Veðurstofa Íslands
Report

Kristján Jónasson
Þorsteinn Arnalds

Pilot Hazard Zoning for Seyðisfjörður
IMO hazard zoning for the north side

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1. Introduction

This report is part of a project that is being carried out at the Icelandic Meteorological Office, "Pilot avalanche hazard map for Seyðisfjörður". The project is described in [2]. The report describes assessment of the risk due to avalanches from the mountain Bjólfur that stands to the north-west of the town Seyðisfjörður in Eastern Iceland. The risk has been calculated using the method described in [1]. This method has been used at the IMO over the last year for preliminary hazard zoning in about 10 places. It is assumed that the reader of this report is familiar with the material in [1].

The report begins with a short overview of the landscape and avalanche history of Seyðisfjörður. Following this there are three chapters that parallel chapters under the same headings in [1]. These chapters explain runout index distribution, survival probability and avalanche frequency estimation. Finally, the results of the risk assessment are presented in chapter 6.

2. Landscape and avalanche history

Two maps of avalanches in Seyðisfjörður have been prepared for the pilot hazard mapping project, one in size A1 that covers the whole town and one in size A3 that covers the north side south of Fornistekkur. An avalanche list has been compiled for the avalanches shown on the second map but no list accompanies the large map. The avalanche list is reproduced in Table 1 and a reduction of the A3 map is the basis of map 1 below.

For this study the north side of Seyðisfjörður under the mountain Bjólfur has been split into four areas as follows. The areas are marked on map 1.

1. **Inner area** (from Fjörður inwards to the limits of the settled area)

   This area is marked by two big gullies, Jókugil and Fálkagil. These may redirect avalanches that fall from the slopes above them. Jókugil is however too far south to be a real defence for the settlement and Fálkagil is the smaller of the two and probably not big enough to either reduce the power of the biggest avalanches or change their direction much.

   There are very few recorded avalanches in the area. One source states that an avalanche fell some time ago (maybe around the turn of the century) somewhere in the area and that "some people say that it reached Fjarðará". From the references it seems likely that the avalanche reached down to the area that has since been built or else to a comparable run-length further south. A different source states that the big avalanche of 1885 reached the area that was built up in the seventies. There is a well documented avalanche from Jókugil in 1986 but this stopped before reaching the lowland.

   The farm Fjörður on the outer edge of the inner area is said to have stood here since around the year 1000 and there are no records of any harm to it caused by avalanches. This does not prove that an avalanche has never hit Fjörður as there are gaps in the annals especially before about 1550. There is a small ridge above the farm (from 10 to 25 m a.s.l.) that may have saved it from the 1885 avalanche.

   Map 2 below shows building years and runout indices in this area. This information is discussed at the end of section 5 below.

   The width of the area is 600 m.

2. **Hlaupgjá-area**

This area has more recorded avalanches than the areas on each side (1882, 1885, 1894, 1904, 1988), and in particular a number of big avalanches that reached the sea are recorded. Above Hlaupgjá there is *Kálfabotn* that is reported as the starting zone of the big avalanche of 1885 and some of the other avalanches may also have come from there. Kálfabotn is a bowl about 200 m in diameter and with 30°–35° slope. Although this is not very large it may be the reason for the high frequency of big avalanches.

The width of the area is 300 m.

3. **Outer area** (between Hlaupgjá and Fornistekkur)

In this area there are 10 reported avalanches. Inspection of an aerial photo shows that there are much more gullies here than in the inner area. These gullies are about 150 to 350 m a.s.l. and this may be the reason for the higher frequency of (reported) avalanches here than in the inner area.

The width of this area is 800 m.

4. **Nautabás-area** (from Fornistekkur and outwards)

This is the area in Seyðisfjörður where avalanches are most frequent. The fish-factory Hafsíld/Vestdalsmjöl was built here in 1965 and it was hit several times by avalanches until it was removed due to the avalanche hazard in 1995. This area is not included in the current work, the IMO hazard zoning for the north side.

3. Runout index distribution

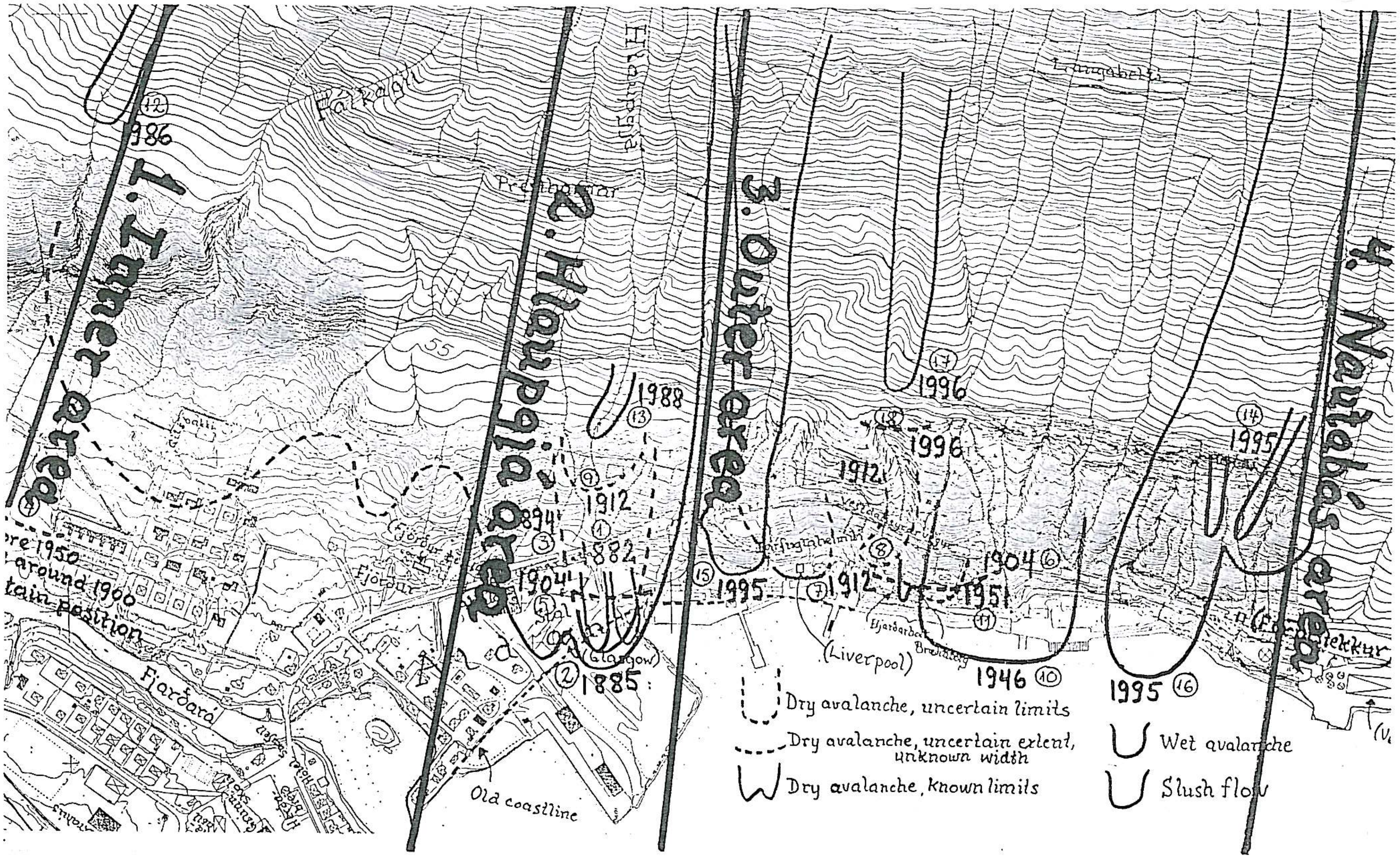
The distribution of runout indices used here is based on all the 197 avalanches in the collection of Icelandic avalanches described in [1]. The density and distribution functions are shown in Figure 5 on page 8 in [1].

The basic assumption of the method of [1] is that the relative frequency of short and long avalanches (measured by their runout index) is the same in the hill under consideration as it is on average in all the hills in the collection. Of course this never holds exactly and sometimes the difference may be considerable. On the other hand it is rare that there are enough recorded avalanches from a single hill to enable the statistical estimation of the distribution of run-lengths for that particular hill. They are certainly not many enough in Seyðisfjörður. The mountain Bjólfur has all the characteristics of a real avalanche mountain. On the other hand it does not have deep bowls like the mountain above Flateyri that would possibly imply a higher than average proportion of long avalanches.

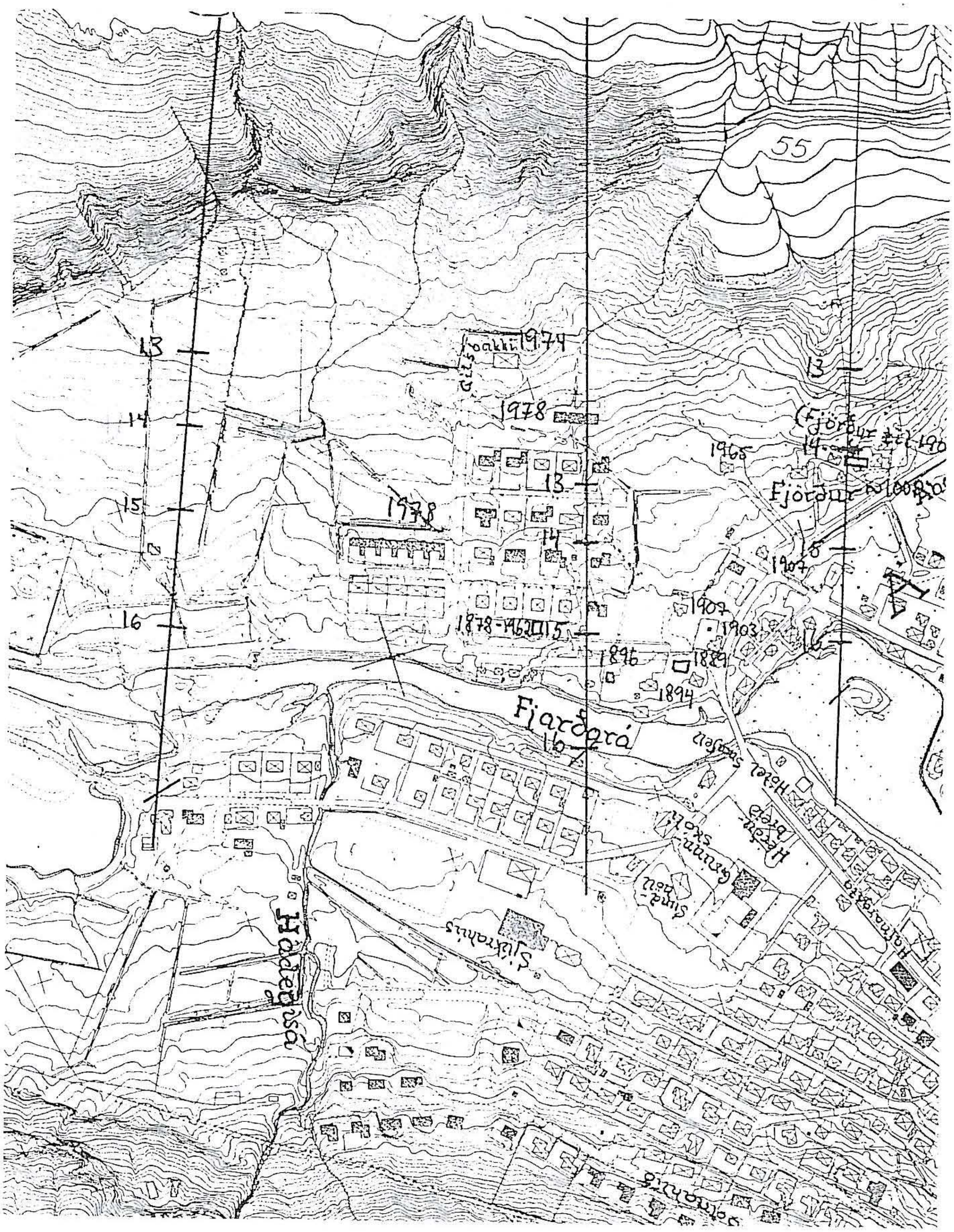
A different source of error is the problem of missing avalanches discussed in section 4.4 in [1]. In most hills, long avalanches are much more likely to have been recorded than shorter ones. The tail of a distribution calculated from these recordings will therefore be too thick. If the probability of an avalanche being recorded at a particular runout index is the same in the hillside in question as for the data set in general then we may proceed as explained in [1] and the fact that there are unrecorded avalanches will be of no consequence beyond the runout index 16 line. On the hillside of this line the risk will however be underestimated as was pointed out at the end of section 4.4 on page 10 in [1].

Date	Description	Map reference	Runout index
13.1.–14.1. 1882	Many slush-flows came from the slope above Aldan. The starting zone was not high up and the flows reached the sea. Two children were killed but four escaped or were rescued. Two houses and many huts (used to dry fish) were damaged.	1	>14.4
18.2.1885	A large avalanche fell from Bjólfur reaching from Jókugil to further out than Hlaup-gjá. Many houses were destroyed and 24 people were killed. Some sources say that in the town the extent of the avalanche was from Fjörður and out towards Liverpool. The starting zone is thought to have been in Kálfabotnar (some say in Hlaupgjá below Kálfabotnar). The avalanche reached the sea. Some references state that the avalanche split on a small hill around Fjörður and the inner tongue reached Fjarðará. A separate source says that part of the avalanche overran the area below Fálkagil where houses have since been built.	2	>14.5
31.1.1894	A dry avalanche with similar runout zone as the one in 1885 fell, but it started lower down and had a (much) narrower tongue. It destroyed a storage-hut.	3	>14.3
ca. 1900?	There is somewhat vague information about an avalanche that is said to have fallen south-west of Fjörður in the area below Fálkagil and Jókugil and these records state that it reached Fjarðará. The date of this avalanche is very unclear.	4	15.4?
21.2.1904	Wet avalanches fell in many places in Seyðisfjörður. One fell in the same area as the avalanches of 1882 and 1885.	5	14.3
21.2.1904	A wet avalanche fell in the area of Hjarðarholt and Bræðraborg.	6	11.5
3.3.1912	Avalanches, probably dry ones, fell in many places in Seyðisfjörður. The largest one fell a little bit to the north-east of the avalanche of 1885. This one reached the sea and destroyed a warehouse, merchandise, boats and sheep-shed. It also killed 12 sheep. Two other avalanches fell in the area on the same day, one on each side of this largest one.	7	12.1
3.3.1912	Later in the same day another avalanche fell in the area and damaged a telephone line.	8	10.0
3.3.1912	An avalanche came from Hlaupgjá this day but did not reach very far down.	9	10.2
19.3.1946	An avalanche fell just north-east of Bræðraborg. It was about 200 m wide and reached the sea. It overran a sheep-shed but did not damage it (it was protected by snow).	10	>12.2
1951	An avalanche (or perhaps avalanches) fell between Bræðraborg and Hjarðarholt and also out from Bræðraborg.	11	11.6
8.2.–12.2. 1974	Many avalanches (at least 8), probably dry ones, fell from Bjólfur. The references state that "avalanches fell from each gully". No damage is reported but the great snowfall damaged two roofs. **These avalanches are not marked on the map.**		
22.1.1986	A dry avalanche fell from Jókugil and stopped about 115 m a.s.l.	12	9.1
1.2.1988	A dry avalanche came from the gully below Hlaupgjá. The most probable starting-zone is in Presthamrar after a collapse of a cornice. The avalanche stopped about 30 m a.s.l. and was about 25 m wide.	13	9.0
20.2.1995	Two small avalanches fell about 200 m south-west of Vestdalsmjöl.	14	
2.3.1995	An avalanche fell on the outermost part of Aldan. It ran over the road and was about 30 m wide on the road and 1 m thick.	15	12.5
17.3.1995	An avalanche fell between Aldan and Vestdalseyri. It reached into the sea and was 150 m wide on the road but wider further up. The starting zone was 500 m a.s.l.	16	>10.6
1996	An avalanche fell from Bjólfur above Hjarðarholt stopped about 50 m a.s.l.	17	9.2
1996	Another avalanche fell above Hjarðarholt and also stopped about 50 m a.s.l.	18	9.2

Table 1. Recorded avalanches from Bjólfur south-west of Fornistekkur



Map 1. Overview of areas along with recorded avalanches. The original scale is 1:5000 but the map is reduced A3 → A4.



Map 2. Building years and runout indices in the inner area.

Town	Width of area (m)	Total width (km)	Runout index at uppermost houses	Average runout index at uppermost houses	L=low hill (<350 m) H=high hill (>350 m)	S=An avalanche is recorded in the area
Patreksfjörður	300		12		L	S
	300		11		L	S
	100		11		L	
	100		12		L	S
	400		12.5		L	
	200	1.4	12	11.9	L	
Flateyri	200		16		H	S
	200	0.4	15	15.5	H	S
* Bolungarvík	100		11		H	
	100		12		H	
	100		12.5		H	
	300		13		H	
	100		13.5		L	
	100	0.8	14.5	12.8	L	
Hnífsdalur	600		11.5		L	S
	100		12.5		L	
	100		13		H	S
	100		15		H	S
	300		14.5		H	S
	200	1.4	13	12.8	H	S
Ísafjörður Kubbi	100		12		L	S
	200		13		L	S
	100		14		L	S
	100		14		L	
	100	0.6	15	13.5	L	
Ísafjörður Seljalandshlíð	100		14		H	
	300		14		H	S
	100		15		H	S
	400	0.9	12.5	13.4	H	S
Ísafjörður Gleiðarhjalli	100		13		H	
	150		12		H	S
	250		12		H	
	600		11.5		H	
	200		12.5		H	
	100		13		H	
	300	1.7	11.5	11.9	H	
Súðavík	400		15.5		H	
	350		16.5		H	
	150		16.5		H	S
	300		15.5		H	S
	600	1.8	14.5	15.4	H	S

Town	Width of area (m)	Total width (km)	Runout index at uppermost houses	Average runout index at uppermost houses	L=low hill (<350 m) H=high hill (>350 m)	S=An avalanche is recorded in the area
Siglufjörður	50		14		H	S
	250		13.5		H	S
	50		13		H	S
	250		12.5		H	S
	50		12		H	S
	100		11.5		H	S
	100		11		H	S
	100		10		H	S
	150		10.5		H	S
	100		12		H	S
	250		10.5		H	S
	50		10		H	S
	50		10		H	
	100		10.5		H	
	200		10		H	
	100		11.5		L	S
	150		10		L	S
	100		10.5		L	
	100	2.3	11	11.3	L	
Seyðisfjörður Bjólfur	100		15		H	S
	100		14.5		H	S
	50		13		H	S
	300		14		H	S
	150		15		H	S
	50		14.5		H	S
	100		14		H	S
	100		13.5		H	S
	350		12		H	S
	50	1.35	11.5	13.6	H	S
Neskaupstaður	350		16		H	S
	350		15.5		H	S
	250		15		H	S
	150		14.5		H	S
	600		14		H	S
	700		13.5		H	S
	200		13		H	S
	200		13.5		H	S
	350		14		H	S
	150		14.5		H	S
	100		15		H	S
	650		15.5		H	S
	250	4.3	16.5	14.6	H	S
Total / average		17.0		13.3		

Table 2. The runout index at the uppermost houses in the towns of the avalanche data set
* Bolungarvík included here was not one of these towns

Table 2 shows the placement of the uppermost houses in the towns where the avalanches of the collection fell. This table is summarised in Figure 1 which shows the total width of the settlement areas with recorded avalanches (marked with S in the last column of the table) as a function of the runout index. There is for instance an 1150 m wide settlement area in total, where the uppermost houses are at runout index 12. The shaded bars show the situation in Seyðisfjörður and this is obviously not different from the general situation. The average runout index at the uppermost house row for all the areas with recorded avalanches is 13.6 and the average in Seyðisfjörður is also 13.6. This indicates that the distribution of unrecorded avalanches in Seyðisfjörður is similar as in the towns in general. Before this statement can be made with confidence it will be necessary to investigate further the placement of buildings with respect to runout index in Seyðisfjörður and elsewhere, taking into account such factors as the ages of the buildings and the frequency of avalanches.

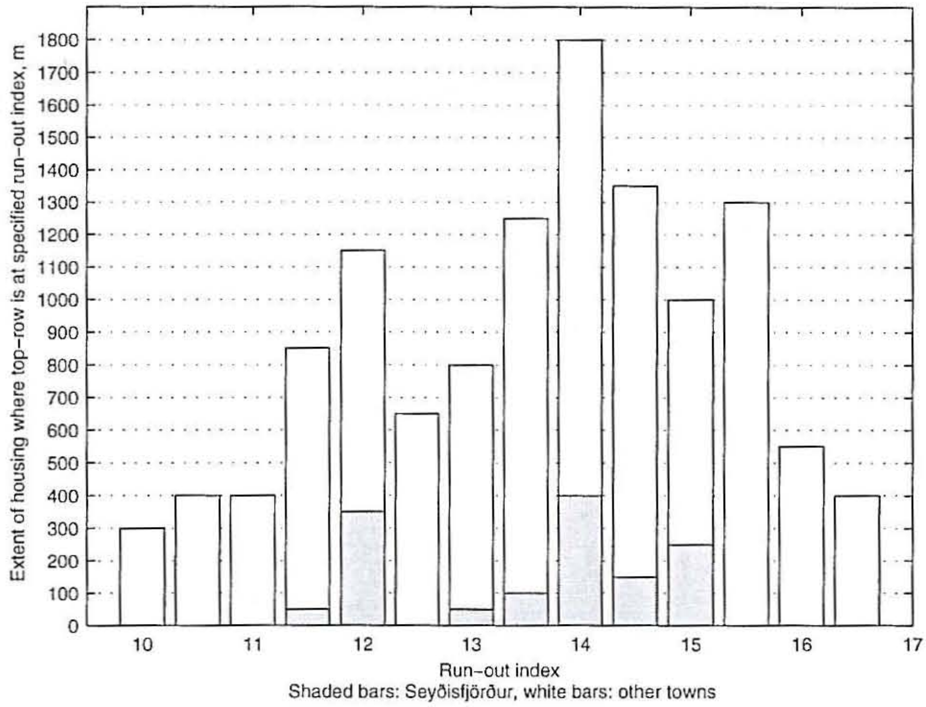


Figure 1. Distribution of settlements in areas with recorded avalanches according to the runout index at the uppermost houses.

On the grounds discussed above we have chosen to use the runout index distribution calculated from all the avalanches in the collection. To warrant the use of a different runout index distribution further research will be necessary.

4. Survival probability

The survival rate curve that is used here is also described in [1] (see Figure 6 on page 10). This curve describes the probability of surviving if an avalanche with a given speed hits an unstrengthened house, and it is based on actual survival rates in the avalanches in Súðavík and Flateyri in 1995. Most of the houses in Seyðisfjörður are of similar standard as the ones hit by these avalanches.

5. Avalanche frequency

In addition to the runout index distribution and survival rate the third basic ingredient in the method is the frequency of avalanches from the hill under consideration. Contrary to the first two, that are estimated globally and once and for all, the frequency estimate is based on the local history of avalanches. As explained in [1] there are two different ways of tackling the frequency estimation, one is suitable where avalanches fall mostly from isolated gullies and the other where they can fall anywhere. In Bjólfur we have chosen to take the second approach.

We estimate F_{16}, the frequency of avalanches reaching runout index 16, from the number of recorded avalanches that have reached a lower index using the formula (5) on page 13 in [1]. We have chosen to estimate the frequency at index 16 separately for $r = 13$, 14, 15 and 16.

In the *inner area* in Seyðisfjörður there are two recorded avalanches that may have reached a runout index of 13. The extent of both of these avalanches is however very uncertain and for one of them the time is also quite uncertain.

and both the time and extent of this avalanche are very uncertain. In the *outer area* and the *Hlaupgjá area* we have more avalanches that have reached a relatively high runout index. These avalanches are listed in Table 1.

We have chosen to consider first jointly the Hlaupgjá area and the outer area. The total width of these areas is 1100 m of which the Hlaupgjá area measures 300 m and the rest is 800 m wide. Table 3 lists the avalanches in these areas that have reached an index of 13 and in addition one that ran into the sea where the shoreline is at index 12.2. Unfortunately very few of these avalanches have a well known width and the determination of a probable value for the width of an extreme avalanche will necessarily involve some guesswork. In the nearby town Neskaupstaður there are more recorded avalanches than in Seyðisfjörður. There the average maximum width of the 10 avalanches that have a runout index of 14 or higher is 244 m and there is some evidence that the width increases with runout distance (c.f. Table 4 on page 12 in [1]). In Seljalandshlíð in Ísafjörður we decided to work with an average width of 400 m. We have chosen to base the Seyðisfjörður calculations on an average width of 300 m.

Table 3 also shows the calculation of the estimates of F_{16} using formula (5) in [1]. This calculation is based on the observation period being 120 years. The N_r values for individual avalanches are 1 if the avalanche reached r and 0 otherwise, except for avalanches that ran into the sea where the coastline is at index less than r. For these the value of N_r is the conditional probability that they have reached r given that they reached the sea. The conditional probability is calculated according to the runout index distribution function so if the sea is at index s and $p(x \geq y)$ denotes the probability that a runout index exceeds y, then

$$N_r = \frac{p(x \geq r)}{p(x \geq s)}$$

The "sum" line contains the combined N_r values for the area the, the N_{16} estimate is

$$N_{16} = N_r^{\text{sum}} \cdot \frac{p(x \geq 16)}{p(x \geq r)}$$

and the F_{16} estimate is

$$F_{16} = \frac{300\text{ m}}{1100\text{ m}} \cdot \frac{1}{120\text{ years}} \cdot N_{16}$$

No.	Year	Run-out index	Width (m)	Comment	Avalanche path	N_{13}	N_{14}	N_{15}	N_{16}	Average
1	1882	>14.4	280-900	in sea	Hlaupgjá	1.00	1.00	0.72	0.35	
2	1885	>14.5	?	in sea	Hlaupgjá	1.00	1.00	0.76	0.37	
3	1894	>14.3	120?	in sea	Hlaupgjá	1.00	1.00	0.68	0.33	
5	1904	14.3	?		Hlaupgjá	1.00	1.00	0.00	0.00	
10	1946	>12.2	200	in sea	N of Bræðraborg	0.80	0.55	0.33	0.16	
					Sum	4.80	4.55	2.49	1.21	
					N_{16} estimate	0.94	1.28	1.18	1.21	1.15
					F_{16} estimate	0.21%	0.29%	0.27%	0.28%	0.26%
					F_{16} for Hlaupgjá alone	0.65%	0.94%	0.85%	0.88%	0.83%

Table 3. Long avalanches in the *Hlaupgjá area* and the *outer area* and calculation of F_{16}.

Now most of the avalanches are in the Hlaupgjá area and we have included in Table 3 a calculation of F_{16} where we take the Hlaupgjá area separately. The formula is

$$F_{16}^{\text{Hlaupgja}} = \frac{300\text{ m}}{300\text{ m}} \cdot \frac{N_r^{\text{Hlaupgja}}}{120\text{ years}} \cdot \frac{p(x \geq 16)}{p(x \geq r)}$$

where N_r^{Hlaupgja} is the sum of the first four rows in the table.

Now we will make a long story short. Based on subjective inspection of the mountain and judgement we have decided to move some of frequency in the Hlaupgjá area to the outer area and set the frequency at 16 in the outer area to be 0.15% and in the Hlaupgjá area to be 0.6%. This corresponds to an overall joint frequency of $(0.6\% \cdot 300\text{ m} + 0.15\% \cdot 800\text{ m})/(1100\text{ m}) = 0.27\%$.

We have then taken the value of F_{16} in the inner area to be 0.05%. This corresponds to the runout index 16 line being the 2000 year avalanche line. One can argue for this value in the following way. Firstly the difference between the highest starting zones in the outer and inner areas is not very large. The higher observed frequency of short avalanches in the outer area may well be explained by the higher numb of gullies there as suggested in section 2 above. If however we choose a much higher value than 0.05% for the frequency at 16 it starts to disagree with the assumed fact that the farm Fjörður has been here for a millennium.

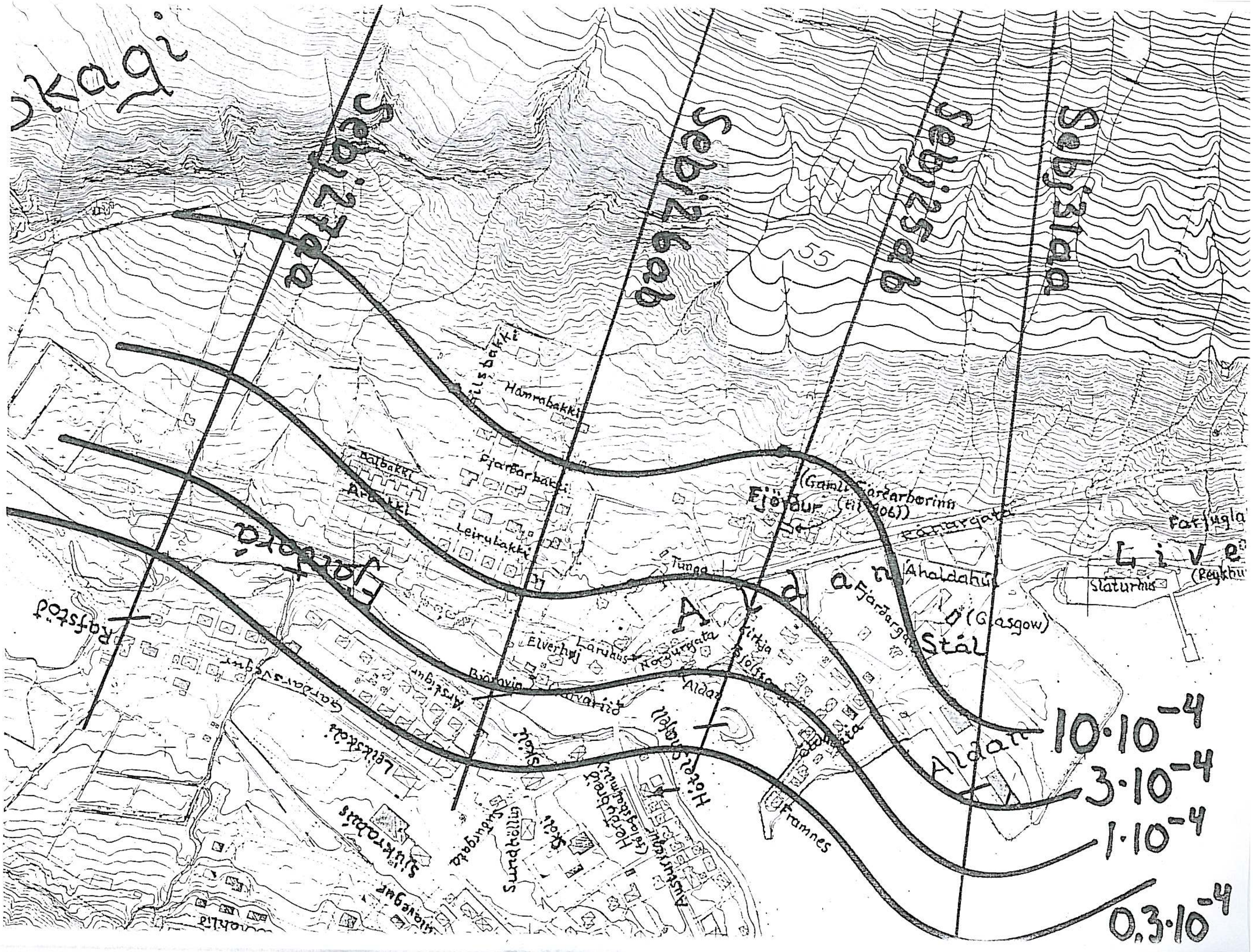
The inner area is 600 m wide and we were assuming the avalanche width to be 300 m. Thus the 0.05% frequency at index 16 corresponds to one avalanche reaching index 16 somewhere in the area every 1000 years. Since $p(x \geq 16) = 12\%$ this corresponds to one recorded avalanche (of any runout index) every 120 years. This is admittedly somewhat less than the actual number of recorded avalanches, there are 3 of them in a little more than a century, but two of the recordings are uncertain.

The farm Fjörður is at runout index 14.2. If we estimate the number of missing avalanches between runout indices 15 and 16 to be 50% of the number of recorded ones, and that between 14 and 15 there are as many missing as recorded avalanches then a simple calculation based on the 0.05% frequency at 16 and the runout index distribution of section 4.2 in [1] gives a return period of 400 years. We find this believable but a much higher frequency not.

An inspection of Map 2 does not indicate that the position of any of the other houses contradicts this frequency.

6. The risk calculation

The risk has been calculated along three profiles using the formulas in chapter 8 in [1]. The result is shown in Table 4, Figure 2 and on Map 3. No correction of the $10 \cdot 10^{-4}$ line has been carried out and this has to be borne in mind when interpreting the results (cf. [1], the paragraph at the end of section 4.4 on page 10 and in section 8.1 at the bottom of page 14). The necessary correction will move the line somewhat away from the hillside. The $3 \cdot 10^{-4}$ line is quite close to the runout index 16 line and should need little correction. The other 2 lines, being outside the 16 line, do not need correcting under the assumptions of chapter 4 in [1].



Map 3. Calculated risk lines

	Metres from profile reference point				Run out index				Return period			
Profile \ Risk	$0.3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$10 \cdot 10^{-4}$	$0.3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$10 \cdot 10^{-4}$	$0.3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$10 \cdot 10^{-4}$
sebj31aa	166	91	16	-75	18.2	17.5	16.8	16	3600	1450	620	260
sebj25ab	31	-58	-156	-314	16.7	15.9	14.8	13	6300	2700	1240	500
sebj26ab	75	-10	-116	-263	16.6	15.9	14.8	12.6	6200	2200	1230	500
sebj27aa	-71	-161	-285	-441	16.7	16	14.8	12.5	6100	2600	1200	480

Table 4. Results of risk calculation.

To check the results we have compared them with the Norwegian alpha-beta model To get a consistent comparison we have used the β-angles of the runout index maps compiled at the IMO last year. We have used the same procedure as was used there to automatically determine the β-angles of the 3 profiles in Seyðisfjörður. The formula used for α is

$$\alpha = 0.92\beta$$

and the standard deviation used is 2.6°. This is the formula and the standard deviation of the runout index maps. The results of the alpha beta calculation are shown in Figure 2. We see that the calculated $0.3 \cdot 10^{-4}$ risk contour is very close to being 2 standard deviations beyond the alpha point.

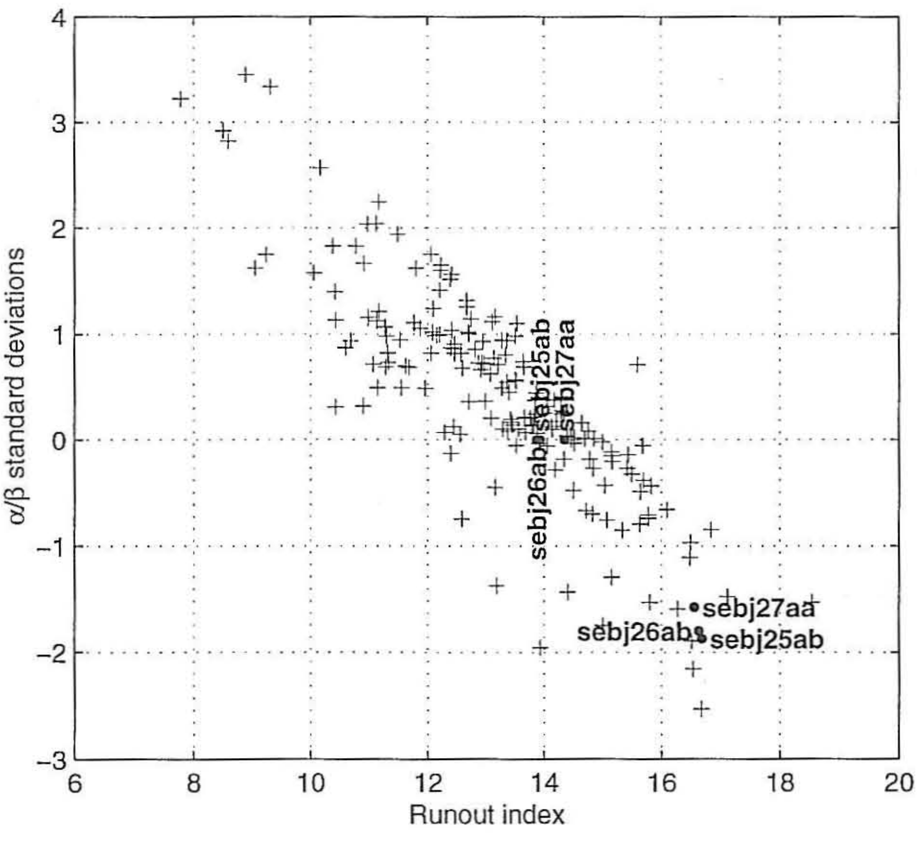


Figure 2. Alpha-beta standard deviations and runout indices for 197 Icelandic avalanches and at the alpha point and $0.3 \cdot 10^{-4}$ risk point of 3 profiles in Seyðisfjörður.

We are aware of the fact that the alpha-beta method and the runout index method of transferring avalanches can produce different results. To check this out we have plotted the alpha-beta standard deviations against the runout index for all the 197 avalanches in the Icelandic data set. On the same plot we have plotted corresponding points for the $0.3 \cdot 10^{-4}$ risk point and for the alpha point of each of the three Seyðisfjörður profiles. The fact that these points lie in among the other points indicates that the alpha-beta scale and the runout index scale for measuring runout distance give similar results for the three profiles in Seyðisfjörður.

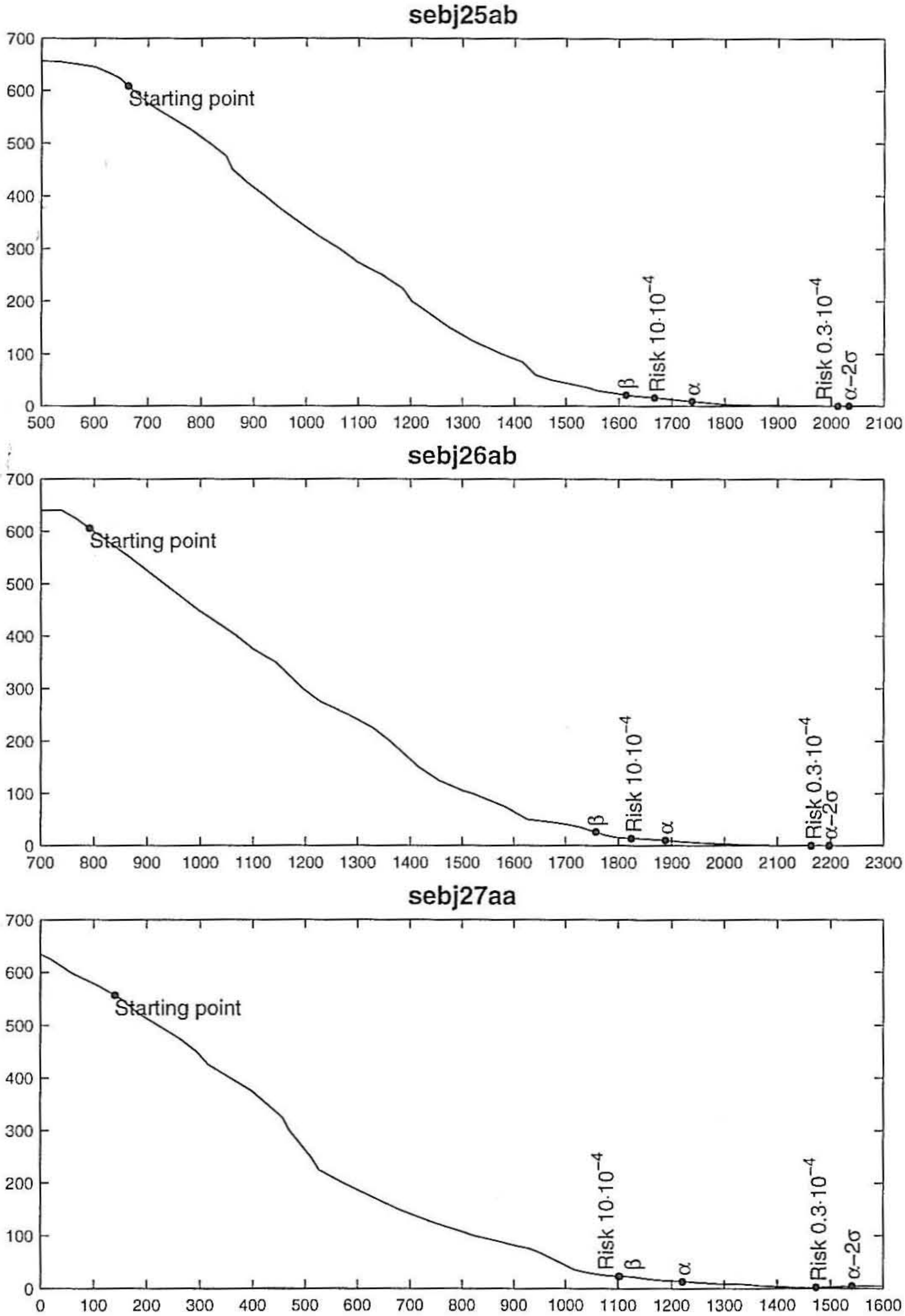


Figure 3. Three profiles in Seyðisfjörður.

7. References

[1] Kristján Jónasson and Þorsteinn Arnalds. "A Method for Avalanche Risk Assessmen; Short description", IMO report VÍ-G97036-ÚR28, November 1997.

[2] Kristján Jónasson and Þorsteinn Arnalds. "Tilraunahættumat fyrir Seyðisfjörð; Verkáætlun" (Pilot hazard zoning for Seyðisfjörður; Project plan), IMO report VÍ-G97017-ÚR13, with English translation, August 1997.