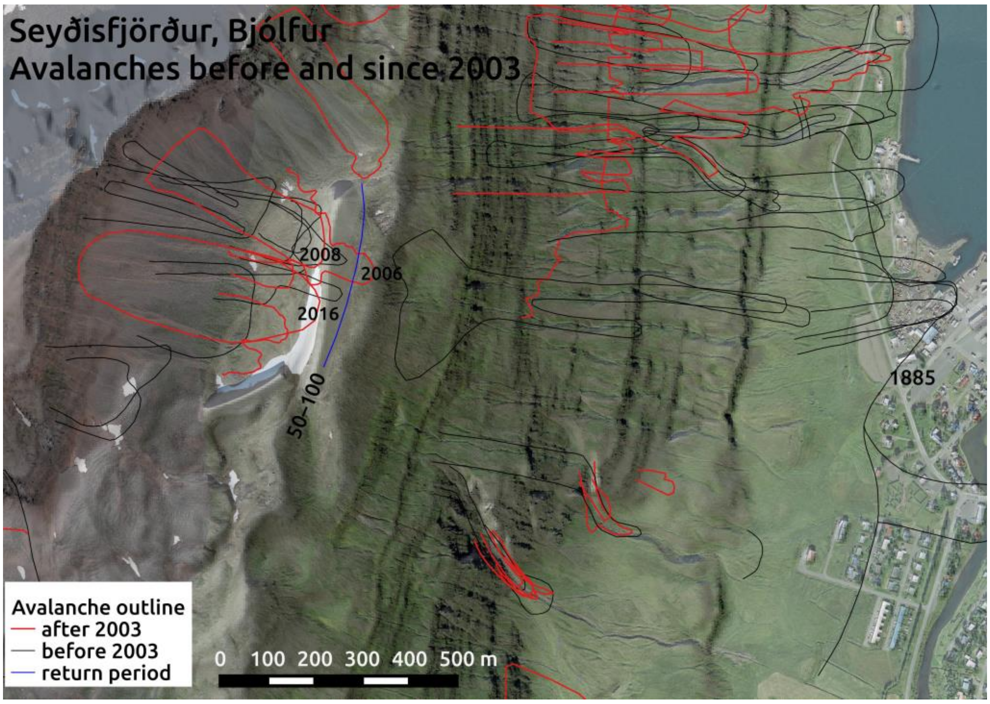

Figure 4 Outlines of snow avalanches from the Bjólfur mountain above the town of Seyðisfjörður, E-Iceland, since the construction of 20-m high catching dam and a deflecting dam on the shelf Brún at 650 m a.s.l. in the mountainside in the year 2003 (red curves), as well as all recorded avalanches before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

3. DISCUSSION AND CONCLUSIONS

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

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

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