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Results of the 2D avalanche model SAMOS for Eskifjörður

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BACKGROUND

The 2D avalanche model SAMOS, developed by the Advanced Simulation Technologies (AVL) of Graz, Austria, has been run for several starting zones in the mountain above the village Eskifjörður, eastern Iceland, and for one large starting zone in Hólmatindur on the opposite side of the fjord. The runs are intended to shed light on the following aspects of the avalanche hazard situation in the village:

1. The runout potential of avalanches that are released from starting zones at 500-600 m a.s.l. in Harðskafi and at 600-700 m a.s.l. in Ófeigsfjall in comparison to modelled runout in more typical avalanche paths such as in Neskaupstaður. In particular, the effect of the comparatively small area of the starting zones and the reduced slope in the middle part of the mountainside will be investigated.
2. The shortening of avalanche runout due to lateral spreading of avalanches. This is particularly relevant for avalanches released from the starting zones in Ófeigsfjall and some of the small starting zones in the outer part of the mountainside below Lambeyrardalur. The influence of the complex topography of the slope on the flow of avalanches that are released from the small starting zones in the mountainside below Lambeyrardalur.
3. The direction of the main avalanche tongues from the starting zones that have been defined in the mountains as a part of the hazard zoning for Eskifjörður.
4. The potential runout of large avalanches that are released from the upper part of the mountainside in Hólmatindur on the opposite side of the fjord.

The results of the runs will be used in the delineation of the hazard zones for the village. Similar results have previously been used for the same purpose for the villages Bolungarvík, Neskaupstaður, Siglufjörður and Seyðisfjörður (Jóhannesson *et al.*, 2001a,b,c). The section about the application of the model to the 1995 avalanche at Flateyri is identical to a section in the previous reports about SAMOS simulations for other villages in Iceland in order to make the present report independent of the previous reports.

The SAMOS model was developed for the Austrian Avalanche and Torrent Research Institute in Innsbruck by AVL and has recently been taken into operational use in some district offices of the Austrian Foresttechnical Service in Avalanche and Torrent Control. The model is based on similar assumptions regarding avalanche dynamics as other depth integrated 2D avalanche models that are used in Switzerland and France. Friction in the dense flow part of the model is assumed to be composed of a Coulomb friction term proportional to a coefficient $\mu = \tan(\delta)$ with $\delta = 16.0°$ ($\mu = 0.287$) and a turbulent friction term which may be represented by a coefficient $\xi = 446\,\mathrm{m}^2/\mathrm{s}$ (Sampl and Zwinger, 1999). Rather than adding the two friction components as is done in the Swiss and French 2D models, the SAMOS model uses the maximum of the two friction terms and ignores the smaller term. This leads to slightly higher modelled velocities than for the Swiss and French 2D models for avalanches with similar runout. The velocities are, also, somewhat higher than corresponding velocities in the same path from the Swiss AVAL-1D model or the PCM model (Sauermoser, personal communication). The model runs are, furthermore, based on an assumed value $\rho = 200\,\mathrm{kg/m}^3$ for the density of flowing snow. The density is used to convert a given mass of snow in the starting zone to a corresponding volume or depth perpendicular to the terrain of the snow that is released at the start of the simulation.

MODELING OF AVALANCHE AT FLATEYRI ON 26.10.1995

The SAMOS model had not been used to model Icelandic avalanches before it was run in connection with hazard zoning of several Icelandic villages in the years 2000 to 2002. The model was first run for the catastrophic avalanche from Skollahvilft at Flateyri on 26 October 1995 (Fig. 1) in order to check the applicability of the parameter values that are traditionally adopted for the model in Austria. The values for μ, ξ and ρ listed above were used. About 90,000 tons of snow were released from the starting zone between about 400 and 640 m a.s.l. based on measurements of the mass of the deposit of the avalanche and observations of the fracture height and density of the snow at the fracture line. The starting zone was divided into an upper and a lower area with a larger snow depth in the upper area. The run was defined by the following input data:

Input	Value
Map area of upper starting zone (10^3m^2)	58
Map area of lower starting zone (10^3m^2)	52
Total map area of starting zone (10^3m^2)	110
Area of upper starting zone (10^3m^2	73
Area of lower starting zone (10^3m^2)	63
Total area of starting zone (10^3m^2)	136
Snow depth, upper area (d_u, m, ρ = 200 kg/m^3)	4.3
Snow depth, lower area (d_l, m, ρ = 200 kg/m^3)	2.0
Snow depth, average (m)	3.25
Mass (10^3t)	89
Volume (10^3m^3, ρ = 200 kg/m^3)	440
Volume (10^3m^3, ρ = 350 kg/m^3)	220
Volume (10^3m^3, ρ = 420 kg/m^3)	210

The snow depth in the table is defined perpendicular to the terrain. The above values of the snow depth in the two subareas correspond to an average of 3.25 m with a density ρ = 200 kg/m^3 over the whole starting zone or 1.85 m with a density ρ = 350 kg/m^3. This higher value of the density may be assumed to have been close to the density of the snow in the fracture line before the release of the avalanche. The average density of the snow in the deposit in 1995 was close to ρ = 420 kg/m^3.

No entrainment was specified and therefore the total mass of the avalanche in the model is smaller than for the real avalanche. This is typical in avalanche models of this kind.

The results of a run of the dense flow model for Flateyri with the above specification of input parameters are displayed as coloured contour plots of the depth and velocity of the flowing avalanche at 10 s intervals (file fl.ppt on the attached CD). The modelled location and geometry of the deposit at the end of the run (denoted as "h6") is in a fair agreement with the outlines of the 1995 avalanche (Fig. 1). The eastward margin of the deposit is close to the buildings at Sólbakki, in a good agreement with the observed outline of the avalanche. The western margin extends slightly further to the west than the observed outline. This may be caused by the retarding effect of the buildings in the village on the runout of the avalanche, but it could also be caused by slightly too high modelled velocities as the avalanche flows out of the gully at about 200 m a.s.l. The outline to the east of the gully at about 300 m a.s.l. seems to be too high and too far from the centerline of the gully compared with the measured outline, indicating too high velocities at that location of the path. The maximum velocity of the avalanche below the Skollahvilft gully is close to 60 m/s, which is higher than obtained with the Swiss 2D model for the 1995 avalanche (about 45 m/s). The channelisation of the avalanche as it flows into the gully and the direction of the avalanche out of the gully seem to be well modelled.

A coupled dense flow/powder flow simulation was also made for the 1995 avalanche from Skollahvilft using a rather high grain size parameter (2 mm) which leads to a comparatively little transfer of snow into the powder part of the avalanche. This is believed to be appropriate for Icelandic conditions. The results for the dense core of the coupled dense flow/powder flow model were essentially the same as for the previously described run with dense core model. Maximum powder pressures reached about 10 kPa in the gully at 2.5 m above the avalanche and 2-3 kPa in the uppermost part of the village.

It was concluded from the runs for Flateyri that the same input parameters can be used for the SAMOS model for Icelandic conditions as are traditionally used in Austria. The dense core model can be used without the powder part for modeling the dense core of avalanches without this leading to significant changes in the model results. The model appears to take the effect of the geometry of the avalanche path on the flow of the avalanche into account in a realistic manner. This applies to the channelisation of the flow into the gully, the spreading of the avalanche on the unconfined slope and the deflection of the avalanche when it flows at an angle to the fall line of the terrain. The modelled speed of the avalanche may be slightly too high although it is not possible to determine whether the speeds of the SAMOS model or the Swiss 2D model are more realistic without further analysis.

RESULTS FOR ESKIFJÖRÐUR

Avalanche starting zones were defined in the mountainside north of the inhabited area in Eskifjörður and also in the mountain Hólmatindur on the opposite side of the fjord. A total of 21 different subareas were defined on the north side of the fjord, in addition to one large starting zone in Hólmatindur. The areas on the north side of the fjord are numbered from 1-21 on the maps.

Only one very large starting zone was delineated in Hólmatindur. The geometry of this starting zone was not based on detailed field investigations as the delineation of the starting zones on the north side of the fjord. The SAMOS simulations of avalanches from Hólmatindur are only intended to give an upper bound for the runout of avalanches from this mountain so that the southern limit of the investigated area in Eskifjörður could be placed at a safe distance from Hólmatindur. Detailed hazard zoning was not performed for the area below Hólmatindur and therefore more detailed simulations were not needed there. The total area of the delineated starting zone in Hólmatindur is much larger than may be expected to be released in a single avalanche. The mountainside is cut by deep gullies separated by high cliffbands and the area has a high roughness. The simulated runout should, therefore, be interpreted as an upper bound for the runout of avalanches from Hólmatindur rather than a realistic estimate of an event that may be expected to occur in Nature.

The starting zones near the top of Harðskafi and Ófeigsfjall are believed to accumulate more snow than the starting zones at lower elevations. The different snow accumulation conditions in the starting zones were described by classifying the zones into five snow depth classes as defined in the following table. The snow depth is defined relative to the specified snow depth in class I areas which are defined to be large deep bowls or gullies near the top of the mountain.

Class	Relative snow depth	Comment
I+	2	Deep and narrow gullies near the top of the mountain
I	1	Large deep bowls or gullies near the top of the mountain
II	2/3	Shallow bowls or relatively flat areas near the top of the mountain
III	1/2	Small and shallow bowls at comparatively low elevations
IV	1/4	Other parts of the mountain with a small snow accumulation potential

This classification is the same as the classification previously used in Bolungarvík, Neskaupstaður, Siglufjörður and Seyðisfjörður. Only classes I and III were used for the Eskifjörður runs.

Four runs with the SAMOS model were made in Eskifjörður, two on the north side (run1 and run2) and two from Hólmatindur on the south side (run1h and run2h) . The first run in on each side was started with a uniform snow depth of 1.25 m in class I starting areas and the other run was started with a snow depth of 2.5 m in class I starting areas. The snow depth in all the runs was determined from the relative snow depth class for the respective areas as given in the above table.

The following table gives the total mass and volume of snow for each of the runs:

Input	run1	run2	run1h	run2h
Snow depth in class I areas (m)	1.25	2.5	1.25	2.5
Total mass (10^3t)	90	180	121	243
Total volume (10^3m^3, $\rho = 200\,$kg/m^3)	449	898	607	1214

The mass and volume are total values for all the avalanches that were released simultaneously in the different starting zones. The snow was released simultaneously from the multiple starting zones in each run in order to simplify the model computations and in order to make them more economical in terms of computer time and time needed to set up the runs. This aspect of the simulations should not be taken to indicate that simultaneous release of this kind is likely to occur in Nature.

The following table summarises the area and the relative snow depth for each of the starting zones in Eskifjörður. The last column of the table lists the runs where snow was released from the zone.

Starting zone id	 name	Map area (10^3m^2)	Area (10^3m^2)	Relative snow depth	Runs
1	Harðskafi, westernmost	26.4	35.2	1	1,2
2	Harðskafi, west of gully	44.5	56.1	1	1,2
3	Harðskafi, gully	15.5	19.7	1	1,2
4	Harðskafi, east of gully	19.7	24.8	1	1,2
5	Ófeigsfjall, westernmost	33.1	44.0	1	1,2
6	Ófeigsfjall, center area	28.7	38.4	1	1,2
7	Ófeigsfjall, easternmost	30.6	42.6	1	1,2
8	West of Bleiksá, lower area	14.7	16.9	1/2	1,2
9	Bleiksárhlíð, centre	1.7	2.0	1/2	1,2
10	Bleiksárhlíð, west of Grjótá	1.8	2.0	1/2	1,2
11	East of Lambeyrará	5.5	6.7	1/2	1,2
12	Between Lambeyrará and Ljósá	3.1	3.8	1/2	1,2
13	West of Ljósá	13.1	16.0	1/2	1,2
14	East of Hlíðarendaá, lower	5.8	6.8	1/2	1,2
15	Between Ljósá and Hlíðarendaá	11.2	13.4	1/2	1,2
16	East of Hlíðarendaá, upper	12.9	16.1	1/2	1,2
17	East of settlement, 1	32.6	41.5	1/2	1,2
18	East of settlement, 2	54.4	69.5	1/2	1,2
19	By Hlíðarendaá, 1	2.0	2.2	1/2	1,2
20	By Hlíðarendaá, 2	2.5	2.8	1/2	1,2
21	By Hlíðarendaá, 3	2.7	3.0	1/2	1,2
1h	Hólmatindur	356.0	478.9	1	1h,2h
Total, without Hólmatindur		362.5	463.6	—	—

It should be noted that avalanches from some of the starting zones in Eskifjörður, particularly for zones 1-4 in Harðskafi and 6 and 7 in Ófeigsfjall, interact with neighbouring avalanches and this leads to longer runout than would otherwise be obtained. It should also be noted that the starting zones í Ófeigsfjall and Hólmatindur cover a large area with some protruding cliffs and ridges. One may expect that several independent avalanches, extending over a part of the area each, will be released rather than a single avalanche encompassing the entire area. Thus, the runout indicated by the SAMOS simulations for avalanches from these starting zones may be too long.

As in the simulations for Flateyri described above, and in the separate reports for Bolungarvík and Neskaupstaður, Siglufjörður and Seyðisfjörður, snow entrained in the lower part of the path is not considered in the computations. Therefore, the volume of the avalanches from each starting zone is smaller than for real, large avalanches that might be released from the corresponding part of the mountain.

The results of the runs are displayed as coloured contour plots of the depth and velocity of the flowing avalanche at 10 s intervals (files es_run1-2.ppt and ht_run1-2.ppt on the attached CD. The CD also contains similar files for other Icelandic villages where SAMOS computations have been carried out). Plots of the maximum dynamic pressure (given by $p = \rho u^2$) along the paths were also made (also on the CD). Some of the results are shown on Figs. 3-10 (the flow depths are in m and the maximum pressure in kPa on the figures).

The runs illustrate a persistent tendency of the avalanches to form tongues below the gullies and bowls that constitute the main starting zones in the mountain. This is particularly evident for the avalanches from Hólmatindur.

The release volume ($\rho = 200\,\mathrm{kg/m^3}$) and runout index (Jónasson and others, 1999) for the avalanches from the different starting zones for each of the four Eskifjörður/Hólmatindur simulations is summarised in the table on the next page. The first of each pair of the columns corresponds to a snow depth of 1.25 m in class I starting zones and the second column corresponds to a snow depth of 2.5 m in class I starting zones.

A runout index is not given in several cases where interaction with avalanches from neighbouring starting zones makes it impossible to determine the runout of an avalanche from the starting zone in question.

It should be noted that the volumes given in the tables are not completely consistent with the volumes given in the previous tables that summarise the mass and volume of snow in each run. This discrepancy, which is in all cases less than 1-2%, is caused by discretisation errors in the computational grid because the delineation of the starting zones does not run along grid cell boundaries.

Previous simulations for Bolungarvík, Neskaupstaður, Siglufjörður and Seyðisfjörður (Jóhannesson *et al.*, 2001a,b,c) showed that the large bowl shaped class I starting zones in Neskaupstaður release avalanches that reach a runout index in the approximate range 15.5-16.5 for a snow depth of 1.25 m and runout index in the range 17-18 for a snow depth of 2.5 m. The much smaller class I starting zones in Bolungarvík produced shorter avalanches that reached runout index 13.5-14 and 15-15.5 for snow depths of 1.25 and 2.5 m, respectively. The class II and III starting zones in Neskaupstaður produced avalanches with a runout similar as in Bolungarvík in some cases, whereas other starting zones, for example in Urðarbotn, released avalanches with an intermediate runout index of about 15 for runs with a class I snow depth of 1.25 m. In the Eskifjörður simulations, only the large avalanches from Hólmatindur reached a similar runout to avalanches from the large, confined avalanche paths in Neskaupstaður.

Starting zone		Volume ($10^3 m^3$)		Runout index	
id	name	run1/1h	run2/2h	run1/1h	run2/2h
1	Harðskafi, westernmost	44	88	13-14	13-14
2	Harðskafi, west of gully	70	140	14.1	15.3
3	Harðskafi, gully	25	49	14.1	15.0
4	Harðskafi, east of gully	31	62	14.2	15.1
5	Ófeigsfjall, westernmost	55	110	13.5	14.0
6	Ófeigsfjall, center area	48	96	14-15[1]	≈15[1]
7	Ófeigsfjall, easternmost	53	107	14-15[1]	≈15[1]
8	West of Bleiksá, lower area	10	21	—	—
9	Bleiksárhlíð, centre	1.2	2.5	13.2	14.4
10	Bleiksárhlíð, west of Grjótá	1.3	2.6	12.7	13.2
11	East of Lambeyrará	4.2	8.3	13.3	14.2
12	Between Lambeyrará and Ljósá	2.4	4.7	—	—
13	West of Ljósá	10	20	13.3	14.0
14	East of Hlíðarendaá, lower	4.3	8.5	—	—
15	Between Ljósá and Hlíðarendaá	8.4	16.8	13.0	13.7
16	East of Hlíðarendaá, upper	10	20	14-15	14-15
17	East of settlement, 1	26	52	13.4	14-15
18	East of settlement, 2	43	87	14-15	14-15
19	By Hlíðarendaá, 1	1.4	2.8	—	—
20	By Hlíðarendaá, 2	1.8	3.6	—	—
21	By Hlíðarendaá, 3	1.9	3.8	—	—
1h	Hólmatindur	599	1197	≈16.0	≈18
Total, without Hólmatindur		453	905	—	—

[1] Avalanches from starting zones 6 and 7 are mixed into one tongue in the runout area. The runout indices for all these zones are therefore identical. The potential runout for avalanches from these zones is likely to be overpredicted by the SAMOS computations.

The avalanches released from Harðskafi and Ófeigsfjall are modelled to pass the area of reduced slope in the middle of the mountainside and terminate in the lowland. These avalanches reach similar runout as avalanches from the relatively small starting zones in Bolungarvík, *i.e.* runout index ≈14 and ≈15 for snow depths of 1.25 and 2.5 m, respectively. The comparatively short runout of the avalanches from Harðskafi and Ófeigsfjall is due to the narrow altitude range of the starting areas and consequently a relatively small volume of the avalanches, and to the modelled lateral spreading of the avalanches on the lower part of the mountainside. A large part of the volume of the avalanches from Harðskafi and Ófeigsfjall stops in the area of reduced slope in the middle of mountainside.

Avalanches from the small starting zones 9 and 10 in Bleiksárhlíð reach low runout indices, but they nevertheless reach into the settlement. These locations are considered improbable for the release of dry snow avalanches due to the low slope and small area.

Avalanches released from starting areas 11-21 above the easternmost part of the village stop for the most part on the shelves between 100 and 300 m a.s.l. These areas, in particular areas 19-21, are also not considered probable for the release of dry snow avalanches, except perhaps areas 17 and 18 that are east of the settlement.

The simulated runout from the large starting zone in Hólmatindur is as expected very long. The runout distance is comparable to the runout from the large bowl shaped class I starting zones in

Neskaupstaður. This area is very large and it is unlikely that a single slab avalanche extending over the whole area is released as noted before. Furthermore, the aspect of the area is towards NE which makes it less likely for the release of catastrophic avalanches than SE to SW facing starting areas in this part of the country. Although detailed hazard zoning will not be carried out for the area below Hólmatindur, an outer bound on the category A hazard zone may be determined from these results as being no further away from the mountain than runout index 17.

The following conclusions may be drawn from the model results for Eskifjörður:

1. Avalanches released from the starting zones in Harðskafi and Ófeigsfjall are modelled to pass the area of reduced slope in the middle of the mountainside and terminate in the lowland. The simulated runout of these avalanches is similar to the runout of avalanches in Bolungarvík, and about 2 runout indices shorter than the runout from the large bowl shaped class I starting zones in Neskaupstaður. This is due to the narrow altitude range of the starting areas and consequently a relatively small volume of the avalanches, and to the modelled lateral spreading of the avalanches.
2. Avalanches from the small starting areas in Bleiksárhlíð reach into the settlement but these areas are considered improbable for the release of dry snow avalanches.
3. Avalanches released from starting areas 11-21 above the easternmost part of the village stop for the most part on the shelves between 100 and 300 m a.s.l.
4. The results of the runs from Hólmatindur may, together with other considerations, be used to determine an outer bound on the category A hazard zone in this area below Hólmatindur as being no further from the mountain than runout index 17.

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LIST OF FIGURES