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The proposed open-pit protection of Bolungarvík, Iceland

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ABSTRACT. Snow avalanches threaten a large part of the residential area of Bolungarvík, a town of 1100 inhabitants located in the Vestfirðir peninsula, northwest Iceland. Methods for the complete protection of all the houses were requested by the Ministry of Environment. As conventional deflecting and catching dams were not feasible due to avalanche velocities of $>40\ \mathrm{m\,s^{-1}}$ in the actual defence area, a huge open pit built into the lower mountainside was proposed. The pit is designed to dissipate the energy of avalanches of any expected size. It is 1000 m long, and the upper and lower pit walls are 30–40 and 15–20 m high, respectively. The downhill side of the pit is increased to 30 m by a nearly vertical, 10–15 m high dam. The bottom is 25–40 m wide, and the effective cross-sections are 700–2300 m^2. The total storage capacity is approximately $10^6\ m^3$. Cost–benefit analyses indicate that the development cost of the pit protection is favourable compared to the value of the houses as well as alternative safety solutions.

INTRODUCTION

The safety of the small town Bolungarvík, Iceland, was first questioned when a disastrous avalanche struck the nearby town of Súðavík in January 1995, causing 16 deaths. Ten months later another catastrophic avalanche struck the nearby town of Flateyri and 20 people perished. In February 1997 a small avalanche struck three houses in the residential area of Bolungarvík, causing minor structural damage to one of the houses. These incidents indicated, beyond doubt, that catastrophic avalanches could hit the town, and led to an appraisal study on the avalanche problems of Bolungarvík (Jónsson and Hestnes, 1999) (Fig. 1).

After field investigations and calculations of avalanche runout it was concluded that almost half of the town was in the endangered zone, and that conventional mitigative measures were not feasible due to the size and amount of snow in the starting zones and the estimated velocities and limited space above the residential area. To fulfil the safety requirements specified by the Ministry of Environment, an unconventional solution had to be figured out. After thorough assessments an open-pit protection along the foot of the mountain was proposed for the whole town. It was designed to trap avalanches of any expected size occurring anytime during winter. Tests of optimum design of rim areas, as well as end and cross-sections, were recommended.

SITE CHARACTERISTICS

Bolungarvík is a fishing town with 1100 inhabitants, located in the Vestfirðir peninsula in northwest Iceland. It is situated on level ground below the steep south-to-east facing slope of Traðarhyrna (Fig. 1). To the east is an open fjord, and to the west is a broad open valley with a few farmyards. The residential area, extending approximately 1000 m along the foot of the mountain, was mostly developed during 1960–80.

The steep slopes of Traðarhyrna tower 600 m above the town. The flat-lying tertiary basalt layers are in the upper part, intersected by five major avalanche chutes and some minor ones. The mid- and lower part of the slope is covered by scree cones and a thin talus. The slope angle is $>30°$ down to 60–80 m a.s.l., and the 10° point is almost at the elevation of the houses. The exposed houses are located on debris and moraine deposit 20–40 m a.s.l.

Avalanches are most frequently released in the chutes. However, both the scree area below the steep cliffs, and the talus and scree slope below the level of Ufsir, are individual starting zones that may be triggered by avalanches from above (Figs 1 and 2).

The mouth of the large chutes is 20–30 m wide at approximately 350 m a.s.l., while the width above is 50–100 m. The

Fig. 1. Aerial view of Bolungarvík and Traðarhyrna mountain. Photo by O. Sigurðsson.

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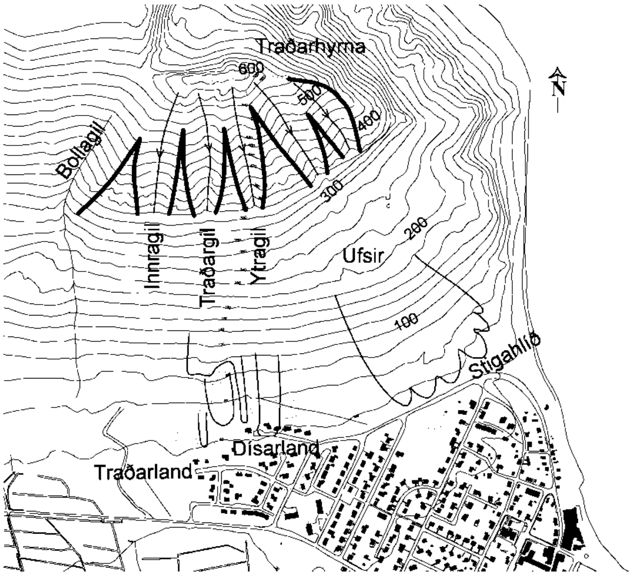

Fig. 2. Runout of well-documented avalanches (black) and others (dashed lines and hatched areas).

depth of their cross-sections is 15–25 m. Three of the main chutes face south, while the two others face southeast. The south-facing chutes are the most critical starting zones above the residential area (Fig. 2).

Precipitation coming from the sea by northerly wind blows across the sharp ridge of Traðarhyrna, and deposits snow in the different starting zones on the lee side. Easterly winds sweeping along the mountainside supply snow mainly to the south-facing chutes, while westerly winds add snow in all chutes. The snow in central parts of the chutes can be very deep. In fact, >4 m of snow are registered on the ridges in the upper part between the south-facing chutes. In the starting zones below the cliff area, winds blowing in or out of the valley will mainly redistribute snow.

RISK ASSESSMENT

Safety standard

The Ministry of Environment has specified that avalanche-protection works in residential areas in Iceland shall fulfil a safety requirement of $0.2–0.5 \times 10^{-4}$ per person per year. For comparison, this level is somewhat lower than the average risk due to traffic accidents, which is around 1×10^{-4} per year (Jóhannesson and others, 1996). The practical consequence of this standard is that a chosen method of protection must give a nominal level of 100% security.

Avalanche history

Records of avalanches reaching or passing the 10° gradient

Table 1. Runout calculations

	Site	H	β		α			α − 1SD				PCM	
			Angle	Height	Angle	Runout	Vertical	Angle	Runout	Vertical	my	MD	Runout
		m	°	m	°	m	m	°	m	m			m
P00	Bollagil	625	28.5	55	24.2	1329	598	20.8	1613	611	0.17	1000	1613
											0.13	700	1596
P001		425	29.6	56	25.1	837	393	22.8	949	400	0.23	700	945
											0.18	500	941
											0.12	300	949
P01		450	29.2	44	24.8	980	424	22.5	1045	433	0.20	700	1035
											0.15	500	1046
											0.10	300	1037
P02	Innragil	550	31.1	42	26.4	1058	526	24.1	1196	535	0.25	1000	1200
											0.20	700	1189
											0.15	500	1187
P021		425	28.5	40	24.2	895	403	21.9	1022	412	0.18	700	1029
											0.14	500	1014
P03	Traðargil	575	30.0	34	25.5	1170	559	23.2	1310	562	0.21	1000	1324
											0.16	700	1309
											0.11	500	1312
P031		400	29.3	38	24.9	908	397	22.6	981	408	0.20	700	985
											0.15	500	990
											0.10	300	971
P04	Ytragil	600	31.7	40	26.4	1123	571	24.6	1247	572	0.25	1000	1242
											0.20	700	1225
											0.14	500	1240
P041		400	28.3	36	24.0	842	375	21.7	951	379	0.20	700	940
											0.15	500	943
P042		400	28.6	40	24.3	830	374	22.0	882	379	0.21	700	942
											0.16	500	949
											0.10	300	942
P05	Ofan Ufsa	480	29.7	32	25.2	974	459	24.1	1030	460	0.23	700	1021
											0.18	500	1019
											0.11	300	1020
P06	Ofan Ufsa	575	30.3	28	25.8	1168	564	24.6	1246	571	0.20	700	1241
											0.16	500	1239
											0.11	300	1249

Notes: my, Coulombs friction (coefficient); MD, mass to drag friction (coefficient).

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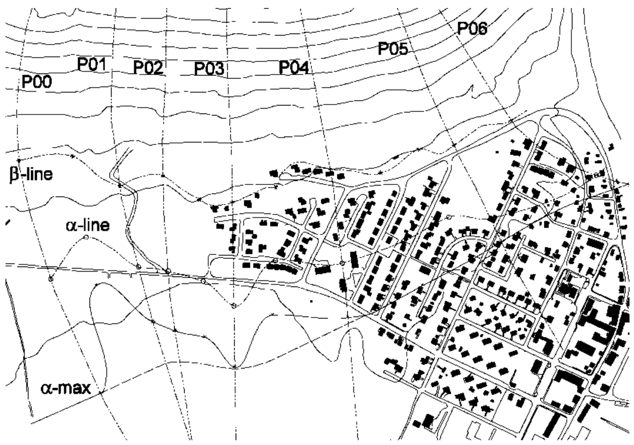

Fig. 3. The residential area, with main profiles and runout lines (β-line, α-line, α-max line).

of the slope date back only to 1957. Altogether 15 events are reported, mainly small ones. Some larger avalanches, registered far into the residential area, occurred before the town expanded inland (Fig. 2). The starting zones of the documented avalanches are not identified, but most of them are believed to have started from the chutes in the higher part of the mountainside.

Numerous loose rocks of different size spread on the ground within and outside the western part of the housing area indicate that far-reaching avalanches may have occurred occasionally. Information on large avalanches in the 18th century, recently discovered in old documents, may throw some light on former events.

Runout calculation

Runout calculations were conducted for 12 path profiles using the Icelandic α/β model (Jóhannesson, 1998). The results were compared with calculations by the Perla/Cheng/McClung (PCM) model (Perla and others, 1980) (Table 1). The standard deviation of the extreme runout was determined based on the characteristics of the avalanche paths, their aspect and comparison with extreme runout along comparable path profiles (Bakkehøi and Norem, 1999; Jónsson and Hestnes, 1999).

The runout was adjusted for some profiles where paths overlapped in the runout zone. The standard deviation chosen varied from −0.5 in the east to −1.5 in the west. The lower part of the profile of the seven major paths, the chosen 10° points (β-line), the calculated average α and the estimated extreme runout are shown in Figure 3. According to the Icelandic safety standard, almost half of the residential area is within the endangered zone.

Comparison of avalanche profiles

The main path profiles of Bolungarvík have been correlated with the main profiles of the catastrophic avalanches in Súðavík (January 1995) and Flateyri (October 1995) (Jónsson and Hestnes, 1999). After scaling of the paths, the Súðavík path showed a very close relation to the three south-facing paths of Bolungarvík. The standard deviation (SD) between the Súðavík and the Traðargil path was only 9 m, and the runout at Súðavík corresponds to $\alpha - 1\text{SD}$ of the Traðargil path (Fig. 4). The runout at Flateyri corresponds to approximately $\alpha - 1.5\text{SD}$.

However, there are two main differences between the avalanche sites in Súðavík and Bolungarvík. The upper starting zones in Bolungarvík are much longer than in Súðavík. On the other hand, there is a large plateau above the starting zone in Súðavík, feeding snow into the potential starting areas during northwesterly and westerly winds. The role of these differences in respect of extreme runout calculations is, however, uncertain.

MITIGATIVE MEASURES

After the expected extreme runout along the different paths had been decided on, the velocity profiles of the design avalanches were estimated by the PCM model (Perla and others, 1980). The results were cross-checked by the Norem/Irgens/Schieldrop (NIS) model (Norem and others, 1987). The velocity profiles of the design avalanches were calculated by the PCM model. The results indicated that the velocity by the houses in Dísarland and Traðarland is around 40 m s^{-1}. Above the residential area to the east the velocity was estimated to be 30–35 m s^{-1} (Figs 2 and 3).

Different layouts of deflecting and catching dams for pro-

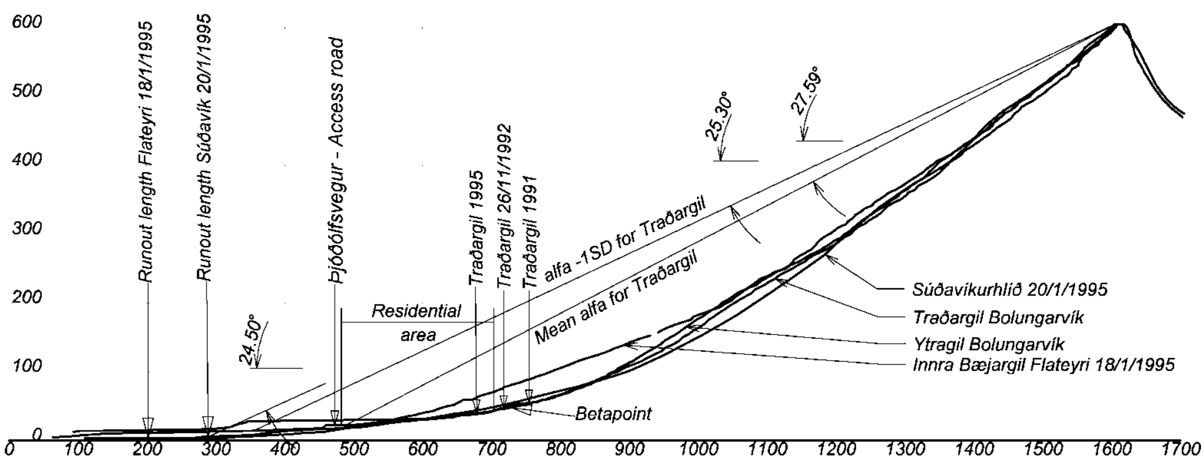

Fig. 4. Comparison of avalanche profiles.

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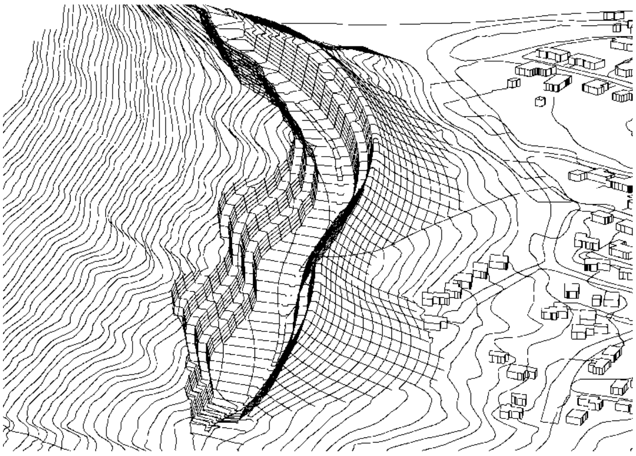

Fig. 5. Aerial view of the pit protection. Viewed towards east.

tecting the western part of the area were examined, but there was no real alternative, due to the steep terrain and the even higher velocities above the houses. In fact, the preliminary conclusion was that only a few houses above the α-average line could be protected by conventional mitigative methods in the runout zone (Fig. 3). The value of these houses was less than the cost of the actual protection works.

The possibilities of using supporting structures, including a rough estimate of total length and costs, were also examined. To secure the residential area the upper, mid- and lower starting zones, approximately down to the 150 m contour line, all have to be covered. Snow-depth measurements registered since 1996 at 11 stakes mainly located on ridges were available, and additional probing was carried out in late March 1999. The results of these investigations indicate that the snow depth of the upper starting zones within 5 year return periods can be >4 m on the ridges and at least 8 m in the chutes. The preliminary snow measurements and cost estimates showed conclusively that conventional supporting structures and nets were unrealistic for protection of the residential area under Ytragil to Innragil. Steel bridges and nets may be an option in the chutes east of Ytragil, but additional snow-depth measurements are essential (Jónsson and Hestnes, 1999).

Removal of the houses above the α-average line and protection of those below with deflecting and catching dams was an option (Fig. 3), but the Ministry of Environment did not approve the solution. Nor was there any enthusiasm for abandoning a residential area where the assessed property value of all the houses was estimated to be USD12 million, the rebuilding cost to be USD30 million and the total

Table 2. Dimensions and design parameters of the pit

Profile/Pit station	Calculated velocity above pit $m\,s^{-1}$	Estimated avalanche volume $10^3\,m^3$	Estimated width of avalanche above the pit m	Cross-sectional area of profile at pit m^2
P02/~60	48	90	120	400
P03/~220	52	110	130	2300
P04/~420	51	90	105	1700
P05/~700	40	40	115	1350
P06/~820	43	90	180	1150

re-establishment costs to be USD40 million. A search for unconventional safety methods was therefore started.

THE OPEN-PIT PROTECTION

It was a challenging task to design a mitigative measure that could stop avalanches running at velocities of $>40\,ms^{-1}$. The proposed protection had to dissipate the avalanche energy completely. Hardly any dense avalanche flow should overtop the barrier.

An open pit built into the lower part of the slope was proposed (Figs 5 and 6). The pit is 1000 m long, and the upper and lower pit walls are 30–40 and 15–20 m high, respectively. Along the lower edge a 10–15 m high dam is located, which makes the total height of the downhill side 30 m. The bottom is 25–45 m wide. At both ends a 100 m long grade goes from rim to bottom. The estimated volume of the pit is about 700 000 m^3. Approximately 200 000 m^3 is needed for the dam on the lower edge. The rest has to be removed and can be used for other purposes by the community. The total storage capacity of the protection is about $10^6\,m^3$.

The cross-sections are 700–2300 m^2. The dimensions are based on the estimation of design volume, velocity and retardation of one design avalanche per chute per year, as well as the expected total mass balance of the sections of the pit during a whole winter. The capacity is well above the design volume, as there are uncertainties concerning the accumulation of drifting snow in the pit. The estimated maximum avalanche to be trapped is about 110 000 m^3 (Table 2).

The purpose of the pit is to trap the dense part of the avalanche and dissipate the energy. The estimated velocity at the upper edge of the pit is 40–52 $m\,s^{-1}$. It is important that the edge is in steep terrain so that the drop of the ava-

Fig. 6. Perspective from inside the pit. A car can be seen to the left.

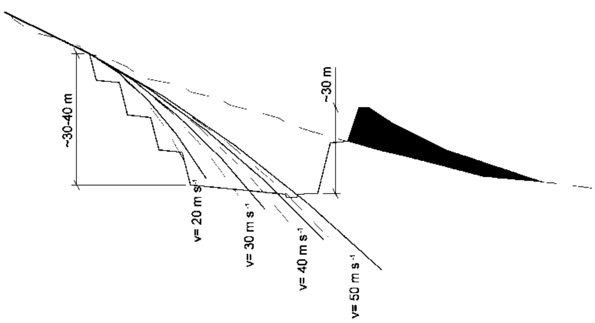

Fig. 7. Cross-section of the pit and dam, with estimated parabolic paths of avalanche masses. The initial velocity is 20–50 $m\,s^{-1}$. The dashed lines represent 15% velocity reduction.

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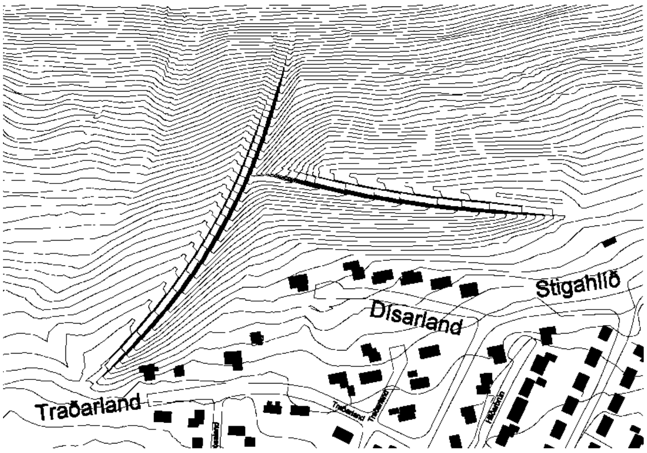

Fig. 8. A sketch of the actual protection. Safety is secured by combining conventional mitigative methods with evacuation.

lanche mass is as steep as possible. The average inclination of the natural slope above the edge is 15–40°.

The trajectory of frictionless particles as well as particles affected by air friction was calculated. Assuming that masses subjected to air friction lose 15% of their velocity between the edge and the bottom of the pit, they will have a slightly higher impact angle (Fig. 7). No air-cushion effect of any significance is supposed to occur within the pit, because of the large size of the pit compared to the influx of avalanche masses (Irgens, 1999).

Avalanches will dissipate energy by impact, due to the damping and compression of the snow masses, and scattering and changes in the direction of movement. The rate of energy loss will vary. A preliminary model study of the behaviour of a design avalanche was carried out. Only a minor part of the mass overtopped the 30 m high barrier.

Radiation of compressed air will occur when avalanche masses are falling into the pit. However, it is unlikely that air blasts or snow clouds can cause damage to houses below the dam.

In between the hard flat-lying tertiary basalt of Traðarhyrna there is soft material. For stability reasons and optimum design, the pit walls will have benches adapted to the in situ geological conditions (Fig. 7). The wall design is in accordance with recommendations from Icelandic engineering experts. The ultimate layout will require structural and strength analysis based on field tests. To prevent loose material from the talus above the protection site from falling into the pit, a flat area will have to be cut above the upper rim and lined with a low rock wall or dam. The huge dam along the lower edge is planned with a nearly vertical retaining wall on the upstream side. Alternatively, a boulder or corrugated steel front of the dam is suggested. The stability and environmental problems are discussed in Jónsson and Hestnes (1999).

Ground-water will seep into the pit especially during spring, summer and fall. Water from melting snow will seep into the pit during thaws. Drainage of the pit will take place through a corrugated steel tunnel located above Stigahlíð. This tube will be the main construction entrance to the pit and may, if necessary, be used to remove snow from the site by the end of the melting season.

The grade at both ends of the pit is supposed to help funnel easterly and westerly winds through the pit, keeping it almost free of drifting snow. Southerly winds may create cornices along the crown of the dam, but the total volume will probably be negligible. However, tests of optimum design of rim areas and end sections are recommended.

The estimated cost of the pit project is USD14 million. Thus, the economy of the proposed open-pit protection is very favourable compared to rebuilding costs and the total re-establishment costs of the houses. An open-pit protection may be used for part of the town as well.

EPILOGUE

During spring 1999 the Ministry of Environment reconsidered the safety management for the residential area and asked for a supplementary appraisal study of Bolungarvík based on conventional methods. The safety standard per person per year will remain the same, but alternative methods may be used to achieve it. According to the new criteria, avalanches are allowed to overtop a dam every 10–30 years. The safety of the residents will be secured by evacuation.

Five alternative layouts were proposed in early summer 1999, based on combinations of deflecting and catching dams and the removal of houses (Jónsson and others, 1999). Improving the safety of all houses below Ytragil and Traðargil by combining a catching and a deflecting dam may be the ultimate choice (Fig. 8).

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