Rit Veðurstofu Íslands

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An overview of the need for avalanche protection measures in Iceland

Report prepared for the Icelandic Ministry for the Environment and local authorities in towns threatened by avalanches

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FOREWORD

The present report is prepared by the Icelandic Meteorological Office for the Icelandic Ministry for the Environment and local authorities in towns threatened by avalanches. It is partly financed by the Icelandic Avalanche Fund and partly by funds from the joint avalanche research project "Norway-Iceland" supported by the Nordic Council of Ministers. Avalanche experts from Norges Geotekniske Institutt in Norway and Eidgenössisches Institut für Schnee- und Lawinenforschung in Switzerland took part in the preparation of the report in addition to the staff of the Icelandic Meteorological Office.

The Icelandic Meteorological Office gratefully acknowledges the support that made it possible to accomplish the study.

CONTENTS

SUMMARY

Preliminary proposals for avalanche protection measures for 8 communities in Iceland are described and the cost of the measures is estimated. These communities include the largest densely populated avalanche prone areas in the country. The cost of the protection measures is compared to the value of buildings and infrastructure in the respective areas which are threatened by avalanches. The total cost of all the proposed defense structures is about 7000 million IKR. The estimated total value of buildings and infrastructure in the areas is usually several times higher than the estimated cost of the protection measures.

Potential cost of direct avalanche defenses of individual buildings in areas, where explicit defense proposals are not made in this report, may be expected to exceed several hundred million IKR. Furthermore, the cost of avalanche protection measures in communities, which were not explicitly considered in this overview, and the cost of slush and debris flow protection measures, which were only briefly considered in the overview, needs to be considered. This cost may also be expected to exceed several hundred million IKR. The cost of permanent evacuation of buildings in avalanche hazard areas, where avalanche protection measures are not practical, will depend on future regulation about the purchasing of property in hazard areas by the government. This cost is difficult to estimate, but it may also possibly exceed several hundred million IKR. When all this is taken into consideration, the result is that the total cost of avalanche protection measures, including purchasing of buildings in avalanche hazard areas, may be estimated to be on the order of 9000 million IKR. There is an uncertainty in the cost estimate due to the uncertain extent of avalanche hazard areas and due to uncertain design assumptions for the proposed defense structures. There is also considerable uncertainty in the cost estimate due to the additional protection measures in areas which were not explicitly considered in the report. This uncertainty is difficult to quantify, but it reasonable to assume that the total cost of protection measures will be in the range 7000 to 14000 million IKR.

The avalanche hazard in the different areas is indicated with a risk index which is based on the frequency and magnitude of avalanches, on one hand, and on the number of people in the endangered areas, on the other hand. More than half of the total cost of the proposed protection measures is in areas where the risk index indicates the highest avalanche risk.

Direct economic loss due to avalanches in towns in Iceland in the 22 year period between 1974 and 1995, together with the cost of purchasing buildings and the construction cost of defense structures, is about 3800 million IKR. This includes the cost associated with the relocation of Súðavík, the purchasing of houses in Hnífsdalur and the estimated cost of defense structures for Flateyri, which are under construction. The loss does not include damage due to avalanches in rural areas (*e.g.* farm buildings, power and telephone lines and ski lifts), which is substantial, but may be assumed to be much smaller than the estimated total loss in major avalanche accidents in and near towns.

A total of 52 people have been killed by avalanches in buildings, at work sites or within towns during the same period. If the death of a person in an avalanche accident is included in the economic loss in a similar way as in a recent study of the economic loss due to traffic accidents in Iceland (100 million IKR per fatal accident), the total cost of avalanche accidents in Iceland in the last 22 years is similar to the total cost of avalanche protection measures which are described in this report.

It is necessary to initiate research of the avalanche conditions in Iceland in order to improve the observational basis for the design of protection measures. The most important research areas in this respect are hazard mapping, regular monitoring of the distribution of snow in the starting zones of avalanches, research of the effectivity of dams and breaking mounds, measurements of

the physical properties of snow in Iceland with special regard to design assumptions for supporting structures and investigation of the utility of snow fences under Icelandic conditions.

It must be stressed that continuous monitoring of avalanche danger must be performed in the future in all areas where there is avalanche danger. Conditions for the construction of avalanche protection measures are sometimes difficult due to lack of space for dams or uncertainty about the location of the most important starting zones for the construction of supporting structures. In such circumstances, the construction of the defense structures must be combined with the monitoring of the avalanche conditions and a readiness to execute an appropriate evacuation plan in extreme situations. Even when the conditions for the construction of the protection measures are good, one must also monitor avalanche conditions carefully in order to be able to see whether unforeseen conditions are developing so that appropriate measures can then be taken to insure the safety of the community.

1. INTRODUCTION

Catastrophic avalanches in the villages Súðavík and Flateyri in 1995, which killed a total of 34 people and caused extensive economic damage, have totally changed the view regarding avalanche safety in Iceland. These avalanches made it clear that a substantial number of people in several Icelandic towns and villages live in areas where avalanche risk is unacceptable. Although extensive evacuations may be used to reduce this risk to some extent, they can only be viewed as a temporary measure and avalanche protection or land use changes are necessary for a permanent solution to this problem.

The goal of this study is to give an overview of the need for avalanche protection in Iceland. The overview will provide governmental agencies and local authorities with an estimate of the likely cost of avalanche protection for the towns threatened by avalanches in the most important avalanche regions in Iceland. The Icelandic Meteorological Office was requested to prepare this overview following a meeting in Reykjavík on 9 February 1996 where officials from the Icelandic Ministry for the Environment met with representatives of the local authorities in towns threatened by avalanches.

A classification of the avalanche risk in the areas where the protection measures are proposed, is based on rough estimates of the avalanche frequency and magnitude and on the number of people in the endangered areas. Protection measures against avalanches in all hazardous locations in Iceland will be costly. Hence, the construction of defense structures for all areas, where avalanche protection is judged economical, may be expected to take a long time. The risk classification is meant as a rough guidance for the necessary prioritization of the protection measures, but it must be stressed that more exact hazard mapping is necessary before a large effort in avalanche protection in Iceland is initiated.

The estimated value of buildings in endangered areas is based on the current extent of inhabited areas in or near avalanche hazard zones in Iceland. Social changes or political decisions, which might influence the demography of these areas in the future, are not considered.

The report starts with a description of the field work that was carried out for the study in section 2 and a summary of the avalanche problems of Iceland in sections 3 and 4. Avalanche protection measures and the scope of the overview study are discussed in section 5. The proposed avalanche protection measures are summarized in several tables and discussed in general terms in section 6. Sections 7-16 describe the avalanche situation and the proposed protection measures for each of the towns which are considered. Section 17 lists several recommendations of the work group for research or other measures that can lead to future improvement in the avalanche safety in Iceland. A description of each proposed dam and deflector is contained in Appendix I and a detailed description of the underlying assumptions for the cost estimates of dams and deflectors is described in Appendix II.

2. FIELD WORK

Each site was visited by a work group of 4-5 people. It consisted of two foreign avalanche experts, two or three scientists from the Icelandic Meteorological Office (IMO) and in most cases an Icelandic civil engineer. The local avalanche observer met with the group in each place and participated in most of the field work. The work group examined the slopes above each site, walked up to possible starting zones for avalanches and examined the conditions on the plateau above the slopes where possible. Conditions for different protection types, *i.e.* supporting structures in the starting zones, deflectors or dams further down the avalanche path and snow fences above the starting zones, were evaluated and a rough cost estimate derived for the construction of the defense structures which were considered most appropriate by the group.

The examination of the sites was organized as two separate 10 day visits by the foreign avalanche experts to Iceland. One visit involved trips to sites in Vestfirðir and the other trips to sites in Austfirðir and Norðurland.

The first visit was during the period 5-14 May 1996. Ísafjörður, Hnífsdalur, Bolungarvík, Patreksfjörður and Bíldudalur were examined. The work group members were Frode Sandersen from Norges Geotekniske Institutt in Norway (NGI), Stefan Margreth from Eidgenössisches Institut für Schnee- und Lawinenforschung in Switzerland (EISLF), Tómas Jóhannesson and Þorsteinn Sæmundsson from IMO. Árni Jónsson from HNIT Ltd. participated in the trips to Ísafjörður, Hnífsdalur and Bolungarvík. Gunnar Guðni Tómasson from Verkfræðistofa Sigurðar Thoroddsen Ltd. (VST) participated in the trips to Patreksfjörður and Bíldudalur. Oddur Pétursson, the local avalanche observer for Ísafjörður, joined the work group in Ísafjörður, Hnífsdalur and Bolungarvík. Jóhann Hannibalsson, the local avalanche observer for Bolungarvík, joined the work group in Bolungarvík. Jónas Sigurðsson and Jónas Þór, the local avalanche observers for Patreksfjörður, joined the work group in Patreksfjörður. The work schedule was as follows.

7-8 May	Ísafjörður.
9 May	Hnífsdalur.
10 May	Bolungarvík.
11 May	Patreksfjörður.
12 May	Bíldudalur.

The second visit was during the period 2-11 June 1996. Neskaupstaður, Seyðisfjörður and Siglufjörður were examined. The work group members were Karstein Lied from NGI, Stefan Margreth from EISLF, Tómas Jóhannesson, Þorsteinn Sæmundsson and Kristján Jónasson from IMO. Guðmundur Helgi Sigfússon, the local community engineer and avalanche observer in Neskaupstaður and Sigurður Jónsson, the local community engineer in Seyðisfjörður participated in the work in the respective towns. Þorsteinn Jóhannesson from Verkfræðistofa Siglufjarðar and Sigurður Hlöðversson, the local community engineer in Siglufjörður, participated in the work in Siglufjörður. The local avalanche observers Tómas Zoëga from Neskaupstaður, Hallgrímur Jónsson from Seyðisfjörður and Örlygur Kristfinnsson and Sverrir Júlíusson from Siglufjörður, joined the work group in the respective towns. The work schedule was as follows.

4-5 June Neskaupstaður.
6-7 June Seyðisfjörður.
8-9 June Siglufjörður.

3. SNOW AVALANCHES IN ICELAND

3.1 Historical overview

Snow avalanches have caused many catastrophic accidents and extreme economical damage in Iceland since the settlement of the country in the ninth century. The pioneering work of Ólafur Jónsson (1957), which was updated in 1992 (Ólafur Jónsson and others 1992), lists avalanches reported in annals and other sources since the twelfth century. It lists predominantly avalanches which caused damage to inhabited areas and avalanches which caused fatal accidents.

The first reported avalanche accident dates back to 1118 when a snow avalanche killed 5 people in Dalir in Western Iceland. Altogether about 680 deaths by avalanches have been reported in Iceland since this first report (Ólafur Jónsson and others 1992, Helgi Björnsson 1980). Unaccounted deaths may be assumed to have been several hundreds, especially during two gaps in the written records before 1600.

Before the middle of the nineteenth century, the population of Iceland lived almost exclusively in rural areas. Most of the accidents occurred on farms, when avalanches hit farmhouses or farm workers working or traveling near the farms, and during winter travels, for example from farms to coastal fishing stations and to church. Near the end of the nineteenth century, a number of fishing towns were established in deep fjords in western, northern and eastern Iceland. Parts of these towns turned out to be located in avalanche prone areas and several catastrophic accidents occurred in the years 1880-1920, a period of relatively harsh winters.

An expansion of the fishing towns in western, northern and eastern Iceland into areas further up into the mountain slopes occurred during the decades from 1930 to 1980 and led to a dramatic increase in the number of buildings in avalanche exposed areas. Records of the avalanche activity in most of these areas do not exist as the areas had not been inhabited, and avalanches which did not cause damage were not recorded in Iceland until recently. Relatively mild climate between 1925 and 1965 led to fewer avalanche accidents during this period compared with the period around the turn of the century. Climatic deterioration after 1965 has brought an increase in the avalanche activity. Several catastrophic avalanche accidents have occurred in recent decades in relatively new neighbourhoods in towns in western and eastern Iceland as is further described below in a separate section on fatal avalanche accidents.

3.2 Topographic characteristics

Almost all the inhabited areas where avalanches pose a threat to the local population are located close to the coast in western, northern and eastern Iceland. The mountain slopes above the hazard areas usually rise to between 400 and 700 m above sea level. The mountains above the slopes are often flat and formed as large plateaus, especially in the Vestfirðir region. Mountains in the Austfirðir region are more often formed as narrow ridges with Alpine characteristics. The plateaus are important as catchment areas for snow drift which can transport large amounts of drifting snow to the starting zones of avalanches under unfavourable circumstances during storms.

Starting slopes of the more extreme of the reported avalanches in Iceland are usually between 30° and 45°, although both lower and steeper inclinations occur. The average slope of the avalanche tracks, β (measured from the starting zone to the foot of the slope, which is defined here as the location where the inclination equals $\psi = 10°$), usually varies between 24° and 30°.

Forests are almost non-existent in Iceland. Natural avalanche protection, which is in many countries provided by dense forests covering steep slopes, is therefore not relevant in Iceland. Absence of forests, furthermore, means that information about the age or distribution of tree species cannot be used for evaluating avalanche hazard in Iceland. Geological evidence, such as earth profiles and scattered boulders, which are often transported by avalanches, may sometimes be used to estimate the frequency and the maximum historical runout distance of snow avalanches, but studies of such evidence have only recently been initiated.

3.3 Climatic characteristics

Meteorological conditions that lead to avalanches in Iceland have not been extensively studied to date. Helgi Björnsson (1980) gives a general outline of avalanche conditions in Iceland and includes a brief discussion of the meteorological conditions associated with the major avalanche cycles of this century. Weather in Vestfirðir during the most important avalanche cycles in the last 46 years was analyzed by Tómas Jóhannesson and Trausti Jónsson (1996). They found that the most dangerous avalanche cycles are associated with intense lows that direct strong north or northeasterly winds to the Vestfirðir region. Heavy snow fall and accumulation of drifting snow in the starting zones in the very high winds are important components that lead to the most dangerous avalanche cycles (average wind speeds in excess of 90 knots have been observed in the mountains under such conditions). The snow drift is particularly important where large plateaus are located near steep slopes in which case snow drift during storms can deposit huge amounts of snow in avalanche starting zones adjacent to the plateaus.

The meteorological conditions associated with the largest avalanches in N- and E-Iceland appear to be less extreme than in Vestfirðir, *i.e.* the major avalanches are often released after prolonged periods of intense snowfall, not necessarily combined with violent storms although winds in the mountains tend to be strong during the days immediately before the release of the avalanches.

Return periods of the weather conditions that have led to the worst avalanche incidents have not been thoroughly studied, but are briefly discussed in Tómas Jóhannesson and Trausti Jónsson (1996). They find that storms similar to the ones that have caused the worst avalanche cycles in Vestfirðir have a return period on the order of one year. Storms that are particularly unfavourable for a specific starting zone (*e.g.* the storm that caused the Súðavík accident in January 1995) are expected to have significantly longer return periods, perhaps 5-10 years. Violent storms that combine a high wind intensity with an unusual timing in the season (*e.g.* the storm that caused the Flateyri accident in October 1995) are expected to have an even longer return period, perhaps several decades. It appears clear that weather conditions essentially similar to the Súðavík and Flateyri storms are not unusual or unexpected when the climate at Vestfirðir is viewed on a time scale of decades to a century.

Return periods for avalanches in specific avalanche paths have not been studied much either. Return periods of avalanches in the Skollahvilft avalanche path on Flateyri in Vestfirðir are analyzed in Tómas Jóhannesson (1996) who also summarizes some other related work. The return period of avalanches with a similar runout as the catastrophic avalanche on 26 October 1995 was estimated to be in the range 90 to 130 years and a similar estimate is given in the avalanche protection appraisal of VST and NGI (1996), *i.e.* a return period in the range 100 to 200 years.

4. LOSS DUE TO AVALANCHES IN RECENT DECADES

4.1 Fatal accidents

A total of 164 people have been killed in snow avalanches and slush flows in Iceland since 1900 (Ólafur Jónsson and others 1992, sources from the Icelandic Meteorological Office). Of these people, 107 were killed in buildings, at work sites or within towns, and 57 were killed on roads or traveling in backcountry areas.

Since the catastrophic avalanches in Neskaupstaður in 1974, a total of 64 people have been killed in avalanches and slush flows. Of these people, 52 were killed in buildings, at work sites or within towns, and 12 were killed on roads or traveling in backcountry areas.

The following table lists the date and location of fatal avalanches hitting towns and farm buildings since 1974.

Table 1: Recent fatal avalanche accidents in populated areas.

Date	Location	Fatalities
20-12-1974	Neskaupstaður	12
22-01-1983	Patreksfjörður	4
04-05-1994	Tungudalur, Skutulsfirði	1
16-01-1995	Súðavík	14
18-01-1995	Grund, Reykhólahreppi	1
26-10-1995	Flateyri	20
Total		52

The number of deaths in avalanche accidents in the 22 year period since 1974 may not be representative of the current avalanche risk in Iceland because the catastrophic accidents mark the beginning and end of the time period between 1974 and 1995. One must, however, note that a considerable number of residential buildings have been built in avalanche hazard areas in Iceland since 1974 so that one may expect the avalanche risk to have increased during this period. It is difficult to decide which of these effects is more important.

4.2 Economic loss

The economic loss that has been inflicted by avalanches in Iceland has been enormous. It is convenient to divide this loss into three components. First, the direct loss due to damaged buildings and infrastructure and properties such as roads or subsurface constructions which may be abandoned after an avalanche accident, *etc.* The direct loss is mainly born by an insurance operated by the state, the Iceland Catastrophe Insurance, but rebuilding of infrastructure after an accident and compensation for properties, which are not insured by the Iceland Catastrophe Insurance, may partly be financed by funds established from private donations after an accident. Second, the cost of rescue and relief operations and other such operational cost associated with an accident. The operational cost is mainly paid by the state. Third, the direct and indirect economic loss due to the disruption of the local society where an avalanche accident occurs. This cost is not paid by a definite institute or agency and must be estimated subjectively.

The total direct and operational loss due to avalanche accidents in towns in Iceland following the accident in Neskaupstaður in 1974, together with the cost of purchasing buildings and the construction cost of defense structures, is about 3800 million IKR at current price levels (*i.e.* December 1995). This includes the cost associated with the relocation of Súðavík, the purchasing of houses in Hnífsdalur and the estimated cost of defense structures for Flateyri, which are under construction. This estimate is based on information from the Ministry for the Environment and from the Iceland Catastrophe Insurance. It includes loss due to damaged buildings, the cost of rescue operations, relocation and defense structures, and the cost of various rebuilding financed by the government and funds established from private donations. Cost arising from avalanche accidents in Neskaupstaður (1974), Patreksfjörður (1983), Ólafsvík (1984), Seyðisfjörður (Hafsíld 1992, Vestdalsmjöl 1995), Ísafjörður (Tungudalur 1994, Steiniðjan 1995, Funi 1995), Súðavík (1995) and Flateyri (1995) is included in this estimate. The cost of rescue operations for other accidents than Súðavík and Flateyri 1995 was not available for this study and was estimated subjectively. Loss due to other smaller accidents in towns in Iceland in the time period from 1974 to 1995 is negligible in comparison with the loss in these largest accidents. The loss estimate does not include damage due to avalanches in rural areas (*e.g.* farm buildings, power and telephone lines and ski lifts), which is substantial, but may be assumed to be much smaller than the estimated total loss in major avalanche accidents in and near towns. The cost associated with the relocation of Súðavík, the purchasing of houses in Hnífsdalur and the defense structures for Flateyri, is about 1300 million IKR of the estimated 3800 million IKR total cost which is given above.

The loss due to the disruption of the local society following an avalanche accident is not explicitly estimated here. It involves a more or less total disruption of all ordinary activity in a society of several hundred people for several weeks and a recovery period where a significant proportion of the society is absorbed in planning the recovery, involved in rebuilding of damaged property and taking part in other activities connected with the accident.

An additional loss component, which is difficult if not impossible to determine economically, is the loss of lives in the accidents. Although it is not particularly meaningful to attach a certain sum of money to each lost life, one may try to approach this question from the viewpoint that the society spends money on lifesaving operations in hospitals, by building more secure traffic infrastructure *etc.* There is general willingness in the society to spend a certain but not a very well defined amount of money for saving a life, and this amount is definitely not unlimited. If a life is lost in an accident, and it is clear that the accident could have been prevented with a much lower cost than is often spent for saving the lives of patients in hospitals or spent on other lifesaving operations in the society, then this may be considered a lost opportunity to prevent an accident. We will here adopt this view and assume that the society is willing to spend on the order of 100 million IKR to save the life of one person that otherwise might be lost in an accident. This amount is approximately the same as the amount adopted in a recent report about the economic loss caused by traffic accidents in Iceland (Hagfræðistofnun Háskóla Íslands 1996). For comparison, a value of 55 million IKR is sometimes used for the same purpose in Switzerland and about 60 million IKR has been used in Austria. A value of about 60 million IKR has been used in traffic risk analyzes in Britain (VST 1995) and several hundred million IKR have been used in statistical evaluations of life saving measures for the oil industry in Britain (VST 1995). The Swiss and Austrian values are an estimate of the economic loss caused by one fatal accident. In Switzerland, it is sometimes assumed that the amount the society is willing to spend in order to prevent one fatal accident is about 250-500 million IKR.

The deaths due to avalanche accidents in populated areas in Iceland over the last 22 years thus correspond to an economic loss of 52x100 million IKR in the above sense that the society is assumed to have been willing to spend this amount of money on measures for preventing the accidents in addition to the cost of the more direct economic damage which was estimated above.

Yet another aspect of the loss caused by avalanches, which is also almost impossible to estimate in economic terms, is the disruption and inconvenience caused by impending avalanche danger even when no avalanches fall. The most obvious effect of this type is the inconvenience cause by frequent evacuations of buildings in avalanche hazard areas, which is further described in the subsequent section. Insecurity and anxiety among the local population in the endangered areas is also an important negative aspect of the avalanche problem which cannot be expressed in economic terms.

4.3 Evacuations

Although evacuations are not a direct loss in the same sense as fatal accidents or buildings damaged in avalanches, it is relevant here to give an idea of the scale of evacuations as they have been practiced in Iceland in recent years. The following table summarizes evacuations in the towns that are considered in this report since 1990. It is based on information supplied by the Icelandic Civil Defense and by the local authorities in the towns.

Table 2: Evacuations since 1990.

Location	Number of occasions	Number of buildings
Ísafjörður/Hnífsdalur	11	21, 5, 18, 18, 22, 16, 18, 19, 19, 19, 29
Flateyri	9	10, 10, 10, 10, 17, 18, 9, 9, 5
Súðavík	6	7, 7, 56, 56, 7, 56
Bolungarvík	4	40, 45, 31, 4
Patreksfjörður	4	12, 46, 16, 105
Neskaupstaður	1	6
Seyðisfjörður	4	3, 3, 3, 3
Siglufjörður	5	4, 3, 26, 6, 7

The evacuations usually last for 1 to 4 days, but evacuations for 5 or 6 days have sometimes occurred during prolonged avalanche cycles, and there are instances where people did not move back into their houses until spring.

5. AVALANCHE PROTECTION MEASURES AND THE SCOPE OF THE OVERVIEW

5.1 Purpose of the study

The purpose of the study is to make an overview of the need for avalanche protection measures in Iceland and estimate the order of magnitude of the cost of such measures. The study, furthermore, presents a crude classification of the risk in each area. This information will serve as background for political decisions about further work in this field, both with regard to the priority of avalanche protection measures and focusing of future avalanche research in Iceland.

It is clear that a full appraisal of protection measures for all the sites considered is impossible within the time frame of the study. Rather, the study will propose protection which is of a magnitude that is judged appropriate for the sites under consideration and determine the dimensions, *e.g.* the relevant lengths and heights of dams, that are necessary for a rough cost estimate. A detailed dimensioning of the defense structures is a task that will be attempted at a later point in time during the appraisal phase in the design of protection for each site. The suggested protection should therefore not be considered as an explicit recommendation for a certain solution to the avalanche problems of each area, but rather as a solution which is likely to be of an appropriate magnitude when a further study is carried out.

5.2 Areas examined in the study

The towns/villages Ísafjörður (including Hnífsdalur), Bolungarvík, Vesturbyggð (*i.e.* Patreksfjörður and Bíldudalur), Neskaupstaður, Seyðisfjörður and Siglufjörður were examined in the study. In addition the study incorporates the results from avalanche protection appraisals for Flateyri (VST and NGI 1996) and Súðavík (HNIT 1995a,b). The towns considered in the study include the largest densely populated avalanche hazard areas in Iceland. The total cost of future avalanche protection projects in Iceland will to a large extent be determined by defense structures constructed for these towns, although the need for some snow avalanche protection for other towns is likely to arise after further studies of avalanche hazard in Iceland.

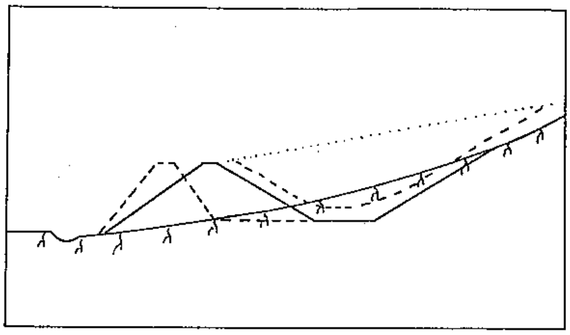
The report focuses primarily on snow avalanche protection. Protection against slush and debris flows is also considered for a few areas. Several towns, which are not considered in this study, are endangered by slush and debris flows. The possible cost of the required protection for these towns is not explicitly considered. The total cost of slush and debris flow protection is, however, unlikely to significantly alter the estimate of the total cost of future avalanche protection in Iceland given in this report.

5.3 Hazard assessment and acceptable risk

A formal decision about an acceptable level of risk due to avalanches in Iceland has not yet been made. The recent avalanche protection appraisals for Flateyri (VST and NGI 1996) and Seljalandshverfi (HNIT and NGI 1996) are based on the assumption that the rest risk facing the population after avalanche protection is implemented for inhabited areas should be determined from the current or accepted risk associated with other sources of accidents in society. As an example, traffic accidents are associated with approximately one fatal accident per year per 10000 persons when averaged over all age groups. The total number of deaths by accidents for children in the age group 1-14 years is also on the order of one fatal accident per year per 10000 persons.

Avalanche risk is non-voluntary and avalanche accidents have a high "risk aversion factor". It is therefore desirable that avalanche risk in inhabited areas is significantly less than for example risk due to fatal traffic accidents or the total risk of death by accidents for children. This line of argument leads to an acceptable risk level due to avalanches on the order of 0.2 to 0.5 fatal accidents per year per 10000 persons assuming that a risk aversions factor in the range 5 to 2 compared to traffic accidents is adopted. This corresponds to a return period of avalanches on the order of several thousand years when the probability of death of a person in a building which is hit by an avalanche is taken into account. It is conceivable that different acceptable risk levels will be adopted for existing settlements and for new development of housing areas, respectively, but this has not been decided.

Revised hazard maps for Iceland after the catastrophic avalanches in Súðavík and Flateyri have not yet been made, except for Súðavík (NGI, HNIT and VÍ 1995). The overview study could therefore not be based on such revised maps, whereas the hazard areas indicated by the current hazard maps are clearly insufficient as the recent accidents have shown. The proposed protective measures which are described here are based on a subjective estimate of the avalanche danger with the aim to reach a reduction in the risk to an acceptable level as described above. The estimated avalanche danger will change when more detailed hazard mapping is carried out. A revision of avalanche hazard maps for Iceland is, therefore, necessary parallel with and as a part of further planning of avalanche protective measures.



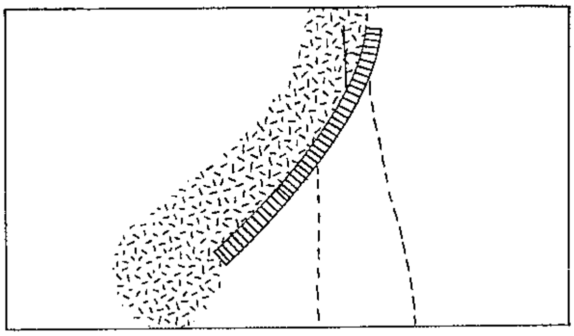


Figure 1. A schematic drawing of a catching dam. The drawing shows the shape of the mountainside before and after the construction of a dam (solid curves), snow lying on the ground (dashed curve), avalanche deposits of an avalanche stopped by the dam (dotted curve) and a sketch of a steeper dam which could be located further down the slope if space is limited (dashed curves).

Figure 2. A schematic drawing of a deflecting dam. The drawing shows an avalanche deflected by the dam (shaded area) and an outline indicating the path taken by an avalanche that falls before the dam is constructed (dashed curves).

5.4 Avalanche defense structures and safety measures

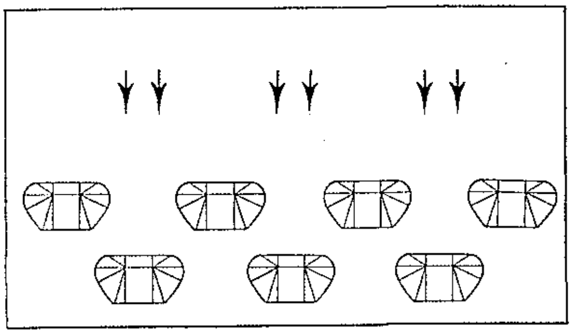
Several different methods for increasing the safety in avalanche hazard areas can be used. Some of them reduce the likelihood of the release of an avalanche by supporting the snow cover in the starting zones. Others consist of constructions in the track or the runout zone of the avalanches and prevent the avalanches from reaching buildings by stopping them or deflecting them away from the buildings. Reinforcement of individual buildings can be used to reduce the likelihood of fatal accidents if the buildings are hit by an avalanche. Transport of snow to the starting zones can be reduced by snow fences on plateaus adjacent to the starting zones. Evacuations of people from the hazard area during impending avalanche danger may also be used in order to reduce the likelihood of fatal avalanche accidents.

5.4.1 Catching dams

A catching dam is a dam construction of sand, gravel, stones or concrete which is built in the runout zone approximately perpendicular to the flow direction of avalanches (*cf.* Figure 1). It is intended to stop the avalanches completely. The required height is proportional to the square of the velocity of the avalanche and must often be quite high unless the dam can be located relatively far out in the runout zone where the velocity of the avalanche is low. It is important to have sufficient space upstream from the dam to hold the volume of the avalanches hitting the dam.

5.4.2 Deflecting dams

A deflecting dam is a dam construction of sand, gravel, stones or concrete which is built at an angle to the direction of the avalanches (*cf.* Figure 2). It is preferable that the deflecting angle is as low as possible, but achieving a low deflecting angle is sometimes difficult due to limited space at the site for the dam. By choosing a sufficiently low deflecting angle, the height of a deflector can be lower than the height of a catching dam in a similar location and it can therefore sometimes be placed much further up in the runout zone or in the track of the avalanches. On the other hand, a deflecting dam must usually be longer than a catching dam to protect the same area.



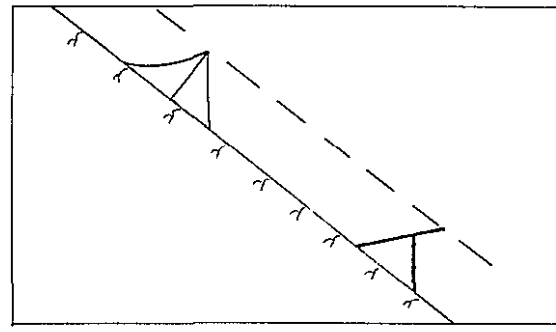


Figure 3. A schematic drawing of retarding mounds. The arrows indicate the flow direction of an avalanche.

Figure 4. A schematic drawing of a supporting structures (snow nets to the left and snow bridges to the right).

5.4.3 Retarding mounds

Retarding mounds are constructions which are built in a chessboard pattern in the runout zone of avalanches (*cf.* Figure 3) and intended to reduce their speed and deposit a part of their mass and thereby shorten the runout or reduce the necessary height of a dam that is placed further down the path. Retarding mounds work best against wet avalanches and seem to have little effect on dry avalanches with high velocity or on powder avalanches. Retarding mounds with a steep uphill side and an elongated shape in the direction along the slope are believed to have a greater retarding effect than cone shaped mounds.

5.4.4 Supporting structures

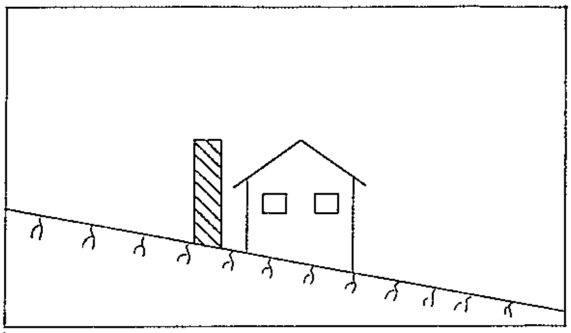
Supporting structures are built in the starting zones of avalanches. They are intended to support the snow cover and prevent the release of an avalanche and to stop minor avalanches which may be released between the rows of the structures (*cf.* Figure 4). Supporting structures normally consist of several rows which are typically between 3 and 5 m high depending on the extreme snow depth and placed 25-30 m apart. The structures are normally made of steel and formed as solid steel constructions or flexible nets. Supporting structures are widely used for avalanche protection of settlements in the Alps.

5.4.5 Reinforcement of individual buildings and direct defenses with concrete walls

Significant safety improvement can often be achieved by reinforcing buildings that are built near the margins of avalanche hazard areas so that they can withstand the expected impact. Similar effect can sometimes be reached with an earth fill on the upstream side of the building. Another related possibility is the construction of concrete walls close to the uphill side of buildings that need to be protected (*cf.* Figure 5). Such measures are, however, often difficult to implement after a building has been constructed if the measures were not planned in the design of the building. It is impractical to reinforce residential buildings to withstand the high pressures deep within the avalanche runout area where the avalanche velocity is high. Reinforcement of individual buildings must be combined with an avalanche warning system so that traffic in the neighbourhood of the buildings can be limited during impending avalanche danger.

5.4.6 Snow fences

Snow fences are used to trap the drifting snow on a plateau before the snow accumulates in the starting zone of avalanches below the plateau (*cf.* Figure 6). The snow fences can either be used alone or in combination with other defense structures, especially supporting structures, which can sometimes be designed somewhat lower or their safety improved by the addition of the snow fences. Snow fences are usually not used for the protection of inhabited areas except in combination with other protection measures because it is difficult to estimate their effectivity for



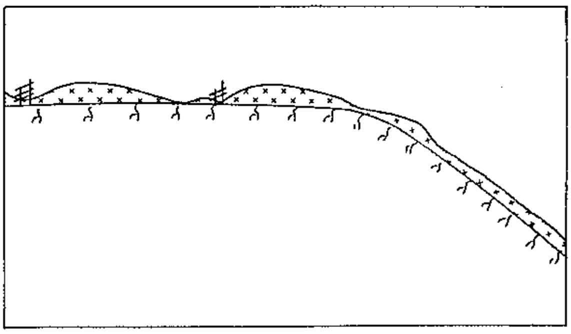


Figure 5. A schematic drawing of direct defenses with a concrete wall.
Figure 6. A schematic drawing of a snow fences.

reducing the runout of extreme avalanches.

5.4.7 Evacuations

A significant reduction in the risk to people's lives can be achieved by evacuating people from the hazard area during impending avalanche danger. This requires continuous monitoring of avalanche danger and a readiness of the local population to evacuate on a short notice. The destruction of buildings and other valuables by avalanches is of course not reduced by evacuations. Evacuations during impending avalanche danger are in general not considered a viable, permanent solution to avalanche problems in avalanche hazard areas except where the avalanche frequency is low. This is due to practical difficulties of predicting avalanches in advance and due to the high number of evacuations that need to be ordered where the avalanche frequency is high.

Permanent evacuations of buildings in avalanche hazard areas where protection measures are impractical or too costly can be used as a solution of a dangerous avalanche situation. Permanent evacuation of a significant number of buildings was decided in Súðavík and Hnífsdalur after the avalanche accident in Súðavík in 1995.

5.4.8 Advantages and disadvantages of different safety measures

Each of the defense structures and safety measures described above is associated with a certain rest risk which is defined as the risk that remains after protection measures are implemented. The rest risk depends on the type of the protection measures. The rest risk associated with catching dams and deflectors arises from the possibility that the dams are overrun by an avalanche with a higher speed, volume or flow height than assumed in the design of the dam. An avalanche may also overrun the dam if it falls when snow on the ground or deposits from previous avalanches are thicker than assumed in the design. Finally, the powder component of an avalanche is not stopped by a dam and it may cause some damage to inhabited areas below the dam.

The rest risk associated with supporting structures is due to the possibility that the snow depth might become higher than the height of the structures. Avalanches may also be released outside of the area where the structures are constructed. A release of an avalanche above the area of the supporting structures is particularly dangerous because the supporting structures cannot withstand the impact from an avalanche. Therefore, it is important that the area of the supporting structures reaches high enough so that avalanche release above the structures is prevented.

The different types of defense structures have very different environmental impacts. Avalanche protection dams are most often located close to inhabited areas and are often 10-20 m high. A significant environmental impact is therefore associated with their construction. An environmental impact may also be associated with the excavation of the large amounts of fill material which is required for the construction of the dams.

A significant visual impact is associated with the construction of supporting structures in the starting zones of avalanches. The starting zones are, however, located high in the slopes and thus far away from the inhabited areas. This impact is therefore in most cases not considered serious, at least not when viewed in the light of the hazard which the structures are intended to reduce.

The different protection types require different maintenance over time periods of decades. Dams and deflectors are usually viewed as permanent constructions, but steep earth fill dams or dams reinforced with geotextiles may require some repairs for example to mend damages in the vegetation cover due to minor slope instabilities.

Supporting structures and snow fences require regular maintenance to maintain their effectivity over long time periods as further discussed in the section on cost assumptions below.

To summarize, dams and deflectors are permanent constructions which require little maintenance. They are most often associated with a significant environmental impact. Supporting structures require regular control and maintenance. Their environmental impact is usually not considered serious but should not be neglected.

5.5 Design criteria

5.5.1 Design avalanches and design snow depth

Design parameters for the proposed defense structures should be chosen with the aim of reducing the risk of individuals due to avalanches to an acceptable level, *i.e.* to risk on the order of 0.2 to 0.5 fatal accidents per year per 10000 persons. As said above, this corresponds to a return period of avalanches on the order of several thousand years.

Formal computation of the avalanche risk is in practice very difficult to perform, especially an explicit evaluation of the rest risk after protection measures have been implemented. An evaluation of rest risk involves the location of buildings below the defense structures and would ideally be based on a theoretical and practical knowledge of how much the runout of avalanches is reduced by defense structures when conditions become more extreme than assumed in the design criteria of the structures. In some cases, the protection measures would be combined with an evacuation plan and the analysis should also take into account the possible reduction in the risk due to the evacuations.

The height of the dams and deflectors was determined from the modelled velocity of a design avalanche at the location of the dam or deflector. The design avalanches were based on a subjective estimate of an extreme runout for the avalanche path in question. This runout was estimated from the recorded avalanche history, on-site examination of the avalanche conditions, runout indices computed from the results of a PCM model (Perla and others 1980, Erlendur Smári Þorsteinsson and others 1996) and on results from a topographical α/β-model fitted to Icelandic avalanches (Lied and Bakkehøi 1980, Tómas Jóhannesson and others 1996). Where possible, the runout of the chosen design avalanche corresponds to the longest 3-15% of the avalanches from a data-set of the longest avalanches recorded from about 70 avalanche paths in Iceland. The return period of the avalanches in this data-set is considered to be on the order of 50 years. When practical circumstances, such as lack of space for a dam, prevent the choice of a design avalanche according to this criterion, the situation is discussed separately for each case.

The runout of the design avalanche for a particular path was partly determined from an evaluation of existing information about the frequency and magnitude of avalanches in the path. For example, the frequency of major avalanches in the most important avalanche hazard areas in eastern Iceland appears to be significantly lower than the frequency of major avalanches in Vestfirðir. Therefore, a somewhat shorter runout of design avalanches may be chosen in eastern Iceland compared to Vestfirðir to achieve the same level of rest risk.

The choice of the height of supporting structures was partly based on the scarce measurements that exist on snow depth in starting zones in Iceland, *i.e.* essentially only from Neskaupstaður and Seljalandshlíð, Ísafjörður. The design snow depth had to be based mainly on a subjective estimate of the conditions in the respective starting zones where no such measurements were available. The design snow depth was not based on a formal estimate of the variation of the return period with the snow depth due to lack of long term data on snow depth in the starting zones.

The recorded avalanche history is incomplete in many of the towns which were considered. Further information on avalanche runout in previous years, further research in avalanche dynamics together with future political decisions regarding safety requirements in avalanche hazard areas will undoubtedly lead to modifications in the design avalanches which were chosen for this study. The avalanche hazard in many of the areas which were considered is nevertheless undisputed and the design avalanches will in most cases give the order of magnitude of the events that need to be considered by a serious proposal for avalanche protection.

The most difficult problem in this study is the treatment of the avalanche hazard in relatively new neighbourhoods under steep hills. In many cases no or very few and small snow avalanches are recorded, but the recorded avalanche history may reach only 10 to 25 years back. Proper design criteria for defense structures are not easy to define for such situations and it is difficult to propose expensive protection constructions on such a weak observational basis. Regular monitoring of snow depth in these areas in the future is very important in order to provide more information about the level of danger so that appropriate measures for insuring the safety of the inhabitants can be defined.

5.5.2 Dams and deflectors

The height of dams and deflectors was determined from the formula

$$H = H_v + H_s + H_f \quad , \qquad (1)$$

where H_v is the required height due to the kinetic energy or the velocity of the avalanche, H_s is the thickness of snow on the ground on the upstream side of the dam before the avalanche falls and H_f is the thickness of the flowing part of the avalanche.

The location of a catching dam must in addition be chosen so that there is sufficient space on the upstream side to hold the estimated volume of an avalanche that is stopped by the dam. The location of a catching dam should also be chosen so that the inclination of the terrain upstream from the dam is lower than 10-15° for a sufficient distance to insure a satisfactory effectiveness.

The terms H_s and H_f in eq. (1) are assumed to be 2 m each for unconfined slopes unless otherwise stated. This is in accordance with the values adopted in the avalanche protection appraisals for Flateyri (VST and NGI 1996; $H_s = 3$ m, $H_f = 2 - 3$ m for Skollahvilft; $H_s = 2$ m, $H_f = 1 - 2$ m for Innra-Bæjargil) and Seljalandshverfi, Ísafjörður (HNIT and NGI 1996; $H_s = 2$ m, $H_f = 2$ m). A flow height H_f of 2 m is likely to be rather high for avalanche paths where small flow rates with little concentration of the avalanche flow are expected. A somewhat lower flow height is sometimes adopted in such cases.

The term H_v for *catching dams* is computed according to the equation

$$H_v = v^2/(2\lambda g) \quad , \qquad (2)$$

where v is the velocity of the design avalanche at the site of the dam, λ is an empirical parameter and $g = 9.8\ m/s^2$ is the acceleration of gravity. The empirical parameter λ is intended to reflect the effect of momentum loss when the avalanche hits the dam and the effect of the friction of the avalanche against the upstream side of the dam during runup. The value of λ is chosen to be between 1 and 2 based on values sometimes adopted in the design of catching dams in Switzerland. Measurements performed a NGI's at Ryggfonn indicate that $\lambda \approx 1.3$ is appropriate for dry snow avalanches hitting a catching dam with an upstream slope of 1:1.5.

Higher values of λ (lower dams) are chosen where the potential for big avalanches is considered rather small, whereas lower values of λ (higher dams) are chosen for avalanche paths where extreme avalanche with a high volume may be released. λ is assumed to have a value of 2 for catching dams with a steep upstream side unless otherwise stated. Lower values of λ (higher dams) are chosen for paths which are considered most dangerous. The speed v is backcalculated with the PCM avalanche model (Perla and others 1980) by adjusting the friction parameters of the model so that the computed stopping position coincides with the stopping position of the chosen design avalanche. The length of the flowing part of the avalanche is not explicitly considered in this rather simple avalanche modelling approach. The modelled velocities in this study were compared with the velocities used in the studies of VST and NGI (1996) and HNIT and NGI (1996) and found to be similar when model runs with the same runouts were compared.

The term H_v for *deflectors* is computed according to the equation

$$H_v = (v \sin \phi)^2/(2\lambda g) \quad , \tag{3}$$

where v, λ and g have the same meaning as in eq. (2) and ϕ is the deflecting angle. The λ for deflectors is chosen to be 1 in this study in accordance with work practice in the design of deflectors in Norway and Switzerland. The decision to use λ equal to 1 is equivalent to neglecting momentum loss when an avalanche hits the dam and the effect of the friction of the avalanche against the dam. This leads to higher dams compared to the choice of λ higher than 1. This may partly be considered as a safety measure to counteract the uncertainty which is always present in the determination of the deflecting angle from subjectively chosen streamlines of an avalanche and as a safety measure to take into account internal pressure forces which lead to higher runup than assumed in the derivation of eq. (3) where such effects are neglected.

5.5.3 Supporting structures

The basis for the design of areas controlled with supporting structures was the Swiss guidelines (Richtlinien für den Lawinenverbau im Anbruchgebiet, Ausgabe 1990). Slopes from 30° to 50° have been considered to be in the range which justifies constructions. The primary location was below the highest fracture lines that were observed or expected. The area extends downhill until either the slope inclination is definitely less than 30° or it is expected that avalanches breaking off further downhill will be too small to be dangerous. Laterally the area with supporting structures extends if possible to natural borders such as crests or terrain ridges. The arrangement of structures is normally made in continuos rows.

The slope distance between the lines of structures was determined as a function of the height of the structures, the slope inclination and the ground conditions.

The soil/rock conditions for the foundations were judged roughly. Where rock fall is expected, flexible snow net constructions should be used.

Future measurements of snow depth and snow distribution in the starting zones, where supporting structures are proposed, are very important in order to put the design of structures on a firmer basis. Measurements of snow density and snow gliding should also be considered. Information obtained by measurements of the distribution of the snow depth in the potential starting zones may lead to some reduction in the required length of the structures compared to the configurations suggested here where structures are in many cases proposed for an entire area where the inclination of the slope is in the range 30° to 50°.

Below plateaus the snow height can in some cases be reduced by the use of snow drift fences on the plateaus.

5.5.4 Direct defenses with concrete walls
Direct defenses with concrete walls for individual buildings are suggested in a few cases in this report and mentioned as a possibility which should be further studied in several other cases. The design of protection of this type depends on the avalanche velocity and also to a high degree on the height of the buildings to be defended and other local conditions. We assume here for simplicity a fixed unit price per metre of such structures as further described below. The possible use of direct defenses in Iceland was not studied on the same level in this report as the use of dams, deflectors and supporting structures, because the design of direct defenses requires more detailed studies of individual buildings and more detailed estimates of the avalanche hazard than was available for this work.

The total cost of the suggested direct defenses is given separately and should not be interpreted as an estimate of the total cost of possible protection of this type. The total cost of direct defenses is, however, unlikely to significantly alter the estimate of the total cost of future avalanche protection in Iceland given in this report.

5.5.5 Debris and slush flow protection
Several areas in the towns considered in this report are endangered by slush and debris flows. This report focuses primarily on snow avalanche protection, but a need for protection against slush and debris flows is mentioned for several areas which were considered. We assume here for simplicity a fixed unit price per metre of slush and debris flow path banks which need to be strengthened as further described below. A fixed unit price for a culvert or bridge, where such paths cross a road, is also assumed. As for the direct defenses described in the previous section, the design of slush and debris flow protection depends to a high degree on various local conditions and requires more detailed studies of individual flow paths and more detailed estimates of the slush and debris flow hazard than was available for this work.

The total cost of the suggested strengthening of the banks of flow paths is given separately and should not be interpreted as an estimate of the total cost of possible slush and debris flow protection.

5.6 Cost assumptions

5.6.1 Dams and deflectors
The cost of dams and deflectors is based on an estimated volume of the structures. The unit price per m^3 of fill material for earth fill dams is assumed to decrease linearly with the height of the dam because the cost of excavation of overburden material in the dam site and some other cost components become relatively less important as the dam height increases. The unit price of dams is specified below as the price of a 12 m high dam, c_{12}, and the price of a 17 m high dam, c_{17}. The unit price for other dam heights is computed by linear interpolation/extrapolation from these values. The assumptions adopted for the computation of the cost of dams and deflectors are described in Appendix II.

The price estimates are worked out with the participation of the engineers Gunnar Guðni Tómasson from VST Ltd. and Árni Jónsson from HNIT Ltd. who consulted other engineers in their engineering companies regarding the different cost components in the building of dams. Information about some of the various cost components was also provided by the Icelandic

Public Roads Administration and the Icelandic Lighthouse and Harbour Authority which is gratefully acknowledged.

Dams and deflectors are divided into several cost categories.

I Structures where geotextiles, rather large ordered blasted rock boulders, or other means are used to obtain a steep upstream side with a slope on the order of 1:0.5. The landfill on the downstream side is assumed to have a slope of 1:1.5. The top of the dams has a width of 3 m. Building material of reasonable quality for the fill is abundant near the site, but building material for the steep upper side may have to be transported several kilometres to the site. The adopted unit prices are c_{12} = 1200 IKR/m^3 and c_{17} = 1100 IKR/m^3. This is based on information about the price of geotextiles and the cost of building earth fill dams in Iceland.

I' Same as I except that building material of reasonable quality for the fill must be transported several kilometres to the site and perhaps mixed with some local material of inferior quality. The adopted unit prices are c_{12} = 1400 IKR/m^3 and c_{17} = 1300 IKR/m^3. This is based on information about the price of geotextiles and the cost of building earth fill dams in Iceland with an added cost based on a transportation cost corresponding to approximately 5 km distance to the site.

II Structures with the steepness of the sides determined by the angle of repose of the building material. The upstream side is assumed to have a slope of 1:1.3. The downstream side is assumed to have a slope of 1:1.5. The top of the dam has a width of 3 m. Building material of reasonable quality is abundant near the site. The adopted unit prices are c_{12} = 650 IKR/m^3 and c_{17} = 600 IKR/m^3. This is partly based on appraisals of avalanche protection for Flateyri (VST and NGI 1996), Seljalandshverfi, Ísafjörður (HNIT and NGI 1996) and Súðavík (HNIT 1995a,b) and on information from the Icelandic Public Roads Administration.

II' Same as II except that building material of reasonable quality must be transported several kilometres to the site. The adopted unit prices are c_{12} = 850 IKR/m^3 and c_{17} = 800 IKR/m^3. This is based on the same sources as for dams of type II with an added cost based on a transportation cost corresponding to approximately 5 km distance to the site.

III Structures where geotextiles, rather large ordered boulders, or other means are used to obtain a steep dam with a slope on the order of 1:0.5 on the upstream side and 1:1 on the downstream side. Such dams are only suggested when there is very little space for a dam and every effort has to be made to utilize this space in the most effective way. The adopted unit prices, c_{12} = 1800 IKR/m^3 and c_{17} = 1700 IKR/m^3, are based on the price of geotextiles and the cost of building earth fill dams in Iceland.

IV Concrete walls, on the order of 8-10 m high, which are built upstream of individual buildings that are located such that protection of the whole area is judged impractical, but certain buildings in the area are of such importance that direct protection of these buildings is suggested. The walls are built to approximately match the height and width of the building. Such walls are sometimes suggested when there is little space for a dam and every effort has to be made to utilize this space in the most effective way. A unit price of 300000-500000 IKR/m of the length of such dams is assumed. As mentioned in the previous section, the price of direct defenses of this type depends to a high degree on the local conditions and it is not practical to make a general, detailed cost estimate. The unit price given here should be considered as an order of magnitude estimate and may be expected to vary by a factor of two for a particular site where such a construction is adapted to the local conditions.

V Relatively low (3-4 m high) guiding dams with a slope of 1:1.5 along river banks or slush and debris flow paths. The existing riverbank can in many cases be used as landfill but boulders must be transported to the site to construct the guiding dam itself. The paths considered in this report often cross roads and a properly dimensioned culvert or bridge must be built at such crossings as a part of the reshaping of the banks. Proper design of guiding dams along slush and debris flow paths and the necessary culverts and bridges depends to a high degree on the local conditions and lies outside the scope of this report. Here we will adopt a fixed price per unit length of the banks, equal to 13500 IKR/m. This estimate is based on a 4 m high bank of ordered boulders. The preexisting bank is assumed to be 2 m high. The landfill is 3 m wide at the top and has a slope of 1:1.5 at the back of the dam. This leads to approximately 6 m^3 of boulders and 10 m^3 of fill material per metre of the dam. A unit price of 1000 IKR/m^3 for blasted rock boulders is assumed based on information about the cost of building rubble mound breakwaters obtained from the Icelandic Lighthouse and Harbour Authority and information about the cost of building flood protection dams for roads from the Icelandic Public Roads Administration. The cost estimate is raised by 50% to account for design, management and unforeseen costs which may be expected in the varied conditions where dams of this kind are proposed. Bridges or culverts where slush and debris flow paths are crossed by roads are assumed to cost 10 mi IKR each, also based on information from the cost data bank of the Icelandic Public Roads Administration for short bridges. Culverts may be expected to cost significantly less than dams, but will cause an abrupt narrowing of the channel. These cost estimates are clearly very rough and may be expected to change considerably in each case when local conditions are properly taken into account. In particular, debris flow protection measures beyond the simple protection suggested here, may sometimes be required after a further study has been carried out.

The above unit prices cover all construction cost including draining, landscaping, design and other miscellaneous cost components, but not cost of relocating water supply lines, electricity cables and other such cost components which may vary greatly from site to site.

Dams of type I with a steep upstream side are considerably more expensive per m^3 than dams of type II where the angle of repose of the fill material determines the slope of the upstream side. The volume of dams with a steep upstream side is, however, significantly smaller than for a dam of type II with the same height, especially for dams on a sloping terrain. In addition, dams with a steep upstream side are believed to be more effective for stopping avalanches than less steep dams, (*cf.* the discussion of the factor λ in eq. (2) in section 5.5.2). Steep dams of type I can therefore be built somewhat lower than equivalent dams of type II.

Dams of type II will in most cases be less expensive than steep dams of type I where there is enough space for the dam and where abundant fill material of good quality can be found near the dam site. Dams of type I may be more economical when there is little space for the dam and/or where dam construction material must be transported to the dam site.

It should be noted that actual prices of dam constructions will to a considerable degree depend on local conditions, which are ignored here. The price will also depend on various economic factors which can affect the outcome of bids at the time of the construction of a dam.

5.6.2 Supporting structures

The cost of supporting structures in the starting zones of avalanches is based on information from EISLF in Switzerland, and from several manufacturers of supporting structures, and on information gathered for the appraisals of avalanche protection for Flateyri (VST and NGI 1996) and Seljalandshverfi, Ísafjörður (HNIT and NGI 1996). The assumed construction cost in this study depends on the height of the structures.

I. 82000 IKR/m for 2.5 m structures (66000 IKR/m without VAT).
II. 103000 IKR/m for 3.0 m structures (83000 IKR/m without VAT).
III. 127000 IKR/m for 3.5 m structures (102000 IKR/m without VAT).
IV. 154000 IKR/m for 4.0 m structures (124000 IKR/m without VAT).

The price includes the direct cost of the structures themselves and the installation cost including design and management. The price of supporting structures made from steel profiles and structures consisting of nets is assumed to be the same.

Actual cost, when supporting structures are built in Iceland in the future, will in addition to the height of the structures depend on foundation conditions, transportation distance and other parameters which are not considered here. Foundation conditions are particularly important in this connection.

Supporting structures in the starting zones require maintenance which is often assumed to be on the order of 0.5% of the construction cost per year in other countries. Maintenance cost may be expected to be somewhat higher than 1% per year in areas where rock fall is frequent, but lower than 0.5-1% in areas with good ground conditions. The value of 1% per year is here taken as an average value and is assumed to be the same without respect to ground conditions. It is somewhat higher than reported maintenance cost of supporting structures in the Alps because more corrosion is expected under Icelandic conditions compared with the Alps. The maintenance cost is taken into account by computing the sum of the present value of the yearly maintenance cost, *i.e.*

$$M = rC\sum_{n=1}^{N}(1+i)^{-n} = rC(1-(1+i)^{-N})/(1-(1+i)^{-1})/(1+i) \quad ,$$

where $r = 1\%$ is the yearly maintenance cost relative to the construction cost, C is the construction cost, $N = 50$ is the time span adopted for the summation and $i = 0.06$ is the interest rate. The values adopted for r, N and i lead to a present value of the maintenance cost equal to 16% of the construction cost. The total cost of supporting structures adopted in this report, including maintenance over a period of 50 years, is thus:

I. 95000 IKR/m for 2.5 m structures.
II. 119000 IKR/m for 3.0 m structures.
III. 147000 IKR/m for 3.5 m structures.
IV. 179000 IKR/m for 4.0 m structures.

It should be noted that the above prices are considerably higher than per metre prices of supporting structures often seen in the literature. This is due to the inclusion of the Icelandic VAT of 24.5% and the accumulated maintenance of 16%, which together lead to a 44% increase in the prices. For this reason, the prices should be reduced by a factor of about 1.44 before they are compared to price quotations of supporting structures from other countries.

5.6.3 Other cost assumptions

The cost estimates for dams, deflectors and supporting structures given in the preceding sections include a value added tax (VAT) of 24.5%.

Equipment for avalanche protection is exempt from VAT according to the current law about avalanche protection in Iceland. This law may be expected to apply to the cost of materials for supporting structures (roughly 40-50% of the total cost). The estimated cost of the installation of supporting structures and essentially all cost components in the cost of the building of dams should include VAT according to the current law. It was decided that all cost estimates given in this report should include VAT in order to make them internally consistent. This means that VAT is added to the cost of materials for supporting structures in spite of the abovementioned law which exempts equipment for avalanche protection from the tax. Possible refund of the VAT to local authorities according to the current law about VAT is not taken into account either. The reader should be aware of the above assumptions when interpreting the cost estimates given in the report.

In some areas, existing buildings may need to be overrun by a dam or a deflector because of limited space. The cost of purchasing such buildings is in these cases considered a part of the cost of the proposed defense structures.

Avalanche protection measures are not practical in some areas and it is possible that the government will purchase buildings in such areas in the future. The cost of purchasing buildings in these areas is not considered as a cost of protection measures, but it is discussed in the sections where the total cost of avalanche protection measures is summarized.

5.7 Value of defended property

The estimated value of buildings and other properties is based on the Insurance Value of the buildings ("brunabótamat" in Icelandic) which is maintained by the Valuation Office of Iceland. The total value of all buildings within each area was compiled for this report by the local authorities in each town. The value of streets and other infrastructure was estimated based on the community tax collected during the construction of new buildings in small towns in Iceland. A value of 1.3 mi IKR for the infrastructure corresponding to each single family house and 0.28 mi IKR corresponding to each apartment in apartment buildings was adopted based on information from the National Association of Local Authorities in Iceland and applied in all the towns which were considered in the study. The value of streets and infrastructure corresponding to industrial buildings was not considered.

The extent of the area defended by the proposed protection measures was determined from a subjective estimate of an extreme avalanche runout based on the recorded avalanche history, on-site examinations and avalanche modelling.

An appropriate measure for the value of properties in avalanche hazard areas is difficult to define and depends to a high degree on political decisions. Available information about the value of buildings in Iceland is under revision and partly inconsistent. The Insurance Value was judged most appropriate for this study, but it must be kept in mind that the value of the properties is not a well defined entity and the numbers given below are affected by the known flaws in the underlying data.

5.8 Prioritization

An indicator or index of the risk below the proposed defense structures is given in each case. This index is intended as a guide in future prioritization of the protection projects. Decisions about protection priorities will additionally have to be based on the assumed effectiveness of the proposed protection together with the cost of the defense structures, both compared to the available funding allocated to avalanche protection in Iceland and on the estimated benefit of the protection measures.

The risk index is based on a subjective estimate of the magnitude and frequency of dangerous avalanches in the path or the estimated potential of such avalanches, on one hand, and on the number of people that might be endangered by a catastrophic avalanche on the other hand.

The frequency and magnitude of avalanches is classified in the following way.

Frequent (I) Avalanches are frequent (several or many recorded avalanches approach the inhabited area) or potentially very large. Recorded avalanches reach into the populated area or there is a clear potential for such an avalanche.

Infrequent (II) Avalanches are infrequent (one or two recorded avalanches approach the inhabited area) or the potential for large avalanches is considered low. Recorded avalanches reach close to the populated area or the slope is estimated to be similar to nearby slopes where such avalanches have been recorded. The slope may for example become dangerous during weather conditions that are relatively rare in the area.

Potential (III) There is a potential for dangerous avalanches according to topographic conditions, but no or very few and small avalanches have been recorded. The slope may for example become dangerous during weather conditions that are very rare in the area.

The frequency/magnitude is occasionally denoted by a "–" or a "+", *i.e* "I–" or "II+", in order to indicate that the area under consideration is according to the judgement of the work group relatively less or more threatened than other areas classified in the corresponding class.

The number of people that might be endangered by a catastrophic avalanche is classified in the following way.

Many (M) A significant number of residential or public buildings occupied by many people are located in the area that might be endangered. A hospital or a school may be located in the area.

Several (S) Sites where several people in scattered residential buildings are located in the area that might be endangered.

Few (F) Sites where a few people in a single or very few residential buildings are located in the area that might be endangered.

Industrial (I) Sites where industrial buildings with several employees are located in the area that might be endangered. The buildings can relatively easily be evacuated in times of danger. This class should not be used unless the activity in the buildings can easily be interrupted on a short notice. Buildings where an evacuation on a short notice could cause a substantial damage to equipment in the building or to the products of the activity in the building (*e.g.* many fish processing plants) or where an evacuation leads to a substantial disruption of the local society (*e.g.* control rooms for electricity distribution, municipal heating, *etc.*), should not be allocated to this class. Schools, kindergartens, hospitals and such public buildings should not belong to this class either. A good example for this class is a garbage burning plant which is operated by 1-2 people and can easily be shut down on a short notice.

A risk index, which varies from 1 for the highest risk to 6 for the lowest risk, is derived from the above classification as follows.

Table 3: Definition of a risk index.

	Many (M)	Several (S)	Few (F)	Industrial (I)
Frequent (I)	1	2	3	4
Infrequent (II)	2	3	4	5
Potential (III)	3	4	5	6

Intermediate risk indices, *e.g.* "2-3", are sometimes specified, in order to indicate an appropriate ordering of the risk in the different areas according to a subjective estimate of the work group. Risk indices for frequency class III are also sometimes adjusted subjectively from the value corresponding to the above table in order to achieve an appropriate relative ordering of the different areas. The number of people (M, S, F, I) and the frequency (I, II, III) used to derive the risk index are given in parentheses after the risk index, (*e.g.* (M, III)), in each case the risk index is specified in the report.

The effectiveness of the proposed protection measures is graded in each case according to the following classes.

Good (I) The defense structures could be dimensioned according to the dimensioning criteria described in section 5.5. There is sufficient space for dams or deflectors or conditions are favourable for supporting structures. The work group estimates that the proposed protection substantially reduces the avalanche hazard of the site.

Medium (II) Some local conditions prevent the dimensioning of the proposed defense structures according to the dimensioning criteria described above. There may for example be insufficient space above the area that needs to be defended. The work group nevertheless considers the proposed protection to be a significant improvement in the safety of the site. The suggested defense structures should be combined with a readiness to evacuate buildings in the area during impending avalanche danger in order to reduce the rest risk which must be assumed to be present after the structures are built.

Uncertain (III) Lack of data on avalanche frequency and/or snow conditions in the starting zones prevent appropriate dimensioning of defense structures. The dimensioning and the safety effect must be considered very uncertain. The work group nevertheless considers the proposed protection to be an improvement in the safety of the site. The suggested defense structures should be combined with a readiness to evacuate buildings in the area during impending avalanche danger in order to reduce the rest risk which must be assumed to be present after the structures are built. The rest risk is very difficult to quantify in this case due to lack of information about the level of danger.

It must be stressed that continuous monitoring of avalanche conditions must be performed in the future in all the areas where there is avalanche danger. In order to reach acceptable risk level for protection measures in effectiveness categories "Medium" and "Uncertain" above, one must combine the building of the defense structures with such monitoring and a readiness to execute an appropriate evacuation plan in extreme situations. Even when the effectiveness of the protection measures is judged "Good", one must also monitor avalanche conditions carefully in order to be able to see whether unforeseen conditions beyond the adopted design criteria are developing so that appropriate measures can then be taken to insure the safety of the people.

6. SUMMARY OF PROPOSED DEFENCES

The proposed protection measures for each area are summarized in the table on the following page (Table 4). Deflectors are denoted by "L", catching dams by "G", breaking mounds by "K", and supporting structures in the starting zones are denoted by "S". The cost category I, II, III, IV or V of dams and deflectors is given in each case (see section 5.6.1). Thus a dam of type "LI" is a deflector in cost category I.

Additional tables on the following pages summarize the cost of the proposed protection measures and the value of the defended property for the different towns according to the type of protection (Tables 5, 6 and 7) and according to the value of the risk index (Table 8).

All cost and value estimates in Tables 4 to 8 and in the sections that follow are rounded to the nearest 10 mi IKR. Totals given at the bottom of the tables are sometimes not exactly equal to the sum of the corresponding column in the table for this reason.

Table 4: Summary of proposed protection measures (footnotes are located on the following page).

Location	Number of people	Freq. of aval.	Risk index	Type	Effective-ness	Cost (mi IKR)	Property (mi IKR)
ÍSAFJÖRÐUR							
Holtahverfi	M	II	2-3	S+GI	I	220	630
(*second alternative*				*GI*	*II*	*130*	*-„-)*
Seljalandshverfi[1]	M	I-II	2	LI[1]	I	320	430
Seljalandshlíð	I	I	3-4	LII	I	50	160
Gleiðarhjalli	M	II	3	GII	I/III	40	–
Funi	I	I	4	LII	I	30	300
HNÍFSDALUR							
Bakkahyrna, east	M	II	2-3	S	I	200	330
(*second alternative*				*S+GI*	*I-II*	*150*	*-„-)*
Bakkahyrna, west	M	II	2-3	GI	II	90	160
Búðarfjall, east	M	II	2-3	LII	I	20	60
Búðarfjall, west	M	II	2-3	LII	I	20	190
The farm Hraun	F	II	4	LII	I	3	10
FLATEYRI							
Innra-Bæjargil/Skollahvilft[2]	M	I	1	LII + GII[2]	I	310	1960
SÚÐAVÍK							
Súðavíkurhlíð[3]	M	I	1-2	„LII"[3]	I	140	480
BOLUNGARVÍK							
Gullies	M	II	2	GI	III	260	710
Ernir	F	I	3	LII	I	20	220
PATREKSFJÖRÐUR							
Vatneyri, middle part	M	I	1	LI+GI	II	130	230
outer parts	M	II	2	GI+S	I	240	710
Klif, sjúkrahús/skóli	M	III	2-3	GIII	I/III	50	400
Stekkagil	M	I	1-2	LV	I	20	380
Litladalsá	M	I	1-2	LV	I	20	530
Sigtún area	M	III	4	GI	I/II	120	520
BÍLDUDALUR							
Búðargil	M	I	1-2	LII	I	80	500
Milligil/Gilsbakkagil	M	III	3	GII,LV	I/III	80	550
NESKAUPSTAÐUR							
Stóralækjargil	M	II	2-3	GI'	I	120	360
Nesgil/Bakkagil	M	I	1-2	GI'	I	290	2840
Drangaskarð	M	I	1	GI'+KI'	I-II	410	1400
(*second alternative*[4]				*S*	*I-II*	*420*	*-„-)*
Urðarbotnar	M	I-II	2	GI'	I-II	280	1550
Between Tröllag. and Urðarb.	M	III	3	GI'	I-II	60	420
Tröllagil	M	I	1	GI'+KI'	II	710	1130
(*second alternative*[4]				*S*	*I-II*	*710*	*-„-)*
The area west of Tröllagil	M	I	1	GIV	I-II/III	70	880
(total undefended property							440)
SEYÐISFJÖRÐUR							
Öxl (total property)	S	I	2	–	–	–	400
Bjólfur	M	I	1	GII+GI+S	I/II	640	1230
Strandartindur[5]/Botnar	M	I	1-2	LV	–	120	–
Strandartindur	S/M	I/III	1-2	GIV	I-II/III	–	–
(total property							2020)
SIGLUFJÖRÐUR							
Jörundarskál/Strengsgil	M	I	1	LII	I	300	1020
Fífladalasvæði, south	M	III	3	S	I	210	700
Fífladalasvæði, north	M	I	1	S	I	1100	1920
Gimbraklettar	M	I	1	S	I	330	680
Gróuskarðshnjúkur, south	M	II+	2-3	S	I	50	710

The cost of the proposed protection measures for each town is shown in the following tables.

Table 5: Summary of proposed dams, deflectors and supporting structures in each town (excluding debris and slush flow protection and direct defenses).

Location	Cost (mi IKR)	Property (mi IKR)
Ísafjörður	620	1520
Hnífsdalur	330	750
Bolungarvík	280	930
Patreksfjörður	490	1460
Bíldudalur	80	500
Neskaupstaður	1870	7690
Seyðisfjörður	640	1230
Siglufjörður	1990	5020
Súðavík	140	480
Flateyri	310	1960
Total	6750	21550

Table 6: Summary of proposed debris- and slush flow protection in each town.

Location	Cost (mi IKR)	Property (mi IKR)
Ísafjörður	40	–
Patreksfjörður	40	910
Bíldudalur	80	550
Seyðisfjörður	120	–
Total	290	1460

Table 7: Summary of proposed direct defenses in each town.

Location	Cost (mi IKR)	Property (mi IKR)
Patreksfjörður	50	400
Neskaupstaður	70	880
Total	120	1270

1 The dam west of Seljaland is described in HNIT and NGI (1996). It is not strictly of type LI although it is similar.

2 The deflecting dams at Flateyri are described in VST and NGI (1996).

3 The plough below Súðavíkurhlíð is described in HNIT (1995b). It is not strictly of type LII' although it is similar.

4 The supporting structures in Drangaskarð and Tröllagil do not extend to starting zones of nearby gullies which might endanger the same areas of the town. The cost of supporting structures in the starting zones near Drangaskarð and Tröllagil might therefore increase after a further study. See also footnotes below Table 9.

5 The proposed reshaping of the banks of gullies in the Strandartindur and Botnar areas in Seyðisfjörður is only intended for debris and slush flows. The Botnar area is not assigned a risk index corresponding to snow avalanches. The value of defended property corresponding to the reshaping of the banks is not given.

The value of defended property is not specified in a few cases in Table 4. Therefore, the sums of the value of defended property in Tables 5, 6, and 7 are somewhat too low in several cases.

The cost of the proposed protection measures grouped according to the risk index is shown in the following table.

Table 8: Proposed protection measures for each value of the risk index (including debris- and slush flow defenses and direct defenses).

Risk index	Cost (mi IKR)	Property (mi IKR)
1	4000	10440
1-2	670	4720
2	1100	3400
2-3	770	2840
3	410	1890
3-4	50	160
4	150	830
Total	7150	24270

The total cost of all the proposed defense structures is about 7000 mi IKR. Additional supporting structures may be proposed above Stekkagil in Patreksfjörður, and in Bjólfur in Seyðisfjörður upon further consideration of the avalanche problems at these locations. Protection measures in order to reduce the risk associated with a flood wave in Siglufjörður due to an avalanche from Skollaskál on the other side of the fjord are also not included in the cost estimates in the above tables. Direct defenses in the Strandartindur area in Seyðisfjörður were not explicitly considered by the work group and snow fences on plateaus above starting zones might be constructed in several locations as is further described in the corresponding sections below. The cost of these additional defense structures may be expected to exceed several hundred mi IKR.

Furthermore, the cost of avalanche protection measures, in communities which were not explicitly considered here, and the cost of slush and debris flow protection measures, which were only briefly considered and include only dams along debris and slush flow paths, needs to be added to the cost estimates in the above tables. The cost of these additions may also be expected to exceed several hundred mi IKR.

Finally, the cost of permanent evacuation of buildings in avalanche hazard areas, where avalanche protection measures are not practical must be considered. It will depend on future regulation about the purchasing of property in hazard areas by the government. This cost is difficult to estimate, but it may also possibly exceed several hundred mi IKR.

The total cost of the above additions is significant, but it is much smaller than the total cost of the protection measures described in the tables. When the additional cost is taken into consideration, the result is that the total cost of avalanche protection measures, including purchasing of buildings in avalanche hazard areas, **may be estimated to be on the order of 9000 mi IKR.** There is an uncertainty in the cost estimate due to the uncertain extent of avalanche hazard areas and due to uncertain design assumptions for the proposed defense structures. There is also considerable uncertainty in the cost estimate due to the additional protection measures in areas which were not explicitly considered in the report. This uncertainty is difficult to quantify, but it reasonable to assume that the total cost of protection measures will be **in the range 7000 to 14000 million IKR**.

The total cost of dams and deflectors (excluding debris and slush flow protection and direct defenses) given in Table 5 is 4330 mi IKR, and the total cost of supporting structures is 2420 mi IKR. This division of the cost estimate, into dams and deflectors on one side and supporting structures on the other, is not particularly meaningful because it is not clear which protection measures are most suitable for Neskaupstaður.

The economic loss due to avalanche accidents in the time period 1974 to 1995 is estimated to have been approximately 3800 million IKR (*cf.* section 4.2). If fatal avalanche accidents are included in the economic loss as described in section 4.2, *i.e.* 52x100 million IKR, the total cost of avalanche accidents in Iceland in the last 22 years is similar to the total cost of avalanche protection measures which is estimated above.

The proposed supporting structures are summarized in the following table.

Table 9: Summary of proposed supporting structures.

Location	Structure height, D_k (m)	Length of rows (m)	Slope (°)	Soil conditions	Remarks
ÍSAFJÖRÐUR					
Holtahverfi	3.0	200	40-34	good	snow drift over the
	2.5	1600			ridge, some rock fall
HNÍFSDALUR					
Bakkahyrna, east	3.0	900	45-33	good	snow drift over the
	2.5	1000			ridge, some rock fall
PATREKSFJÖRÐUR					
Vatneyri, outer part	3.0	300	40-37	bad	rock fall,
	2.5	1500			snow drift
NESKAUPSTAÐUR[1]					
Drangaskarð[2]	4.0	600	37-34	medium	some rock fall
	3.5	2100			
Ytra-Tröllagil[3]	4.0	400	39	bad (?)	rock fall
	3.5	1800			
Innra-Tröllagil[3]	4.0	600	38	bad (?)	rock fall
	3.5	1800			
SEYÐISFJÖRÐUR					
Kálfabotnar	4.0	1000	37	bad-medium	rock fall problems
SIGLUFJÖRÐUR[4]					
Fífladalir, south (IV)	4.0	300	33	medium	some rock
	3.5	1100			fall, snow drift
Fífladalir, north, upper part (I)	4.0	2300	37-32	good-	some rock
	3.5	1600	35-32	medium	fall, snow drift
Fífladalir, north, lower part (III)	4.0	600	38-34	good-	
	3.5	2300		medium	
Gimbraklettar (II)	3.5	2300	43-33	medium	cliffs, some rock fall
Gróuskarðshnjúkur	3.5	400	32-31	good	snow drift

1 The configuration of supporting structures for Drangaskarð and Tröllagil shown here is only intended for comparison with the proposed dams for these areas. Supporting structures for other areas in Neskaupstaður were not explicitly considered by the work group due to bad weather conditions during the visit to Neskaupstaður. The amount of supporting structures shown here is thus not an estimate of the total amount of supporting structures which would be required if the Tröllagil area and the areas east of Tröllagil were to be defended by supporting structures.

2 The supporting structures in Drangaskarð do not extend to Skágil to the east of Drangaskarð which endangers the same area of the town.

3 The supporting structures in Tröllagil do not extend to the starting zones corresponding to small gullies between Klofagil and Tröllagil which might endanger the same area of the town.

4 The roman numerals in parentheses after the names of the supporting structure areas in Siglufjörður indicate the relative importance of the respective structures.

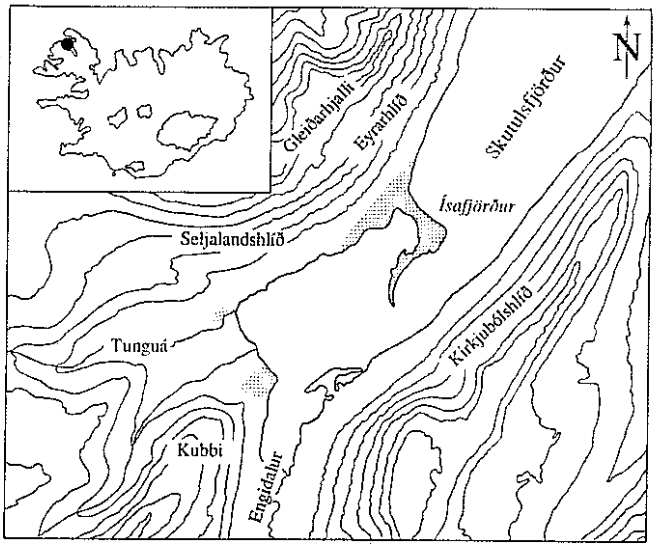


Figure 7. Location map of Ísafjörður.

7. ÍSAFJÖRÐUR

Ísafjörður is located on the western shore of the Skutulsfjörður fjord in the Ísafjarðardjúp fjord in Vestfirðir, North-Western Iceland (*cf.* Figure 7).

7.1 Holtahverfi

7.1.1 Description

The Holtahverfi area is located under the Kubbi mountain. Avalanche tracks are relatively unconfined in a slightly concave north facing slope.

The width of the inhabited area is about 650 m. Buildings are located close to the foot of the slope and the runout zone is short, especially in the eastern part of the area.

There are many residential buildings in the area.

A relatively low catching dam above the houses situated closest to the slope was built around 1988.

7.1.2 Avalanche hazard

There is a danger of avalanches under certain weather conditions (SE wind with heavy snowfall), which are relatively rare in the area. Avalanches reaching to the present location of the uppermost buildings in the area are recorded and it is possible that an avalanche in 1963 reached more than 100 m into what is now a populated area.

Avalanches can under unfavourable conditions reach far into the populated area.

The area below the proposed defense structures is assigned a risk index 2-3 (M, II).

7.1.3 Proposed protection

The eastern part of the Kubbi mountain, where the avalanches that fell in 1981 and 1984 were released, is well suited for supporting structures. Rockfall from the cliffs to the west of this area make supporting structures unfeasible for the western part of the area that needs to be protected.

Two possible configurations of defense structures were considered. First, avalanche nets in the eastern part and a catching dam in the western part. Second, a longer catching dam above both the eastern and the western part.

The height of the nets was chosen to be 3 m in cliffs in the uppermost part of the area and 2.5 m in the lower part. 200 m of the 3 m nets are required and 1600 m of the 2.5 m nets.

The dams are of type GI, *i.e.* they have steep upper sides and an earth fill on the downstream sides. The flow height of the design avalanche was chosen to be 1 m.

The effectiveness of the combination of supporting structures and catching dam is classified as good (I). The effectiveness of the longer catching dam is classified as medium (II) because the eastern wing of the dam must be located quite high up in the runout zone and it is impractical to make the dam as high there as the modelled velocities indicate (see further discussion in Appendix I).

7.1.4 Estimated cost

The cost of the first alternative is estimated to be 40 mi IKR for the dam and 180 mi IKR for the supporting structures, together 220 mi IKR. The cost of the second alternative with the longer catching dam is estimated to be 130 mi IKR.

7.1.5 Estimated value of defended property

The defended area includes 21 single family houses and 3 apartment buildings with 40 apartments. The estimated value of defended property is 630 mi IKR.

7.2 Seljalandshverfi

7.2.1 Description

The Seljalandshverfi area is located under the innermost part of the Seljalandshlíð mountain slope. Several relatively unconfined avalanche tracks are located in a south facing slope. There is an approximately 200 m wide shelf at 100-160 m a.s.l. in the track in the western part of the area. The shelf becomes narrower toward the east and is non-existent in the slope above the farm Seljaland.

The width of the inhabited area is about 500 m. The runout zone above the uppermost apartment buildings in Seljalandshverfi is very short.

There are two apartment buildings and 5 single family houses in the Seljalandshverfi proper. Several buildings are located slightly further away from the foot of the slope at Bræðratunga and Seljalandsbú.

An avalanche protection appraisal has been carried out by HNIT and NGI (1996).

7.2.2 Avalanche hazard

Several avalanches are recorded, one of them reaching almost all the way to the sea at the farm Seljaland.

Extreme avalanches can reach the Tunguá river, endangering buildings in the Seljalandshverfi area and possibly the buildings in Bræðratunga and Seljalandsbú. Farms have been located in the lower part of the area for centuries without reported damage by avalanches, indicating that the frequency of avalanches reaching that far is very low.

The area below the proposed defense structures is assigned a risk index 2 (M, I-II).

7.2.3 Proposed protection

The appraisal by HNIT and NGI recommended a 700 m long deflecting dam with a height between 13.5 and 16 m. The deflector is partly built of blasted rock and partly formed by an embankment of the quarry where the rock is blasted.

The effectiveness of the deflector is classified as good (I).

7.2.4 Estimated cost

The cost of the deflecting dam, including the cost of relocating water supply lines, power lines and other such additional cost, is estimated to be 320 mi IKR.

7.2.5 Estimated value of defended property
The defended area includes 2 apartment buildings with 26 apartments and 6 other residential buildings such as single family houses. The estimated value of defended buildings is 320 mi IKR according to the appraisal by HNIT and NGI and the value of roads and utilities was estimated to be 36 mi IKR. Total value of defended property according to HNIT and NGI is therefore 360 mi IKR. The total value of defended property according to the methodology adopted in this report is 430 mi IKR, which is somewhat higher than the value obtained by HNIT and NGI and reflects the inherent uncertainty of the methods used to estimate the value of defended property. We use the latter value in the tables in this report to be consistent with other areas which are considered here.

7.3 Seljalandshlíð

7.3.1 Description
The Seljalandshlíð mountain slope is located to the west of the main part of the town of Ísafjörður. Several avalanche tracks are located in moderately deep gullies in a south facing slope.

The width of the area is about 1 km.

There is some industrial activity in the area, but no residential buildings except the house Grænigarður.

No defense structures have been proposed to date.

7.3.2 Avalanche hazard
Avalanches are frequent and several reach all the way to sea. Evacuations are frequent and road closures are sometimes ordered during winter.

The area below the proposed defense structures at Steiniðjan and Netagerð Vestfjarða is assigned a risk index 3-4 (I, I). The risk index 3 (F, I) is assigned to the continued residential use of Grænigarður.

7.3.3 Proposed action
The area must be closely monitored during the winter. Traffic in the area and activity in the industrial buildings must be limited in times of impending avalanche danger. Residential use of Grænigarður during winter is not recommended. Avalanche protection for the industrial buildings should be considered because several people may be working there at the same time.

7.3.4 Proposed protection
A plough construction can be built to defend the buildings of Netagerð Vestfjarða and Steiniðjan. The plough is of type LII, *i.e.* both sides have a slope determined by the angle of repose of the building material.

It may be necessary to locate the plough such that the house Grænigarður would have to be overrun by the plough. The closeness to the plough would in any case degrade the neighbourhood of Grænigarður significantly. As mentioned above, the residential use of Grænigarður during winter is not recommended. The cost of purchasing Grænigarður is thus considered a part of the cost of the plough.

The effectiveness of the plough is classified as good (I).

7.3.5 Estimated cost
The cost of the plough is estimated to be 50 mi IKR. The value of the house Grænigarður is estimated to be 8 mi IKR. The total cost is therefore 50 mi IKR (note that the numbers are rounded to the nearest 10 mi IKR).

7.3.6 Estimated value of endangered property
The value of the industrial buildings of Netagerða Vestfjarða and Steiniðjan is estimated to be 160 mi IKR.

7.4 The area below Gleiðarhjalli

7.4.1 Description
Gleiðarhjalli is a large shelf at between 400 and 500 m a.s.l. in the mountain above the main part of the town of Ísafjörður. The slope below Gleiðarhjalli has a convex shape and faces southeast.

The width of the inhabited area is about 1.5 km. The runout zone above the uppermost buildings is essentially non-existent.

A large number of residential and other buildings are located in the area, some of them very near the foot of the slope.

No defense structures have been proposed to date.

7.4.2 Avalanche hazard
Avalanche risk is considered low compared to Seljalandshlíð to the west and to Eyrarhlíð to the east. Very few avalanches are reported in the area. A small, thin avalanche that reached about 50 m a.s.l. was released from the western part of the slope in 1989. Somewhat inconsistent reports indicate that a narrow avalanche reached near Engjavegur 24 around 1953.

The Gleiðarhjalli shelf protects the area from avalanches that might be released from the slope above the shelf. The size of the shelf is approximately 1500x400 m. Prevalent wind directions during winter blow snow from the slope above the area to Seljalandshlíð so that snow accumulation is distinctly less than on the slope to the west and to the east.

The slope above the Gleiðarhjalli shelf is very steep and it is likely that avalanches there, are triggered as small relatively frequent events. There is a sharp break in the slope at the upper part of the shelf which will reduce the momentum of avalanche flowing onto the shelf. These conditions together with the width of the shelf make it very unlikely that avalanches released above the shelf would be able to traverse the shelf and continue down the lower part of the hill. Additionally, the shelf is believed to collect much of the drifting snow which is blown from the mountain plateau above the shelf, thereby reducing the probability of a dangerous accumulation of snow in the slope below the shelf.

The uppermost houses are endangered by rock fall from the steep hill (*cf.* Haukur Tómasson 1969). Rocks which are becoming loose and likely to fall have been blasted to reduce the rock fall danger.

The inhabited area is endangered by debris flows from the lower part of the slope. Several small debris flows are recorded.

7.4.3 Proposed action
The area must be closely monitored during winter. An evacuation plan for the houses along the uppermost streets should be prepared in case a dangerous situation develops.

The hill should be examined every year in order to check the rock fall danger.

7.4.4 Proposed protection
Dams of type GII along the entire slope for controlling debris flows are proposed. The dams would also provide some protection against rock fall. The proposed dams are quite long and the dimensions indicated here are only intended as an order of magnitude estimate.

The effectiveness of the dams is classified as good (I) for protection against rock fall and debris flows. The dams are not intended as protection against snow avalanches, but they will provide some protection against small avalanches that might otherwise reach the uppermost houses. The probability of avalanches in the area is difficult to quantify. The effectiveness against avalanches is thus classified as uncertain (III).

7.4.5 Estimated cost

The estimated cost of the dams is 40 mi IKR.

7.4.6 Estimated value of defended property

For the time being, the estimated value of defended property is not given because it is not clear how many buildings are threatened by the debris flows.

7.5 Eyrarhlíð

7.5.1 Description

The Eyrarhlíð mountain slope is located to the north of the main part of the town of Ísafjörður. Several avalanche tracks are located in deep and moderately deep gullies in an ESE facing slope.

The width of the area is about 2.5 km.

There are no buildings in the area, but a road along the coast connects Hnífsdalur and the main part of the town of Ísafjörður.

No defense structures have been proposed to date.

7.5.2 Avalanche hazard

Avalanches are frequent and lead to frequent closures of a road along the coast.

7.5.3 Proposed action

The area must be closely monitored during the winter. Traffic in the area must be limited in times of impending avalanche danger.

7.6 Funi

7.6.1 Description

The garbage burning plant Funi is located on the eastern side of the Engidalur valley, below the Innri-Kirkjubólshlíð mountain side. This location is somewhat outside of the town of Ísafjörður. The plant is considered in this report because it was damaged in an avalanche that fell on 25 October 1995 and avalanche protection measures are currently being planned for the area.

Several avalanche tracks are located in shallow gullies in a west facing slope.

The immediate neighbourhood of Funi is without residential buildings.

The design of avalanche protection for the plant was opened for tender by the local authorities of Ísafjörður in May 1996 and awarded to the engineering firm VST.

7.6.2 Avalanche hazard

Avalanches are frequent, especially in the part of the slope directly above the plant.

The area below the proposed defense structures is assigned a risk index 4 (I, I), because the main building may be evacuated when the avalanche hazard is high.

7.6.3 Proposed protection

A plough construction can be built to defend the plant. The location and size of the plough depends on the size of the area to be defended, on possible reconfiguration of access roads and on other design decisions which will not be further discussed here. The proposal given here is based on initial ideas that have been put forward in an appraisal of defense structures for the plant and may change during the course of the work.

Protection measures for the plant will be combined with an evacuation plan so that the plant will not be occupied during impending avalanche danger.

The effectiveness of the plough is classified as good (I).

7.6.4 Estimated cost
The cost of the plough is estimated to be 30 mi IKR.

7.6.5 Estimated value of endangered property
The value of the plant is 300 mi IKR according to information from the local authorities of Ísafjörður.

8. HNÍFSDALUR

Hnífsdalur is located north of Ísafjörður on the southern side of the Ísafjarðardjúp fjord in Vestfirðir, North-Western Iceland (*cf.* Figure 8). It is a part of the Ísafjörður community.

8.1 Bakkahyrna

8.1.1 Description
The Bakkahyrna mountain is located south of Hnífsdalur. Potential avalanche tracks are relatively unconfined in a north facing slope.

The width of the inhabited area is about 650 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some industrial buildings in the area.

No defense structures have been proposed to date.

8.1.2 Avalanche hazard
There is some danger of avalanches under certain weather conditions (SE wind with heavy snowfall), which are relatively rare in the area. The slope usually collects much less snow than the slope above the northern part of the town. An avalanche touching the uppermost buildings in the area is recorded in 1983.

The area below the proposed defense structures is assigned a risk index 2-3 (M, II).

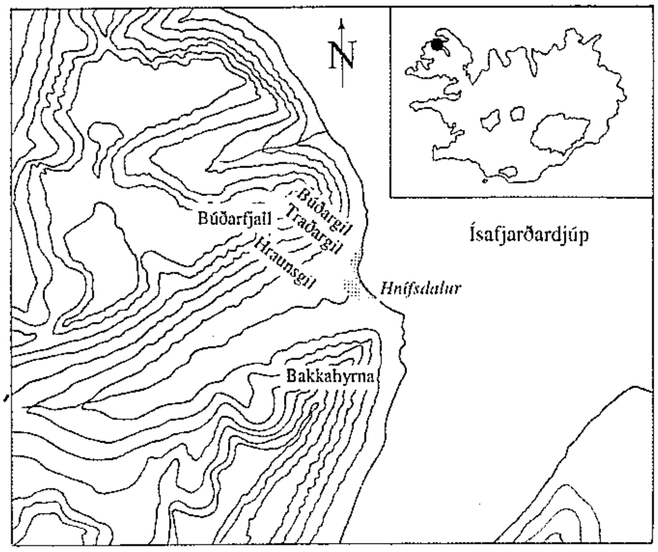
8.1.3 Proposed protection
The eastern part of the Bakkahyrna mountain, where the avalanche that fell in 1983 was released, is well suited for supporting structures, either nets or solid steel constructions. Rockfall from the cliffs to the west of this area make supporting structures less feasible there.

Two possible configurations of defense structures were considered. First, avalanche nets or solid steel constructions in the eastern part and a catching dam in the western part and second a longer catching dam combined with less extensive supporting structures.

The height of the supporting structures was chosen to be 3 m in cliffs in the uppermost part of the area and near the eastern edge of Bakkahyrna and 2.5 m in the western- and lowermost part of the area. The first configuration with the more extensive supporting structures requires 900 m of the 3 m structures and 1000 m of the 2.5 m structures. The second configuration requires 600 m of the 3 m structures and 500 m of the 2.5 m structures.

The dam is of type GI, *i.e.* it should have a steep upper side and an earth fill on the downstream side. The flow height of the design avalanche was chosen to be 1 m. The shorter dam in the first configuration protects a single row of houses and may be relatively uneconomical. The longer dam in the second configuration protects a part of the wider housing area to the east. If the protection of the single row of houses with a dam is judged uneconomical, it is possible to

Figure 8. Location map of Hnífsdalur.



combine the less extensive supporting structures with a short dam above the western part of the relatively wide housing area. The cost of this dam would be equal to the difference of the cost of the dams in the two configurations.

The effectiveness of the supporting structures in the eastern part is classified as good (I). The effectiveness of the smaller amount of supporting structures and a catching dam is classified as good to medium (I-II) because it is impractical to make the dam as high as the modelled velocities indicate (see further discussion in Appendix I). The effectiveness of the dam in the western part of the area is classified as medium (II) for the same reason.

8.1.4 Estimated cost

The cost of the first alternative is 200 mi IKR for the supporting structures and 90 mi IKR for the dam in the western part, together 290 mi IKR.

The cost of the second alternative with the less extensive supporting structures is estimated to be 110 mi IKR for the supporting structures, 40 mi IKR for the dam in the eastern part and 90 mi IKR for the dam in the western part, together 240 mi IKR.

8.1.5 Estimated value of defended property

The defended area includes 34 single family houses and one industrial building. The estimated value of defended property in the eastern part is 330 mi IKR. The estimated value of defended property in the western part is 160 mi IKR. The total is 490 mi IKR.

8.2 Búðarfjall

8.2.1 Description

The Búðarfjall mountain is located north of Hnífsdalur. Three large avalanche tracks, Búðargil, Traðargil and Hraunsgil, are located in deep gullies in a SSE facing slope.

The width of the inhabited area is about 400 m.

There are many residential and some other buildings in the area.

Residential buildings closest to the Traðargil avalanche path and in the neighbourhood of the old farm Heimabær have been purchased by the government in order to guarantee that they are not used during the winter.

Defense structures consisting of deflectors (heights 12-17 m and 7-17 m, lengths 350 m and 130 m) have been proposed (VST 1994a). Representatives from EI in France have considered the installation of avalanche nets in the starting zones and some of the combinations of defense structures proposed by VST included about 300 m of nets in the starting zones.

8.2.2 Avalanche hazard
Avalanches are frequent and several recorded avalanches from Búðargil have reached the ocean. Evacuations of several buildings may occur many times in some winters. A catastrophic avalanche with many fatalities occurred in 1910 in Búðargil in an area which is presently without residential buildings, although some residential buildings are close to this area.

Most of the buildings that were purchased by the government are located in the runout area of an avalanche that fell in 1947 and reached the river Hnífsdalsá.

Privately owned stables are currently located in the dangerous area below Búðargil.

The area below the proposed defense structures outside the zone where buildings were purchased by the government is assigned a risk index 2-3 (M, II). The farm Hraun assigned a risk index 4 (F, II).

The frequency classification of II is used because the buildings which have not been purchased by the government are located so far from the avalanche track that avalanches threatening these buildings must be considered infrequent although the frequency of avalanches in the avalanche tracks is very high.

8.2.3 Proposed action
It is necessary to exercise all possible care with regard to traffic in the stables under Búðargil during impending avalanche danger and it is recommended that the stables are moved to a safer place as soon as possible. The stables are located in an extremely dangerous place in the runout zone avalanches from Búðargil where at least 4 avalanches have reached the sea in the last 3 centuries.

8.2.4 Proposed protection
Avalanche protection was not considered for the buildings in Teigahverfi and at Heimabær which have been purchased by the government. A quick evaluation of the conditions at the site indicates that acceptable protection for these buildings would be difficult to construct and very expensive.

A plough is suggested for the community centre ("félagsheimili") below the old farm at Heimabær. This plough would partly overrun the buildings at Heimabær.

Another plough is suggested to protect the apartment buildings below Teigahverfi. This plough could overrun one of the houses which was bought by the government, but the location and length of the plough should be addressed in a further study in the appraisal phase.

A third and much smaller and lower plough is suggested above the newer of the two residential houses at the farm Hraun. Protection measures were not considered for the older farm house. Although the farm has not been damaged by avalanches for centuries, its location very near the path of avalanches, which extent significantly beyond the location of the farmhouses, indicates that its safety should be improved. The dimensions of this plough were not determined by explicit velocity computations as it is assumed that potential avalanche tongues reaching the farm would be the sidewards margins of avalanches so that the impact toward the farm would be relatively small. A 5-6 m high plough with wings forming a 30-45° angle to the direction of the avalanches is deemed a suitable dimensioning of this plough.

The ploughs are all of type LII, *i.e.* both sides have a slope determined by the angle of repose of the building material.

The effectiveness of the ploughs is classified as good (I).

8.2.5 Estimated cost

The estimated cost of the eastern plough at Heimabær is 20 mi IKR. The estimated cost of the western plough above the apartment buildings is 20 mi IKR. The cost of the plough at Hraun is estimated to be 3 mi IKR.

8.2.6 Estimated value of defended property

The defended area in the town includes 19 single family houses and 2 apartment buildings with a total of 10 apartments. The estimated value of property defended by the eastern plough is 60 mi IKR. The estimated value of property defended by the western plough is 190 mi IKR.

The estimated value of the farm Hraun is 10 mi IKR.

9. FLATEYRI

Flateyri is located on the north shore of the Önundarfjörður fjord, North-Western Iceland (*cf.* Figure 9).

9.1 Innra-Bæjargil/Skollahvilft

9.1.1 Description

Two main avalanche paths, Innra-Bæjargil and Skollahvilft, are located in a 660 m high SSE facing slope above the town of Flateyri.

The width of the inhabited area is about 700 m. The length of the runout zone from the 10°-β point to the uppermost buildings in the western part of the town is approximately 100 m.

There are many residential and other buildings in the area.

An avalanche protection appraisal has been carried out by VST and NGI (1996).

9.1.2 Avalanche hazard

Many avalanches are recorded from both avalanche tracks. Extreme avalanches can potentially reach an area where more than half of the buildings of the town are located. A catastrophic avalanche from Skollahvilft on 26 October 1995 killed 20 people.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

9.1.3 Proposed protection

The appraisal by VST and NGI recommended two 15-20 m high deflecting dams with a combined length of 1250 m, and a 10 high catching dam between the deflectors. The dams are built from local material excavated from the fans below the gullies. They are therefore similar to, but not exactly the same as, dams of type LII and GII as defined in this report.

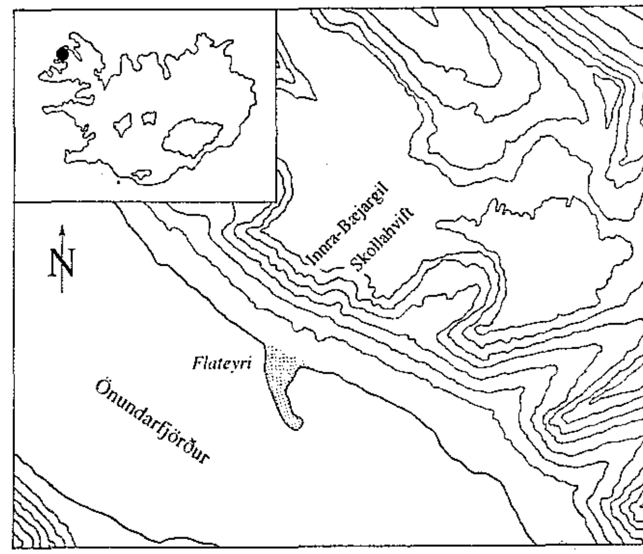
The construction of snow fences on the mountain above Flateyri will reduce the snow accumulation in the starting zones and improve the safety of the dams although the safety improvement is difficult to quantify.

The effectiveness of the deflectors and the catching dam is classified as good (I).

9.1.4 Estimated cost

The cost of the dams, including the cost of relocating water supply lines, and some other such additional cost, is estimated to be 390 mi IKR. Bids for the construction of the dams were opened in August 1996. It appears that the construction cost will be somewhat lower than the initial cost estimates indicated. The total cost according to a revised cost estimate is 310 mi IKR.

Figure 9. Location map of Flateyri.



9.1.5 Estimated value of defended property
The estimated value of defended buildings is 1960 mi IKR according to the appraisal by VST and NGI.

10. SÚÐAVÍK

Súðavík is located in the Álftafjörður fjord in Ísafjarðardjúp in Vestfirðir in North-Western Iceland (*cf.* Figure 10).

10.1 Súðavíkurhlíð

10.1.1 Description
Súðavíkurhlíð is a relatively unconfined east facing mountain side with steep cliffs near the top.

The width of the area is about 850 m. The length of the runout zone from the 10°-β point to the uppermost buildings which have not been purchased by the government after the accident in 1995 is approximately 200 m.

There are many residential and other buildings in the area.

All residential buildings in the area have been purchased by the government in order to guarantee that they are not used during the winter. The remaining industrial buildings and offices are located in a relatively small area near the harbour.

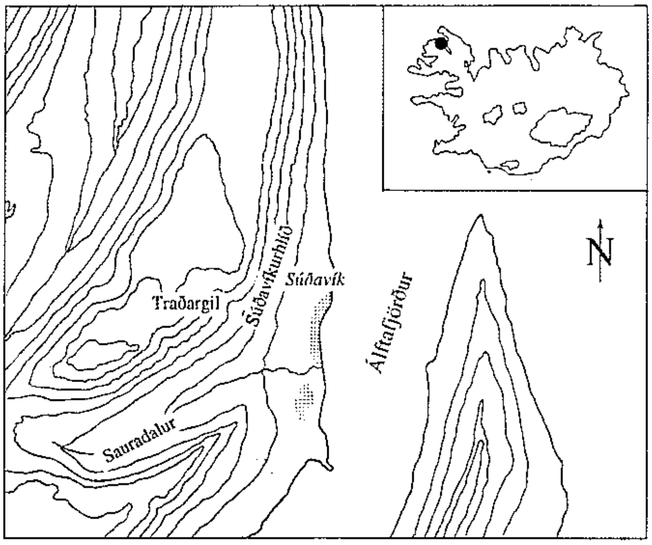
An avalanche protection appraisal has been carried out by HNIT (1995a,b).

10.1.2 Avalanche hazard
Several avalanches reaching close to or beyond the uppermost buildings are recorded from the slope. Extreme avalanches can potentially reach the ocean. A catastrophic avalanche on 16 January 1995 killed 14 people.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I) (the index applies to the remaining buildings after all residential buildings in the area have been purchased by the government).

10.1.3 Proposed protection
The appraisal by HNIT suggested several different alternatives for defending the area. Discussions of these alternative with the local authorities have not reached a final conclusion and the appraisal phase in the design of the defense structures has not been concluded. We choose here the alternative identified as alternative "5" in the report from HNIT (1995b), which consists of a 560 m long plough construction above the harbour area. The plough is partly built

Figure 10. Location map of Súðavík.



from local material and partly from material pumped from the sea. It is therefore similar to, but not exactly the same as, deflectors of type LII' as defined in this report.

The effectiveness of the plough is classified as good (I).

10.1.4 Estimated cost
The cost of the plough is estimated to be 140 mi IKR in HNIT (1995b).

10.1.5 Estimated value of defended property
The estimated value of defended buildings is 480 mi IKR. The plough will additionally defend an apartment building by Aðalgata which has been purchased by the government and is therefore not included in the value of defended property. The value of this building is 80 mi IKR.

10.2 Traðargil

10.2.1 Description
Traðargil is a deep gully in an east facing slope south of Súðavíkurhlíð.

The width of the area is about 400 m.

There are many residential buildings in the area.

All buildings in the area have been purchased by the government in order to guarantee that they are not used during the winter.

One of the protection options considered in HNIT (1995a) defends a part of this area, but this option was not considered as cost effective as some of the other options.

10.2.2 Avalanche hazard
Several avalanches are recorded from the gully, some reaching to the ocean. An avalanche on 16 January 1995 damaged some buildings which had been evacuated the night before.

10.2.3 Proposed action
The area must be closely monitored during the winter. Traffic in the area to and from the industrial buildings in the harbour area under Súðavíkurhlíð must be limited in times of impending avalanche danger.

Avalanche protection was not considered because all buildings in the area have been purchased by the government and will not be used during the winter.

10.3 Eyrardalssvæði

10.3.1 Description
The Eyrardalssvæði area is the new location of the town of Súðavík, which was established after the accident in 1995. The slope above the area, Kofrahögg, has a convex shape and faces east. A valley, Sauradalur, is located west of a part of the area.

The width of the area is more than 1 km.

A large number of residential and other buildings will be located in the area when the relocation of the town of Súðavík to this area is complete.

10.3.2 Avalanche hazard
Avalanche risk is considered low (see the report by NGI, HNIT and VÍ 1995).

10.3.3 Proposed action
The main avalanche danger facing the inhabitants is related to traffic to and from the area as mentioned in the preceding section about Traðargil. Avalanche hazard must be monitored so that the traffic can be limited in times of impending avalanche danger.

11. BOLUNGARVÍK

Bolungarvík is located west of Ísafjörður and Hnífsdalur on the southern side of the Ísafjarðardjúp fjord in Vestfirðir, North-Western Iceland (*cf.* Figure 11).

11.1 Gullies in Traðarhyrna above the western part of the town

11.1.1 Description
The Traðarhyrna mountain is to the north of Bolungarvík. Avalanche tracks above the western part of the town are gullies in a south facing slope.

The width of the inhabited area is about 300 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

There are many residential buildings in the area. Some of them are located so near the bottom of the slope that there is very little space between the buildings and the slope for the construction of defense structures.

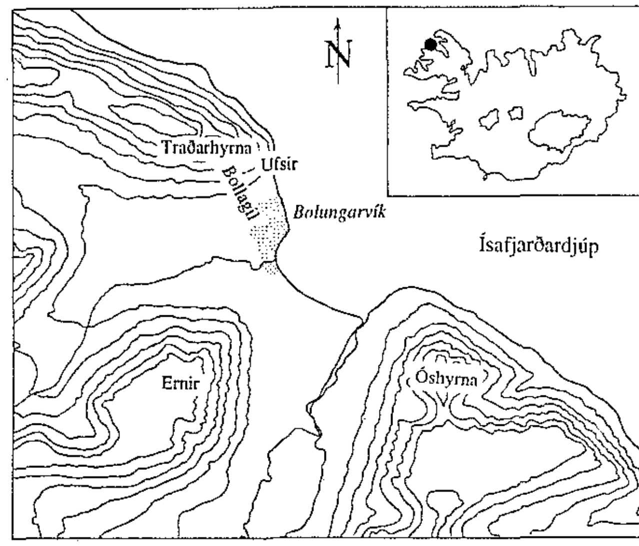
No defense structures have been proposed to date.

11.1.2 Avalanche hazard
There is some avalanche danger, but the avalanche records are very sparse so it is difficult to estimate the avalanche frequency. Recent discussion with the local people indicate that at least 4 avalanches have reached beyond the foot of the slope above Dísarland and Traðarland since 1970. Several avalanches are recorded in the gully Bollagil to the west of the area. Comparison of the conditions in Bollagil with the gullies above the area indicates that there is more potential for dangerous accumulation of snow in Bollagil compared with the gullies above the streets Traðarland and Dísarland, but there is a clear potential for the release of avalanches in the gullies also.

The area below the proposed defense structures is assigned a risk index 2 (M, II).

11.1.3 Proposed protection
A catching dam of type GI at the foot of the slope is proposed. The flow height of the design avalanche was chosen to be 1 m. The dam should have a steep upper side and an earth fill on the downstream side. There is so little space between the uppermost houses and the hill that several houses may have to be overrun by the dam in order to generate sufficient space.

Figure 11. Location map of Bolungarvík.



The effectiveness of the catching dam is classified as uncertain (III) because it is impractical to make the dam as high as the modelled velocities indicate and the lack of recorded avalanche history makes the choice of design avalanche very difficult (see further discussion in Appendix I).

11.1.4 Estimated cost

The estimated cost of the catching dam is 130 mi IKR. The estimated value of the houses that are overrun by the dam is 130 mi IKR. The total cost is therefore 260 mi IKR.

11.1.5 Estimated value of defended property

The defended area includes 47 single family houses. The estimated value of defended property is 710 mi IKR.

11.2 Ufsir

11.2.1 Description

The outermost part of the Traðarhyrna mountain is called Ufsir. The mountain slope has a convex shape and faces S and ESE. A small shelf is located in the middle of the eastern part of the slope.

The width of the inhabited area is about 600 m. The length of the runout zone from the 10°-β point to the uppermost buildings is approximately 100 m over much of the area.

There are many residential and other buildings in the area.

No defense structures have been proposed to date.

11.2.2 Avalanche hazard

The avalanche hazard is believed to be low, but the avalanche records are very short so it is difficult to estimate the avalanche frequency. The mountain slope above this area usually collects little snow due to its convex shape.

11.2.3 Proposed action

The area must be closely monitored during winter. The houses along the uppermost streets must be evacuated in case a dangerous situation develops.

11.3 Ernir

11.3.1 Description
Privately owned stables and some buildings owned by the Vestfirðir Power Company are located at the foot of the slope of the mountain Ernir to the south of Bolungarvík. The main avalanche track above the area is a marked gully in an east facing slope. The buildings of the Power Company are to the side of the main avalanche path. The buildings often need to be occupied 24 hours a day during times of bad weather when the avalanche danger may be very high.

The width of the area is about 200 m. The runout zone above the stables and the buildings of the Power Company is essentially non-existent.

No defense structures have been proposed to date.

11.3.2 Avalanche hazard
Several avalanches are recorded from the gully above the stables. The stables have been hit by an avalanche and there are records of avalanches reaching far beyond the present location of buildings in the area.

Avalanche hazard in the area of the stables is very high. The avalanche hazard in the area where the buildings of the Vestfirðir Power Company are located is not as high, but avalanches could also be released from the hill directly above these buildings and extreme avalanches from the gully appear to be able to reach the area.

It is difficult to prevent the occupation of the buildings of Vestfirðir Power Company during impending avalanche danger because the operation of reserve power must be controlled from a control room in one of the buildings.

The area below the proposed defense structures is assigned a risk index 3 (F, I), because continuous occupation of the main building may be necessary when avalanche hazard is high.

11.3.3 Proposed action
It is necessary to exercise all possible care with regard to traffic in the stables under the gully during impending avalanche danger and it is recommended that the stables are moved to a safer place as soon as possible. The stables are located in an extremely dangerous place 200 m within the runout zone of a recorded avalanche.

11.3.4 Proposed protection
A plough of type LII, *i.e.* both sides have a slope determined by the angle of repose of the building material, is suggested above the main building of the Vestfirðir Power Company. The flow height of the design avalanche was chosen to be 1 m. The layout of the plough depends on the size of the area which should be defended. If it is desired to defend transformers and other equipment, which is currently located to the south of the main building, then either the plough must be made wide enough to defend both the main building and the equipment or the equipment should be relocated to the area east of the main building. This would reduce the probability of breakdown of reserve power generation in case an avalanche falls, although it is not strictly necessary for the safety of people working in the main building. A storage building to the north of the main building could also possibly be moved if the operation of the Vestfirðir Power Company requires access to this building during times of impending avalanche danger. The strength of the main building with respect to pressure from the powder part of an avalanche hitting the plough should be analyzed as a part of the design of the plough. The plough proposed here is based on the assumption that the main building and the equipment are defended in their current configuration, but this must be reevaluated in the appraisal phase of protection for this location.

The effectiveness of the plough is classified as good (I).

11.3.5 Estimated cost

The estimated cost of the plough is 20 mi IKR.

11.3.6 Estimated value of defended property

The estimated value of the main building and together with transformers and other equipment to the south of it is 220 mi IKR. The importance of a continuous operation of the reserve power station in times of avalanche danger is not easy to quantify in economic terms, but it must be significant.

12. PATREKSFJÖRÐUR

The Patreksfjörður town is located on the eastern side of the Patreksfjörður fjord in the southern part of Vestfirðir, North-Western Iceland (*cf.* Figure 12).

12.1 Vatneyri

12.1.1 Description

The area near the harbour in Patreksfjörður is called Vatneyri. The main starting zone of avalanches is a deep bowl at 250-300 m a.s.l. in a southwest facing slope directly above the harbour. The main track is unconfined without major gullies.

The width of the inhabited area is about 700 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings outside of the main avalanche path is essentially non-existent.

There are many residential and industrial buildings in the area.

Defense structures consisting of deflectors (heights 9-10 m and 8 m, lengths 170 m and 250 m) have been proposed (VST 1994b).

12.1.2 Avalanche hazard

Avalanches in the path above the present harbour are frequent and have caused damage to several houses in the area. The avalanches are most frequent in a 150 m wide path in the middle of the area, but there is some danger outside of this path. The deep bowl in the starting zone can collect a large amount of snow. Big cornices frequently form in cliffs above the bowl. Avalanches are often released when the cornices break of and can become very large if there is a large amount of snow in the bowl which can be entrained into the avalanche.

There is a large catchment area for snow drift on the mountain above Patreksfjörður.

The area below the proposed defense structures closest to the main avalanche path is assigned a risk index 1 (M, I). The area further away from the path is assigned a risk index 2 (M, II).

12.1.3 Proposed protection

The proposed defense structures consist of deflectors along the margins of the main path with catching dams to the sides.

Due to little space for dams near the eastern end of the area, the dams must be combined with supporting structures there. Avalanche nets appear to be appropriate for the loose scree where the structures have to be located. The height of the nets was chosen to be 3 m in the uppermost part of the area and 2.5 m in the lower part. 300 m of the 3 m nets are required and 1500 m of the 2.5 m nets.

The deflectors are of type LI and the dams are of type GI, *i.e.* they have steep upper sides and an earth fill on the downstream sides. The defense structures are divided into two parts, firstly the deflectors and the innermost part of the catching dams where the avalanche danger is greatest,

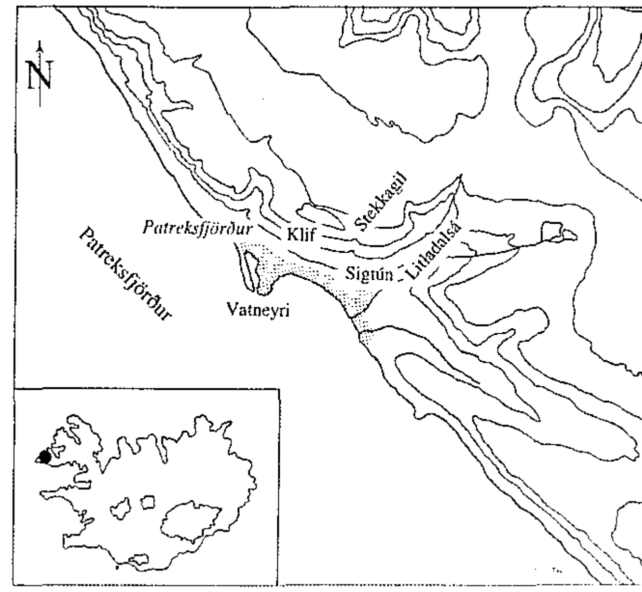


Figure 12. Location map of Patreksfjörður.

and secondly the outermost catching dams and the supporting structures where the avalanche danger is significantly less. The catching dams will protect the area from rock fall in addition to functioning as protection against avalanches. The flow height of the design avalanche was chosen to be 4 m for the deflectors in the main path and 4 m for the catching dams to the sides. The high value of the flow height for the main path was chosen because the deflectors on both sides of the path may be expected to lead to a concentration of the avalanche flow.

There is so little space between the uppermost houses and the hill that 2 houses above the street Hólar may have to be overrun by the dam on the western side of the path in order to generate sufficient space.

There is little space for defense structures at the site and the present location of buildings makes the design of protection measures quite difficult. Large avalanches in the main path may be expected to enter the present harbour and cause significant damage even after the defense structures are built. Proper design assumptions for the catching dams, especially the catching dams to the sides, are very difficult to determine and the configuration suggested here must be considered with this uncertainty in mind.

The effectiveness of the deflectors and the innermost catching dams is classified as medium (II). The effectiveness of the outermost catching dams and the supporting structures is classified as good (I).

The construction of snow fences on the mountain above Patreksfjörður will reduce the probability of dangerous snow accumulation on the slope as further discussed in a subsequent section.

12.1.4 Estimated cost

The estimated cost of the deflectors and dams closer to the main path is 100 mi IKR. The estimated value of the houses that are overrun by the dam is 30 mi IKR. The total cost is therefore 130 mi IKR.

The estimated cost of the dams and the supporting structures further away from the path is 60 mi IKR for the dams and 180 mi IKR for the supporting structures, together 240 mi IKR.

12.1.5 Estimated value of defended property

The defended area includes 72 single family houses and several industrial buildings. The estimated value of defended property is 940 mi IKR (230 mi IKR near the path and 710 mi IKR further away from the path).

12.2 Klif

12.2.1 Description

The mountain slope to the east of Vatneyri is called Klif. The slope above the area has a convex shape and faces SSW.

The width of the inhabited area is about 650 m. The runout zone above the uppermost buildings is essentially non-existent.

There are several residential and other buildings in the area.

No defense structures have been proposed to date.

12.2.2 Avalanche hazard

The avalanche danger is believed to be low. The mountain slope above this area usually collects little snow, but buildings are located very close the slope.

A hospital and a school are located near the bottom of the slope where there is some rock fall danger. Although the avalanche danger is difficult to assess, there is clearly a potential for the release of avalanches which could reach these buildings.

The area below the proposed defense structures is assigned a risk index 2-3 (M, III).

12.2.3 Proposed protection

A 250 m long catching dam of type GIII is proposed above the school and the hospital in order to reduce the rock fall danger and provide some protection against avalanches. The dam should be built as high as is practical, say 6-10 m high, but there is very little space for a dam at the site. The earth fill on the downstream side of the dam should be made as steep as possible in order to better utilize the limited space for the dam.

The effectiveness of the catching dam is classified as good (I) for protection against rock fall and debris flows but uncertain (III) for avalanche protection because the dam is relatively low and it is difficult to determine an appropriate design avalanche.

The construction of snow fences on the mountain above Patreksfjörður will reduce the probability of dangerous snow accumulation on the slope as further discussed in a subsequent section.

12.2.4 Estimated cost

The estimated cost of the catching dam is 50 mi IKR.

12.2.5 Estimated value of defended property

The dam is intended to protect the school and the hospital with an estimated value of 360 mi IKR. It will also defend the building that houses the equipment of the municipal heating utility of Patreksfjörður which has an estimated value of 30 mi IKR. The total value of defended property is therefore 400 mi IKR.

12.3 Stekkagil

12.3.1 Description

Stekkagil is a deep gully to the east of the Klif mountain side. It is a potential starting zone for both slush flows and snow avalanches.

The gully is narrow and the width of the inhabited area below it is about 300 m. The runout zone above the uppermost buildings is essentially non-existent.

There are several residential and other buildings in the area.

Avalanche nets at about 80-150 m a.s.l. in the gully (4 rows, total length 250 m) have been proposed (VST 1994b).

12.3.2 Avalanche hazard

A slush flow from the gully caused 3 fatalities in 1983. There is also a danger of dry snow avalanches from cornices or drift snow that accumulates in the upper part of the gully. There are records of slush flows from Stekkagil around 1948 and 1966 or 1967, in addition to the catastrophic event in 1983, and some indications of additional slush flows before 1948.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I).

12.3.3 Proposed protection

Guiding dams of type LV along the path of slush flows are proposed. There is little space for the dams and they will therefore have to be located very close to several buildings which are nearest to the slush flow path. The path will have to be kept open during winter by removing drift snow that accumulates in the path. A bridge or a culvert needs to be built where the slush flow path crosses the road along the shore.

Measures for improving the drainage of water from the snow pack in the area immediately below the opening of the gully should also be considered.

The Stekkagil path is probably a more dangerous slush flow path than most other paths considered in this report. It is likely that, on further examination, the guiding dams should be made somewhat higher than guiding dams of type LV as defined in subsection 5.6.1 and therefore more expensive than proposed here. This question should be considered in the appraisal stage of protection measures for Stekkagil, but it does not greatly affect the estimated total cost of protection measures for Patreksfjörður which is presented here.

A potential starting zone of snow avalanches is located near the top of the slope to the east of the gully. Reports about the accident in 1983 are not fully consistent as to whether the catastrophic flow started as a snow avalanche from this area which released a slush flow at the bottom of the gully, or whether the flow started below the gully as a slush flow. Further examination of the potential starting zone at the top of the gully must be made and a decision to build supporting structures there must be made on the basis of such an examination. The cost of possible supporting structures in this area is not included in the cost estimate presented here. The area is somewhat smaller than the area above Vatneyri where supporting structures are proposed, but conditions for supporting structures may be expected to be significantly worse in the area east of Stekkagil.

The effectiveness of the guiding dams is classified as good (I).

12.3.4 Estimated cost

The estimated cost of the guiding dams is 20 mi IKR including a bridge or a wide culvert at the road by the sea.

12.3.5 Estimated value of defended property

The defended area includes 28 single family houses. The estimated value of defended property is 380 mi IKR.

12.4 Litladalsá

12.4.1 Description

The river Litladalsá runs through the eastern part of the town of Patreksfjörður. It is a potential path of slush flows which may overrun the river course and endanger buildings on the western bank.

The width of the inhabited area is difficult to define but it is about 150 m.

There are several residential and other buildings in the area.

An appraisal of avalanche protection for Patreksfjörður (VST 1994b) discusses the possibility of dams to contain wet avalanches or slush flows, but explicit proposals for defense structures are not made.

12.4.2 Avalanche hazard
A slush flow or a slush flow triggered flood in the river caused 1 fatality in 1983.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I).

12.4.3 Proposed protection
A guiding dam of type LV along the western bank of the river is proposed. There is enough space for the construction of the dam, but the location of the river course may have to be adjusted in places because of buildings that are presently located very close to the western bank. The path will have to be kept open during winter by removing drift snow that accumulates in the path. A bridge or a culvert needs to be built where the river crosses the road along the shore.

The effectiveness of the guiding dams is classified as good (I).

12.4.4 Estimated cost
The estimated cost of the guiding dam is 20 mi IKR including a bridge or a wide culvert at the road by the sea.

12.4.5 Estimated value of defended property
The defended area includes 34 single family houses. The estimated value of defended property is 530 mi IKR.

12.5 Sigtún area

12.5.1 Description
The Sigtún area is in the eastern part of the town of Patreksfjörður. The slope above the area has a slightly convex shape and faces south. There are several small gullies in cliffs near the top of the slope.

The width of the inhabited area is about 450 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some other buildings in the area.

No defense structures have been proposed to date.

12.5.2 Avalanche hazard
The avalanche danger is believed to be low, but two relatively small avalanches are recorded from the winter of 1994/95 when there was exceptionally much snow in this part of the country. The mountain slope above this area usually collects little snow, but some buildings are located very close to the slope.

The area below the proposed defense structures is assigned a risk index 4 (M, III).

12.5.3 Proposed protection
A catching dam of type GI at the foot of the slope is proposed. The flow height of the design avalanche was chosen to be 1 m. The dam should have a steep upper side and an earth fill on the downstream side.

The effectiveness of the catching dam is classified as good (I) for the protection against rock fall and debris flows but medium (II) for avalanche protection because the avalanche history makes the choice of design avalanche very difficult (see further discussion in Appendix I).

If a dam is not built, the houses along the uppermost streets must be evacuated in case a dangerous situation develops.

The construction of snow fences on the mountain above Patreksfjörður will reduce the probability of dangerous snow accumulation on the slope as further discussed in a subsequent section.

12.5.4 Estimated cost
The estimated cost of the catching dam is 120 mi IKR.

12.5.5 Estimated value of defended property
The defended area includes 36 single family houses. The estimated value of defended property is 520 mi IKR.

12.6 Snow fences

The construction of snow fences to gather snow that might otherwise be blown from the catchment area on the mountain above Patreksfjörður to the potential starting zones above Vatneyri, Klif and the Sigtún area should be examined. It is difficult to quantify the added safety provided by the snow fences, but the conditions seem to be favourable for their construction and they would improve the hazard situation. The length of the snow fences cannot be determined at this point in time and their cost is therefore not given here.

13. BÍLDUDALUR

Bíldudalur is located in Bíldudalsvogur in the Arnarfjörður fjord in the southern part of Vestfirðir, North-Western Iceland (*cf.* Figure 13). It is a part of the same community as Patreksfjörður.

A report on the avalanche hazard in Bíldudalur and a discussion of possible defense structures was written some years ago (Stuðull 1990), but no defense structures have been built yet according to these proposals. The proposed defense structures were deflecting dams near the main slush and debris flow paths in the gullies Búðargil and Gilsbakkagil and below the slope between the two gullies. Some relatively low deflecting dams that are intended to control slush and debris flows have been constructed in the area.

13.1 Búðargil

13.1.1 Description
The Búðargil gully is located above the outermost part of the town of Bíldudalur. A 400-500 m wide bowl shaped starting zone facing SE leads into the deep and narrow gully.

The width of the inhabited area is 400-500 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

There are many residential and other buildings in the area.

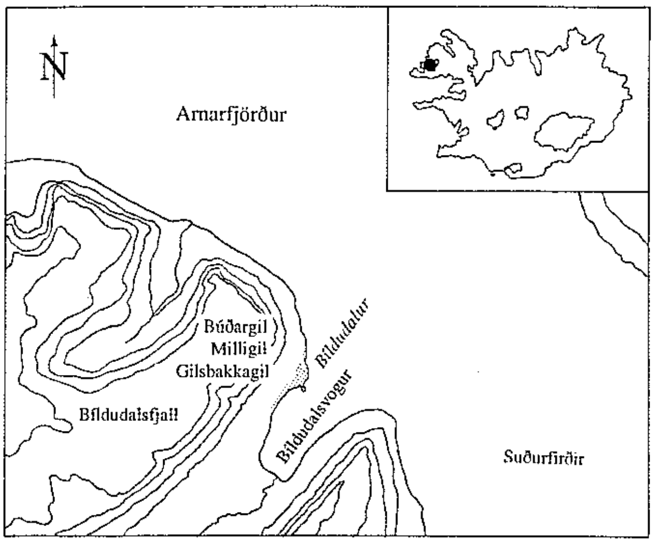
Deflecting dams to control slush and debris flows have been proposed (Stuðull 1990).

13.1.2 Avalanche hazard
Several snow avalanches, slush flows, debris flows and floods from the gully are recorded.

A depression in the mountain above the Búðargil gully collects slush which is believed to have been released into the gully and functioned as a triggering mechanism for large slush flows.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I).

Figure 13. Location map of Bíldudalur.



13.1.3 Proposed protection

A deflecting dam of type LII is proposed, *i.e.* both sides have a slope determined by the angle of repose of the building material. The dam deflects snow avalanches and slush and debris flows to the north where 10 residential houses would have to be purchased by the government in order to prevent their use during winter. The flow height of the design avalanche was chosen to be 3-4 m near the opening of the gully but can be assumed to decrease along the deflector. The dam would meet the southern side of the entrance of the gully with a height in excess of 15 m, but the height would be reduced away from the gully. The opening of the gully should be widened as a part of the construction of the defense structures and the area immediately below the gully should be reshaped in order to minimize the deflecting angle when an avalanche hits the deflector.

In addition, it is suggested that a flow path for slush flows from the depression in the mountain plateau above the Búðargil is opened to the northern side of the mountain. This would provide added safety by eliminating one potential release mechanism for avalanches and slush flows. The cost of opening this flow path is estimated to be relatively small compared to the cost of other proposed defense structures and it is not given separately.

The effectiveness of the deflecting dam is classified as good (I).

13.1.4 Estimated cost

The estimated cost of the deflector is 40 mi IKR. The estimated value of the houses that need to be purchased is 40 mi IKR. The total cost estimate is therefore 80 mi IKR.

13.1.5 Estimated value of defended property

The defended area includes 52 single family houses and several industrial and other buildings. The estimated value of defended property is 500 mi IKR.

13.2 Milligil/Gilsbakkagil

13.2.1 Description

The Gilsbakkagil gully is located above the innermost part of the town of Bíldudalur. Several smaller gullies in the southwest facing slope between Búðargil and Gilsbakkagil are collectively called "Milligil".

The width of the inhabited Milligil area is about 400 m. The width of the inhabited Gilsbakkagil area is about 400 m. The runout zone above the uppermost buildings is essentially non-existent.

There are several residential and some other buildings in the area.

Low dams for the defense against slush and debris flows have been built above the inhabited area, but they have been overrun by wet snow avalanches (*e.g.* in 1969). Deflecting dams to control slush and debris flows have been proposed (Stuðull 1990).

13.2.2 Avalanche hazard

Several debris flows from small ravines in the hill and over the debris fan below the gully Gilsbakkagil are recorded, but no avalanches.

There is a large catchment area for snow drift on the Bíldudalsfjall mountain above Bíldudalur.

The area below the proposed defense structures is assigned a risk index 3 (M, III).

13.2.3 Proposed protection

The area is wide and it is difficult to construct defense structures that are in reasonable relation to the value of the buildings along the shore. There are no records of snow avalanches although there is a potential for the release of avalanches if snow accumulates on the slope in the Milligil area or in Gilsbakkagil. The frequent debris flows need to be controlled by improving the existing dams and making wider culverts or bridges at the road in order to prevent obstructions in the flow of the debris to the sea.

Dams of type GII along the entire slope for controlling debris and slush flows are proposed. They would be combined with guiding dams of type LV along three debris flow paths to the sea where bridges or wide culverts would be built to allow the flows to flow under the road. The dams would be about 6 m high. This is sufficient for controlling the debris flows and would provide some protection against smaller avalanches which might otherwise have reached the uppermost houses. The dams would on the other hand not provide much protection against large snow avalanches. Bridges or culverts need to be built where the three main slush and debris flow paths cross the road along the shore.

The effectiveness of the catching dams is classified as good (I) for protection against rock fall and debris flows but uncertain (III) for avalanche protection because the dams are very low and the avalanche danger is difficult to quantify.

The area must therefore be closely monitored during winter. The uppermost houses along the main road must be evacuated in case a dangerous situation develops.

13.2.4 Estimated cost

The estimated cost of the dams is 40 mi IKR. The estimated cost of the guiding dams is 40 mi IKR including three bridges or wide culverts under the road by the sea. The total cost is thus 80 mi IKR.

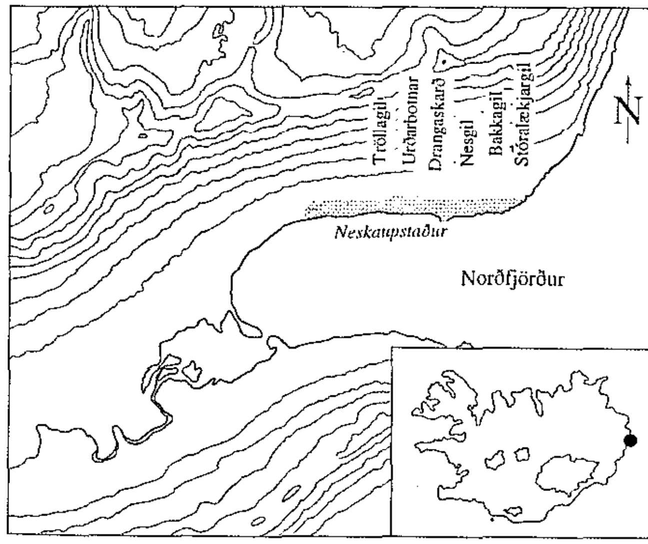
13.2.5 Estimated value of defended property

The defended area includes 59 single family houses, one apartment building with 11 apartments and some other buildings. The estimated value of defended property is 550 mi IKR.

13.3 Snow fences

The construction of snow fences to gather snow that might otherwise be blown from the catchment area on the mountain above Bíldudalur to the potential starting zones above the town should be examined. It is difficult to quantify the added safety provided by the snow fences, but the conditions seem to be favourable for their construction and they would improve the hazard situation. The length of the snow fences cannot be determined at this point in time and their cost is therefore not given here.

Figure 14. Location map of Neskaupstaður.



14. NESKAUPSTAÐUR

Neskaupstaður is located on the northern side of the Norðfjörður fjord in the middle part of Austfirðir, Eastern Iceland (*cf.* Figure 14).

The length of the coastline where most of the residential buildings in the town are located is about 2.7 km. There are some industrial buildings located further to the west.

Several reported avalanches reached far into what is now a populated area and some have reached into the sea. Catastrophic avalanches in 1974 killed 12 people in the industrial area in the western part of the town. The avalanche danger in Neskaupstaður is greatest below distinct gullies in the mountain above the town, but there is also a potential for the release of avalanches from the slopes between the gullies. There are some reports that a single large avalanche covering the innermost part of the mountain to the west of Tröllagil was released at the end of the last century.

Snow depth in the slopes above Neskaupstaður has been monitored for several years. The snow depth is 2-3 m over wide areas in the starting zones in "ordinary" years (*i.e.* every other year or so) and more than 3 m in relatively "bad" years (*i.e.* every 5-10 years or so).

There is a danger from debris and slush flows in parts of Neskaupstaður. A future appraisal of protection measures for the Neskaupstaður must address the debris and slush danger although it is not discussed much in this report.

Avalanche protection for Neskaupstaður have been considered by Quervain (1975), NGI (1976), Árni Jónsson (1987) and VST (1995). The defense structures proposed by NGI consist mainly of retarding mounds, together with deflecting walls and dams in a few locations, combined with recommendations for extensive evacuations in times of impending avalanche danger. The defense structures proposed by Árni Jónsson consist of dams and walls with heights ranging from approximately 10 to 20 m, in addition to several direct protecting structures upstream from individual buildings. The defense structures proposed by VST consist of more than 5 km of avalanche nets in the starting zones of the avalanches combined with extensive retaining mounds above the uppermost buildings in the town. Defense structures consisting of catching dams were also briefly discussed. The defense structures proposed by VST are further described below.

14.1 The avalanche problems of Neskaupstaður

Neskaupstaður represents one of the largest avalanche problems in Iceland. The number of buildings in potential avalanche hazard areas is larger than in any other town in Iceland. The recorded avalanche history and results of avalanche modelling indicate that there is avalanche danger in much of the inhabited area. The elongated shape of the town along the shore of Norðfjörður and the vast area of the potential starting zones make design and construction of avalanche protection for Neskaupstaður a daunting task.

An important aspect of the avalanche problem of Neskaupstaður is the relatively small area of the town which can be considered safe in the sense that an evacuation of people from other more dangerous parts of the town can be recommended during impending avalanche danger. This makes the construction of avalanche protection for Neskaupstaður particularly important, even more so than for other areas of Iceland with a comparable avalanche risk.

The longest recorded avalanches in Neskaupstaður may be assumed to have a return period on the order of 100 years, compared to 50 years or less for many other areas in Iceland which are considered in this report. The frequency of major avalanches in the most dangerous avalanche paths in Neskaupstaður appears to be lower than the frequency of major avalanches in the most frequent avalanche paths in Vestfirðir. Major avalanches hit Neskaupstaður in 1885, 1894, 1936 and 1974. Although other smaller events are also recorded, long periods without significant avalanche danger seem to have elapsed between these major events. Therefore, appropriate design avalanches in Neskaupstaður, corresponding to a certain level of rest risk, can be taken to be somewhat smaller than appropriate design avalanches in the most dangerous avalanche paths in Vestfirðir. This line of analysis cannot be pursued far within the simple framework of this overview study, but should be considered in further analyses of the avalanche problems of Neskaupstaður.

There is a relatively wide runout zone with a slope around or below 10° in the easternmost part of the Neskaupstaður. The distance from the 10°-β point to the uppermost buildings is 300-350 m below Nesgil and Bakkagil in the east and up to about 500 m below Stóralækjargil, which is the easternmost gully above the main inhabited area. The runout zone becomes narrower toward the west and the 10°-β point is at the uppermost buildings below Tröllagil, which is the westernmost gully above the inhabited area. The steepness increases relatively slowly above the 10°-β point and the slope is between 10° and 20° for a distance of 300-500 m upslope from the 10°-β point.

The potential starting zones include large bowls above the major gullies in the mountainside. Relatively unconfined slopes between the bowls are also potential starting zones, but avalanches are predominantly recorded from the gullies below the bowls.

There are two main options for avalanche protection in Neskaupstaður. Large catching dams can be built in the relatively wide runout zone or supporting structures can be constructed in the bowls above the main gullies. Both options are very expensive and have their advantages and disadvantages. The estimated cost of protection is, nevertheless, considerably less (on the order of one quarter or one half) than the total value of buildings that would be protected in the respective areas.

Modelled speed of design avalanches indicates that catching dams below some of the major gullies would have to be combined with breaking mounds above the dams in order to reduce the speed of avalanches before they hit the dams. Design criteria for such breaking mounds are very uncertain, but in the cost estimates presented here it is assumed that 12 m high, elongated mounds with steep upper sides would be used. The combination of breaking mounds and catching dams would utilize the wide runout zone to slow down and stop the avalanches.

The width of the runout zone in the Tröllagil area is smaller than further to the east and the modelled speed of design avalanches at the dam site is consequently higher. It is therefore more difficult to construct dams and breaking mounds in the Tröllagil area compared with the areas further to the east. Here it is assumed that the rest risk in the Tröllagil area after dams are built is further reduced with evacuations under extreme circumstances.

The main advantage of defense structures consisting of catching dams and breaking mounds is that the dams would be built along the entire slope east of and including the Tröllagil area and would serve as protection against avalanches from the bowls above the main gullies and also for avalanches that could potentially be released from the unconfined slopes between the bowls. The main disadvantage of the dams and breaking mounds is the associated environmental impact, the uncertain design criteria of the breaking mounds and the difficulties to construct large enough dams below Tröllagil.

Supporting structures in the main bowls would have to be very extensive. It is especially important that potential starting zones in the upper part of the bowls or above the bowls are not left out because avalanches released above the controlled area could sweep away supporting structures located further down. The main advantage of this solution is that the most important starting zones would be controlled without a significant environmental impact. The main disadvantage is that avalanches released from the unconfined areas between the bowls would still present a risk which is difficult to estimate. Lack of information about extreme snow depth makes the design of supporting structures for Neskaupstaður rather difficult, as in fact for other areas in Iceland, and there will be some rest risk associated with a snow depth that might exceed the height of the structures under extreme circumstances.

The main catching dams can either be made with steep upstream sides (type GI) or somewhat higher with more gentle upstream sides (type GII). It appears that the cost could be roughly similar in both cases. The estimation of the required amount of supporting structures for Neskaupstaður was hampered by bad weather conditions during the visit of the work group. Preliminary estimation of the required supporting structures (see Table 9), indicates that the cost of the structures in the Drangaskarð and Tröllagil areas could be similar to or even higher than the cost of dams and breaking mounds in these areas. Thus, the cost of the three alternatives for the protection of Neskaupstaður, *i.e.* steep dams, traditional earth fill dams and supporting structures, appears to be on the same order of magnitude. The cost given in Tables 4 to 8 is mainly based on steep dams, but the preliminary cost estimates for supporting structures in Drangaskarð and Tröllagil are also given in Table 4 for comparison.

The area west of Tröllagil is endangered by avalanches from many gullies, *i.e.* Klofagil, Miðstrandarskarð, Bræðslugjár and Sultarbotnagjár. This area is outside of the main residential part of Neskaupstaður, but scattered residential buildings and several important industrial buildings are located there. Protection of this area with extensive dams or supporting structures does not seem to be economical. Direct defenses for the most important industrial buildings and permanent evacuation of the scattered residential buildings are recommended.

Yet another possibility for avalanche protection in Neskaupstaður is the combination of less extensive supporting structures in the main bowls and lower catching dams above the inhabited area. This possibility was not explicitly considered by the work group but it should be addressed in a further study.

14.2 Stóralækjargil

14.2.1 Description

Stóralækjargil is the easternmost gully above the inhabited area in Neskaupstaður. It has a large bowl shaped starting zone. Smaller and lower gullies with unconfined starting zones to the west of Stóralækjargil are considered a part of this area.

The width of the inhabited area is about 400 m. The length of runout zone between the 10°-β point and the uppermost buildings is about 500 m.

There are many residential buildings in the area.

No defense structures have been proposed to date.

14.2.2 Avalanche hazard

Avalanches are recorded from Stóralækjargil and also from the smaller gullies in the western part of the area. The recorded avalanches reach to about 100 m a.s.l. which is about 500 m above the uppermost buildings. The avalanche danger is considered much lower than further to the west. Houses in the area are relatively recent and one may therefore expect the recorded avalanche history to be shorter than in the older part of the town further to the west.

The area below the proposed defense structures is assigned a risk index 2-3 (M, II).

14.2.3 Proposed protection

A catching dam of type GI' is proposed. The dam connects to the proposed dam in the Nesgil/Bakkagil area.

The effectiveness of the dam is classified as good (I).

14.2.4 Estimated cost

The estimated cost of the dam is 120 mi IKR.

14.2.5 Estimated value of defended property

The defended area includes 19 single family houses and apartment buildings with 10 apartments. The estimated value of defended property is 360 mi IKR.

14.3 Nesgil/Bakkagil

14.3.1 Description

Nesgil and Bakkagil are two gullies west of Stóralækjargil. The potential starting zones are two rather large bowls above the gullies with little unconfined slope between the bowls.

The width of the inhabited area is about 700 m. The length of runout zone between the 10°-β point and the uppermost buildings is 300-350 m.

There are many residential and other buildings in the area.

Defense structures consisting of retaining mounds above the uppermost buildings have been proposed (VST 1995).

14.3.2 Avalanche hazard

Avalanches reaching within 80-150 m of the uppermost buildings are recorded below Nesgil and an avalanche reaching essentially to the uppermost buildings below Bakkagil is recorded in 1974.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I).

14.3.3 Proposed protection
A catching dam of type GI' is proposed. A lower dam with height 10 m connects this dam to the proposed dam below Drangaskarð to the west.

The effectiveness of the dam is classified as good (I).

14.3.4 Estimated cost
The estimated cost of the dam and the connection toward Drangaskarð is 290 mi IKR.

14.3.5 Estimated value of defended property
The defended area includes 93 single family houses, apartment buildings with 90 apartments and several public buildings. The estimated value of defended property is 2840 mi IKR.

14.4 Drangaskarð

14.4.1 Description
Drangaskarð is considered among the most dangerous gullies above Neskaupstaður. There is a large bowl shaped starting zone above the gully and another much smaller concave starting zone above the gully Skágil to the east of Drangaskarð. Avalanches can also be released from the rather unconfined slope to the west of Drangaskarð.

The width of the inhabited area is about 400 m. The 10°-β point is at the location of the uppermost buildings.

There are many residential and other buildings in the area.

Defense structures consisting of avalanche nets (4 and 5 rows, total length about 1600 m) combined with retaining mounds above the uppermost buildings have been proposed (VST 1995).

14.4.2 Avalanche hazard
An avalanche from Drangaskarð reaching about 250 m into the currently populated area is recorded. Avalanches are also recorded from the slopes immediately to the east and to the west of Drangaskarð.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

14.4.3 Proposed protection
Two alternatives for avalanche protection are considered. The first alternative is a catching dam of type GI' with two rows of 12 m high breaking mounds. The second alternative is the construction of supporting structures in the starting zone in the bowl above Drangaskarð. The height of the structures was somewhat arbitrarily chosen to be 4.0 m and 3.5 m. 600 m of the 4.0 m structures are required and 2100 m of the 3.5 m structures. The construction of supporting structures in Skágil to the east and on the unconfined slope to the west of Drangaskarð was not considered, but may be required after a further study of the problem is carried out.

The effectiveness of the dam and the breaking mounds is classified as good to medium (I-II) because of the uncertain design criteria of the breaking mounds and because of the uncertainty of the extension of the starting zones where supporting structures should be constructed.

14.4.4 Estimated cost
The estimated cost of the alternative with a dam and breaking mounds is 410 mi IKR. The estimated cost of the alternative with the supporting structures is 420 mi IKR.

14.4.5 Estimated value of defended property
The defended area includes 53 single family houses, apartment buildings with 19 apartments and several public and industrial buildings. The estimated value of defended property is 1400 mi IKR.

14.5 Urðarbotnar

14.5.1 Description
Urðarbotnar is relatively unconfined mountain slope to the west of Drangaskarð. There are several gullies in the lower part of the slope.

The width of the inhabited area is about 350 m. The $10°$-β point is at the location of the uppermost buildings.

There are many residential buildings in the area.

No defense structures have been proposed to date.

14.5.2 Avalanche hazard
Avalanches reaching within 50-100 m of the uppermost buildings are recorded. The avalanche danger is considered lower than in the Drangaskarð or Tröllagil areas to the east and west.

The area below the proposed defense structures is assigned a risk index 2 (M, I-II).

14.5.3 Proposed protection
A catching dam of type GI' with two rows of 12 m high breaking mounds is proposed. A lower dam with height 10 m connects this dam to the proposed dam below Drangaskarð to the east.

The effectiveness of the dam and the breaking mounds is classified as good to medium (I-II) because of the uncertain design criteria of the breaking mounds.

14.5.4 Estimated cost
The estimated cost of the dam, breaking mounds and connection toward Drangaskarð is 280 mi IKR.

14.5.5 Estimated value of defended property
The defended area includes 49 single family houses, apartment buildings with 47 apartments and several public and industrial buildings. The estimated value of defended property is 1550 mi IKR.

14.6 Area between Tröllagil and Urðarbotnar

14.6.1 Description
The area between the Tröllagil gully and the Urðarbotnar mountain slope is without major gullies. The upper part has a convex shape and is therefore a less likely starting zone for avalanches than the adjacent slopes to the west and east.

The width of the inhabited area is about 350 m.

There are many residential buildings in the area.

No defense structures have been proposed to date.

14.6.2 Avalanche hazard
The recorded avalanche history shows no avalanches approaching the inhabited area. The avalanche danger is considered lower than in the adjacent areas.

The area below the proposed defense structures is assigned a risk index 3 (M, III).

14.6.3 *Proposed protection*

A relatively low (*i.e.* 10 m high) catching dam of type GI' that connects the dams in Urðarbotnar and Tröllagil is proposed in order to provide defense against smaller avalanches that might be released in the area under extreme circumstances (see further discussion in Appendix I).

The effectiveness of the dam is classified as good to medium (I-II) because of the uncertain choice of a design avalanche.

14.6.4 *Estimated cost*

The estimated cost of the dam is 60 mi IKR.

14.6.5 *Estimated value of defended property*

The defended area includes 27 single family houses and apartment buildings with 17 apartments. The estimated value of defended property is 420 mi IKR.

14.7 Tröllagil

14.7.1 *Description*

Innra-Tröllagil and Ytra-Tröllagil are two large gullies above the western part of Neskaupstaður. They are considered among the most dangerous avalanche paths above the town. There is a large approximately 300 m wide bowl shaped starting zone above Innra-Tröllagil which is channeled into a deep gully. The starting zone above Ytra-Tröllagil is about 200 m wide and rather unconfined. Avalanches are also released from an unconfined slope to the west of Innra-Tröllagil.

The width of the inhabited area is about 600 m. The 10°-β point is at the location of the uppermost buildings.

There are many residential and other buildings in the area.

Supporting structures consisting of avalanche nets (4 to 11 rows depending on configuration, total length at least 2000 m), combined with retaining mounds above the uppermost buildings have been proposed (VST 1995).

14.7.2 *Avalanche hazard*

An avalanche reaching the sea in this area at Tröllanes is recorded and several other avalanches have reached to or almost to the uppermost houses. The buildings form three more or less continuous rows along two main streets parallel to the shore.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

14.7.3 *Proposed protection*

Two alternatives for avalanche protection are considered. The first alternative is a catching dam of type GI' with two rows of 12 m high breaking mounds. The runout zone below Tröllagil is narrower than the runout zone below the avalanche tracks further to the east which are considered in the preceding sections. Modelled avalanche velocities of design avalanches near the uppermost buildings are therefore higher below Tröllagil compared to the avalanche paths to the east and it is impractical to construct a dam for stopping avalanches with this velocity (see further discussion in Appendix I). The proposed dam and breaking mounds are based on a design velocity corresponding to avalanches that reach the shore, *i.e.* similar to the longest recorded avalanches in the area (or perhaps somewhat shorter because these avalanches terminated in the sea and the actual runout distance is therefore not known). It is assumed that the construction of the dam would be combined with an evacuation plan in order to further lower the risk after the dam is built.

The second alternative is the construction of supporting structures in the starting zone above Ytra-Tröllagil and in the bowl above Innra-Tröllagil. 400 m of the supposed 4.0 m structures and 1800 m of 3.5 m structures are required in Ytra-Tröllagil. 600 m of the supposed 4.0 m structures and 1800 m of 3.5 m structures are required Innra-Tröllagil. The construction of supporting structures on the unconfined slope to the west of Innra-Tröllagil was not considered, but may be required after a further study of the problem is carried out.

The effectiveness of the dam and the breaking mounds is classified as medium (II) because of the small design avalanche and also because of the uncertain design criteria of the breaking mounds. The effectiveness of the supporting structures is classified as good to medium (I-II) because of the uncertainty of the extension of the starting zones where the structures should be constructed.

14.7.4 Estimated cost

The estimated cost of the alternative with a dam and breaking mounds is 710 mi IKR. The estimated cost of the alternative with the supporting structures is 710 mi IKR.

14.7.5 Estimated value of defended property

The defended area includes 56 single family houses, apartment buildings with 24 apartments and several public and industrial buildings. The estimated value of defended property is 1130 mi IKR.

14.8 The area west of Tröllagil

14.8.1 Description

Many avalanche paths are located above the extensive area west of the Tröllagil gullies as mentioned in a previous section about the avalanche problems of Neskaupstaður. The main starting zones are above the gullies Klofagil, Miðstrandarskarð, Bræðslugjár and Sultarbotnagjár.

The width of the area is about 1600 m.

Many industrial buildings and some residential buildings are located in the area.

Defense structures consisting of avalanche nets (3 and 4 rows, total length 1800 m), combined with retaining mounds above the uppermost buildings and purchasing of some buildings where protection is uneconomic have been proposed (VST 1995).

14.8.2 Avalanche hazard

Several avalanches have reached to the sea in this area. Catastrophic avalanches from Miðstrandarskarð and Bræðslugjár killed 12 people in 1974. Although there are only a few residential buildings in the area, the potential for an accident involving a large number of people cannot be ignored because of the location of large industrial buildings within the area.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

14.8.3 Proposed protection

Direct defenses with 8-10 m high concrete walls (type GIV) above the main two industrial buildings, Loðnubræðslan (Naustahvammur 67-69) and Saltfiskverkunin (Naustahvammur 41-43), are proposed. The wall above Loðnubræðslan would be about 100 m long and the wall above Saltfiskverkunin would be about 75 m long. The activity in the third main industrial building in the area, Frystihúsið (Strandgata 76-79), will be relocated in the near future and direct defenses for this building were therefore not considered.

Protection of the scattered residential buildings and other industrial buildings than Loðnubræðslan and Saltfiskverkunin are considered uneconomical.

The effectiveness of the direct defenses is classified as good to medium (I-II) with respect to the safety of the people if the defenses are combined with evacuations under impending avalanche danger. The effectiveness is classified as uncertain (III) with respect to protection of properties.

14.8.4 Estimated cost

An order of magnitude estimate of two concrete walls at Loðnubræðslan and Saltfiskverkunin is 70 mi IKR.

The total value of buildings which might have to be purchased by the government in the future in order to prevent their use during winter is 440 mi IKR.

14.8.5 Estimated value of defended property

The estimated value of defended property in Loðnubræðslan and Saltfiskverkunin is 880 mi IKR. The total value of all property in the area including the scattered residential houses and other industrial buildings is 1320 mi IKR.

15. SEYÐISFJÖRÐUR

The town of Seyðisfjörður is located in the innermost part of the Seyðisfjörður fjord in the middle part of Austfirðir, Eastern Iceland (*cf.* Figure 15).

The avalanche situation of Seyðisfjörður has been analyzed by Quervain (1975). He recommended protective measures consisting of direct defenses of single isolated objects in the Strandartindur area and he discusses supporting structures, deflectors and wind baffles for reducing the avalanche risk in the northern part of the town.

15.1 Öxl

15.1.1 Description

The Öxl mountain slope is located on the northern/western side of the fjord. Avalanche tracks in the northern part are relatively deep gullies in an east facing slope. Gullies are less pronounced in the southern part of the area.

The width of the area is about 750 m.

There are several industrial buildings in the area, but almost no residential buildings.

No defense structures have been proposed to date except for the protection measures discussed by Quervain (1975).

15.1.2 Avalanche hazard

Avalanches are frequent and have several times caused damage to the main fish processing plant which was located in the area. Several avalanches reaching all the way to the sea are recorded. Wet avalanches and debris flows are also recorded.

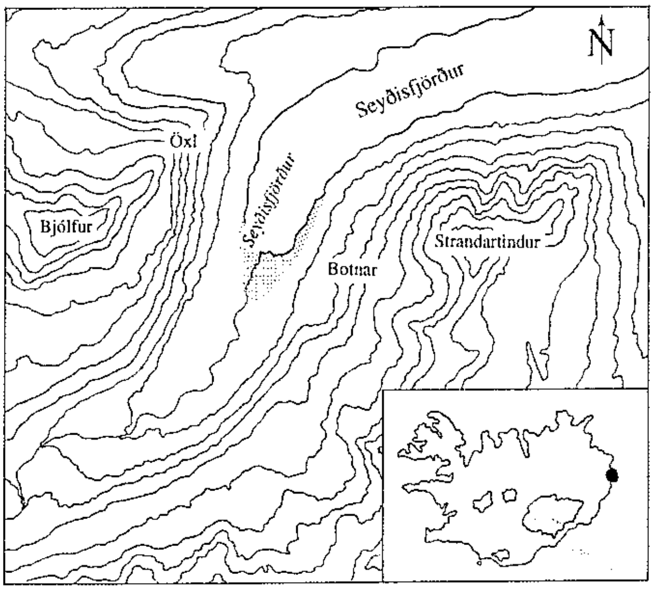
The area is assigned a risk index of 2 (S, I).

15.1.3 Proposed action

Protection of the scattered buildings in the area is considered uneconomical. Therefore it is recommended that the use of buildings in the area during wintertime is limited as much as possible and that future development in the area is restricted. Purchasing of buildings in the area by the government in the future should be considered.

The total value of all property in the area is 400 mi IKR. This estimate includes outdated Insurance Values of industrial buildings and piers and should not be taken as a proper estimate of the value of buildings that need to be purchased by the government if no avalanche protection measures are built for the area.

Figure 15. Location map of Seyðisfjörður.



15.2 Bjólfur

15.2.1 Description

The Bjólfur mountain is located to the west of the town of Seyðisfjörður. A large east facing bowl shaped snow accumulation area is located above a shelf at 650 m a.s.l. in the mountain. Several deep gullies are located in the lower part of the slope.

The width of the area is about 1200 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

There are many residential and other buildings in the area.

A deflecting wall (height about 12 m, length about 200 m) above the area crossed by an avalanche in 1885 has been proposed (Verkfræðistofa Siglufjarðar s.f. and Verkfræðistofa Austurlands h.f. 1992). Other dams and walls ranging in height from approximately 10 to 18 m have also been proposed in this area and somewhat further to the north. Defense structures in the starting zone in the uppermost area of the slope have been considered (Tækniskóli Íslands 1995) and consisted of 2800 m of 3 m high nets.

15.2.2 Avalanche hazard

Catastrophic avalanches reaching all the way to the sea in the last century in a part of the area are recorded. An avalanche in 1885 killed 24 people. Several dangerous wet avalanches and debris flows are also recorded.

The avalanche frequency is highest in the northern part of the area in the path of the 1885 avalanche. The avalanche frequency is much lower in the southern part of the area and gullies in the lower mountainside could divert avalanches away from the main inhabited area. Avalanche hazard can, nevertheless, not be ruled out in the southern part. Avalanches endangering the southernmost part of the inhabited area can be released from the Fálkagil gully, but the runout zone of avalanches from the Jókugil gully is to the south of the inhabited area.

There is some uncertainty about the main starting zone of the recorded avalanches in the area. Some reports indicate that the largest avalanches are released from the upper starting zone above 650 m a.s.l., but this is not certain. Avalanches released from the lower part of the slope below 650 m a.s.l. are recorded. A bowl called Kálfabotnar at between 500 and 625 m a.s.l. below the shelf is considered the most probable starting zone in the lower part of the mountainside. Two bowls at the same elevation about 500 m further to the south are also more likely starting zones than other areas in the lower part of the slope.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

15.2.3 Proposed protection
A large catching dam of type GII on the a shelf at 650 m a.s.l. in Bjólfur is proposed, combined with a lower catching dam of type GI in the runout zone at sea level and supporting structures in a bowl shaped starting zone in Kálfabotnar below the upper dam. Snow depth should be monitored in the two other bowls further to the south in order to investigate snow accumulation conditions and determine whether supporting structures are required there also.

There is considerable uncertainty about an appropriate design avalanche for the upper dam and two possible dam height, 25 m and 35 m were considered for this reason (see further discussion in Appendix I).

Appropriate design avalanches for the lower dam are also difficult to determine and the dam height is not based on explicit avalanche velocity computations (see further discussion in Appendix I). The dam could be shaped as a deflector near the southern margin of the inhabited area. This would improve the protection with regard to avalanches which come from the Fálkagil gully. It is also possible that the northern end of the dam should be built at an angle to the flow direction of avalanches and function as a deflector in that area. These questions should be addressed in a further study of avalanche protection for the area.

There is little space between the uppermost buildings in the southern part of the area and the hill. Apartment building above the street Gilsbakki may have to be overrun by the dam in order to generate sufficient space.

The height of the supporting structures in Kálfabotnar bowl was preliminarily chosen to be 4 m. They are configured as 5 rows between 535 and 625 m a.s.l. A total of 1000 m of the structures is required.

It is assumed that the construction of the dams and the supporting structures would be combined with an evacuation plan in order to further lower the risk due to the uncertain design assumptions described above and in Appendix I.

The effectiveness of the protection measures is classified as good (I) with respect to slush and debris flows and medium (II) with respect to snow avalanches.

15.2.4 Estimated cost
The estimated cost of the two alternatives for the upper dam is 150/270 mi IKR. The cost of the lower dam is estimated to be 170 mi IKR. The total construction cost of the dams with the larger upper dam is 440 mi IKR. The estimated cost of the supporting structures in Kálfabotnar is 170 mi IKR. The estimated value of the building that is overrun by the dam is 40 mi IKR. The total cost with the larger upper dam is therefore 640 mi IKR.

15.2.5 Estimated value of defended property
The estimated value of defended property is 1230 mi IKR[1].

15.3 Botnar

15.3.1 Description
The Botnar area lies to the south and east of the innermost part of the fjord. The slope above the area faces west and has a complicated shape with large bowl shaped valleys in the upper part and deep gullies in the lower part.

The width of the inhabited area is about 1300 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

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1 Existing information on the Insurance Value of buildings in the area is incomplete. The value of buildings, for which the Insurance Value was not available, was estimated by the local authorities in Seyðisfjörður.

There are many residential and other buildings in the area.

No defense structures have been proposed to date.

15.3.2 Avalanche hazard

Avalanche risk is considered low, but a large number of residential buildings is located near the bottom of the slope.

Slush and debris flows are recorded in several gullies in the slope. The banks of the slush and debris flow paths are low and almost non-existent in several places so that the slush and debris flows could potentially endanger buildings in the neighbourhood of the paths.

The area below the proposed defense structures is assigned a risk index 2 (M, I) with respect to the slush and debris flows, but the area is not assigned a risk index corresponding to snow avalanches.

15.3.3 Proposed protection

Deflecting dams of type LV along the banks of the known and potential slush and debris flow paths are proposed. Several bridges or culverts need to be built where the paths cross roads.

15.3.4 Estimated cost

The total cost of the reshaping of the slush and debris flow paths in the Strandartindur/Botnar area is estimated to be 120 mi IKR.

15.3.5 Estimated value of defended property

For the time being, the estimated value of defended property is not given because it is not clear how many buildings are threatened by the slush and debris flows.

15.4 Strandartindur

15.4.1 Description

The Strandartindur mountain is located to the east of the town of Seyðisfjörður. It has a high west and northwesterly facing mountain side with relatively unconfined potential starting zones in the upper part and many deep undulating gullies in the lower part.

The width of the area is about 1300 m. Buildings are located close to the foot of the slope and the runout zone above the uppermost buildings is essentially non-existent.

There are many industrial buildings in the area, but few residential buildings.

No defense structures have been proposed to date.

15.4.2 Avalanche hazard

Avalanches and debris flow from the main gullies are frequent. A debris flow in 1950 killed 5 persons in the outermost part of the Strandartindur area.

There is a potential for the release of dry snow avalanches outside of the main gullies, but no such avalanches are recorded. The avalanche situation is complicated and depends to a large extent on the configuration of gullies and other details in the topography. It was not possible within the time frame of this study to analyze the avalanche situation in the necessary detail to make explicit suggestions for avalanche protection, but a strengthening of the banks of the main slush and debris flow paths is suggested as for the Botnar area.

The area below the proposed defense structures is assigned a risk index 1-2 (M, I) with respect to the slush and debris flows. The risk corresponding to snow avalanches is difficult to determine without a further study. Avalanches from the main gullies are frequent but do not endanger a large area simultaneously (S, I). There is also a potential for the release of a larger avalanche that might not be confined to the gullies (M, III). A risk index of 1-2 corresponding to snow avalanches is assigned to the area based on these considerations.

15.4.3 Proposed protection

Deflecting dams of type LV along the banks of the known and potential slush and debris flow paths are proposed. Several bridges or culverts need to be built where the paths cross roads. Simple bank strengthening of this kind is not sufficient for some of the gullies in the outermost part of the area, in particular the gullies that threaten the SR-Mjöl industrial plant where large buildings are located directly below the gullies.

Avalanche protection for a large part of this area (dams or supporting structures) are impractical due to the size of the area and due to the unfavourable distribution of buildings along the shore line. Direct defenses with concrete walls and small deflectors appear feasible for buildings below the main gullies. Dimensioning of such structures requires more analysis than was possible in this study.

The effectiveness of the proposed protection measures is classified as good to medium (I-II) with respect to slush and debris flows which are confined to the gullies but on the whole the effectiveness must be classified as uncertain (III) due to the potential for debris flows and snow avalanches which might not be confined to the gullies.

The area should be closely monitored during winter. Buildings should be evacuated and traffic in the area restricted during times of impending avalanche danger.

15.4.4 Estimated cost

The total cost of the reshaping of the slush and debris flow paths in the Strandartindur/Botnar area is estimated to be 120 mi IKR.

15.4.5 Estimated value of defended property

The estimated value of defended property is not given here because it is not clear how many buildings are threatened by the slush and debris flows.

The total value of all buildings in the area is 2020 mi IKR[1].

16. SIGLUFJÖRÐUR

The Siglufjörður town is located in the Siglufjörður fjord, Northern Iceland (*cf.* Figure 16).

Catastrophic avalanches killed 18 people in Siglufjörður and neighbouring rural areas in 1919. None of the fatal accidents in 1919 occurred in the area where the town of Siglufjörður presently located, but residential buildings are currently located in the runout zone of an avalanche which fell as a part of the avalanche cycle in 1919.

An avalanche, which fell from Skollaskál east of Siglufjörður in 1919 and killed 9 people, was accompanied with a flood wave which traveled across the fjord and caused extensive damage to boats and piers in the harbour of Siglufjörður. Damage from such a flood wave is among the avalanche hazards which face Siglufjörður. The protection measures described below are limited to protection against avalanches from the slopes directly above the town itself. The risk associated with a flood wave cause by an avalanche on the other side of the fjord must be further investigated in a future assessment of the avalanche hazard in Siglufjörður.

There is a danger from debris and slush flows in parts of Siglufjörður. A future appraisal of protection measures for the Siglufjörður must address the debris and slush danger although it is not discussed much in this report.

1 Existing information on the Insurance Value of buildings in the area is incomplete. The value of buildings, for which the Insurance Value was not available, was estimated by the local authorities in Seyðisfjörður.

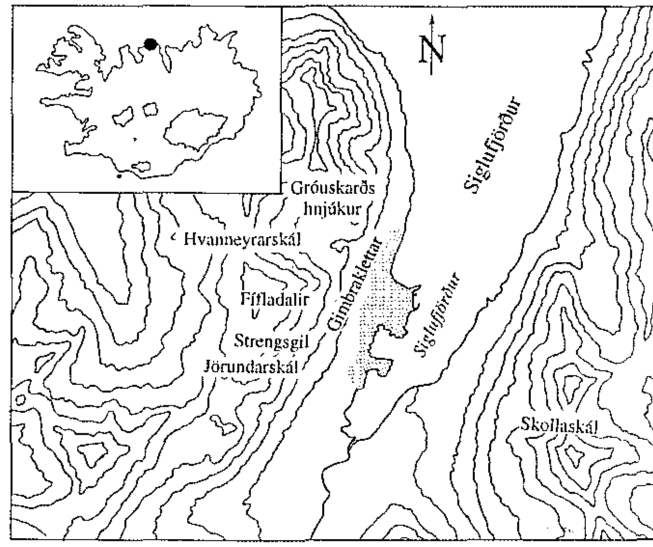

Figure 16. Location map of Siglufjörður.

The avalanche situation of Siglufjörður has been analyzed by Quervain (1975). He recommended supporting structures in Gróuskarðshnjúkur and discussed possibilities for avalanche protection in the area below Strengsgil.

16.1 Jörundarskál/Strengsgil

16.1.1 Description

Jörundarskál and Strengsgil are the main avalanche paths above the southern part of Siglufjörður. They are located in an ESE facing slope. Jörundarskál is a large bowl which opens into a narrow gully. Ytra-Strengsgil is a long narrow gully further to the north. Syðra-Strengsgil is a narrow undulating gully between Jörundarskál and Ytra-Strengsgil.

The width of the inhabited area is about 400 m.

There are many residential buildings in the area.

No defense structures have been proposed to date except for the protection measures discussed by Quervain (1975). Two buildings below Ytra-Strengsgil have been purchased by the government in order to prevent their use during winter.

16.1.2 Avalanche hazard

Avalanches are frequent and evacuations of several buildings may occur many times in some winters. Several avalanches reaching all the way to the sea before the buildings in the area were built, are recorded.

Snow drift from the north along the mountain side accumulates snow in the gullies and in Jörundarskál. Snow may also accumulate near the top of the mountain over this area in NW-ly winds.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

16.1.3 Proposed protection

Deflectors below Ytra-Strengsgil and Jörundarskál are proposed. The layout of the lower part of the deflector below Ytra-Strengsgil and the length of the deflector below Jörundarskál must be further considered in the appraisal phase (see discussion in Appendix I). The deflector below Ytra-Strengsgil is about 825 m long (alternative 1 as described in Appendix I) and the deflector below Jörundarskál is between 100 and 200 m long. Additionally, the opening of the Jörundarskál track at about 100 m a.s.l. should be widened to the south in order to deflect the avalanches away from the populated area.

A conservative value for the flow height, $H_f = 4$ m, was adopted due to the confined avalanche tracks. A conservative value for the snow height, $H_s = 7$ m was adopted, due to accumulation of snow by snow drift and the possibility of previous avalanche deposits on the upstream side of the deflectors. This leads to a deflector height of 18 m (see Appendix I).

The effectiveness of the dams is classified as good (I).

16.1.4 Estimated cost

The estimated cost of the Strengsgil deflector is 260 mi IKR and the cost of the Jörundarskál deflector is 40 mi IKR. The total cost of both deflectors is thus estimated to be 300 mi IKR.

The cost of widening the opening of the Jörundarskál track is expected to be relatively small compared to the cost of the other proposed defense structures and it is not given separately.

16.1.5 Estimated value of defended property

The defended area includes 57 single family houses and 32 apartments in apartment buildings. The estimated value of defended property is 1020 mi IKR.

16.2 Fífladalasvæði, southern part

16.2.1 Description

The Fífladalasvæði area is located to the north of Ytra-Strengsgil. Potential avalanche tracks in the southern part of Fífladalasvæði are relatively shallow gullies in the lower part of an ESE facing slope. An unconfined slope without gullies in the upper part of the mountain is also a potential starting zone.

The width of the inhabited area is about 400 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some other buildings in the area.

No defense structures have been proposed to date.

16.2.2 Avalanche hazard

Few avalanches are recorded in the area. There is some potential for a dangerous snow accumulation in the upper part of the hill in N-NV-ly wind directions, but this potential is considered much lower than in the adjacent area to the north. Although no very long avalanches are recorded, there may be a possibility for the release of a catastrophic avalanche in this area, but it is very difficult to quantify the probability of such an event.

The area below the proposed defense structures is assigned a risk index 3 (M, III).

16.2.3 Proposed protection

Supporting structures in the upper part of the hill are suggested if further study of the snow accumulation in this part of the hill indicates a possibility of dangerous snow accumulation. The height of the supporting structures was chosen to be 4 m in the upper part of the area and 3.5 m in the lower part. 300 m of the 4 m structures and 1100 m of the 3.5 m structures are required.

The effectiveness of the supporting structures is classified as good (I).

16.2.4 Estimated cost

The total cost of the supporting structures is estimated to be 210 mi IKR.

16.2.5 Estimated value of defended property

The defended area includes 41 single family houses and 42 apartments in apartment buildings. The estimated value of defended property is 700 mi IKR.

16.3 Fífladalasvæði, northern part

16.3.1 Description

Avalanche tracks in the northern part of the Fífladalasvæði area are relatively unconfined in an ESE facing slope. The northernmost area in the upper part of the mountain has a concave shape but the lower part of the slope is characterized by shallow gullies.

The width of the inhabited area is about 450 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and other buildings in the area.

No defense structures have been proposed to date. Approximately 200 m of supporting structures were installed in August and September 1996 in Efra-Fífladalagil in the upper part of the slope above the area as a part of a pilot project to test supporting structures in Iceland.

16.3.2 Avalanche hazard

Many avalanches have reached the uppermost houses in the area. There is a potential for a dangerous accumulation of snow in the upper part of the hill in N-NV-ly wind directions. Although no very long avalanches are recorded, there appears to be a possibility for the release of a catastrophic avalanche in this area.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

16.3.3 Proposed protection

Supporting structures in both the upper and the lower part of the hill are suggested. In the upper part of the area, the height of the supporting structures was chosen to be 4 m near the top and in the northernmost part and 3.5 m further down. 2300 m of the 4 m structures and 1600 m of the 3.5 m structures are required. In the lower part of the area, the height of the supporting structures was chosen to be 4 m near the top and 3.5 m further down. 600 m of the 4 m structures and 2300 m of the 3.5 m structures are required.

The effectiveness of the supporting structures is classified as good (I).

16.3.4 Estimated cost

The cost of the supporting structures in the upper part is estimated to be 650 mi IKR and 450 mi IKR in the lower part. The total cost is thus 1100 mi IKR.

16.3.5 Estimated value of defended property

The defended area includes 99 single family houses and 54 apartments in apartment buildings. The estimated value of defended property is 1920 mi IKR.

16.4 Gimbraklettar

16.4.1 Description

Gimbraklettar are cliffs in mountain above the central part of the town of Siglufjörður. Avalanche tracks are relatively unconfined in an east facing slope. The upper part of the hill is convex and does not collect much snow.

The width of the inhabited area is about 250 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and other buildings in the area.

No defense structures have been proposed to date.

16.4.2 Avalanche hazard
Many avalanches have reached the uppermost houses in the southern part of the area. The hill is comparatively low in the northern part and the higher southern part does not collect much snow due to its convex shape. The potential for the release of an extreme avalanche is therefore considered low, but the uppermost houses are endangered by avalanches that are released in the lower part of the hill.

The area below the proposed defense structures is assigned a risk index 1 (M, I).

16.4.3 Proposed protection
Supporting structures of height 3.5 m in the lower part of the hill are suggested. 2300 m of the structures are required.

The effectiveness of the supporting structures is classified as good (I).

16.4.4 Estimated cost
The estimated cost of the supporting structures is 330 mi IKR.

16.4.5 Estimated value of defended property
The defended area includes 52 single family houses and 22 apartments in apartment buildings. The estimated value of defended property is 680 mi IKR.

16.5 Hvanneyrarskál

16.5.1 Description
Hvanneyrarskál is a large bowl shaped valley in the mountain side above the town of Siglufjörður. The slope below the valley is low and faces ESE. There are shallow gullies in the lower part of the slope, but the upper part is rather smooth.

The width of the inhabited area is about 200 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some other buildings in the area.

No defense structures have been proposed to date.

16.5.2 Avalanche hazard
The avalanche danger is considered low. The mountain slope above this area is much lower than to the north and the south, but buildings are located very close to the slope.

16.5.3 Proposed action
The area must be closely monitored during winter.

16.6 Gróuskarðshnjúkur, southern part

16.6.1 Description
The Gróuskarðshnjúkur mountain is located to the north of the Hvanneyrarskál valley. The potential starting zone is located at the northern margin of Hvanneyrarskál and faces south. The slope directly above the area faces ESE.

The width of the inhabited area is about 250 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some other buildings in the area.

No defense structures have been proposed to date except for the protection measures discussed by Quervain (1975).

16.6.2 Avalanche hazard
An avalanche reached into the middle of the area in 1963, but no other avalanches are recorded.

The area below the proposed defense structures is assigned a risk index 2-3 (M, II+).

16.6.3 Proposed protection
Supporting structures of height 3.5 m in the starting zone of the 1963 avalanche are suggested. 400 m of the structures are required.

The effectiveness of the supporting structures is classified as good (I).

16.6.4 Estimated cost
The estimated cost of the supporting structures is 50 mi IKR according to the cost estimates adopted for this report. There is unusually good access to the starting zone due to a road up to 200 m a.s.l. in Hvanneyrarskál. The cost may be somewhat overestimated in this case because cost of helicopter transportation will be lower than assumed in the cost assumptions.

16.6.5 Estimated value of defended property
The defended area includes 23 single family houses and 33 apartments in apartment buildings. The estimated value of defended property is 710 mi IKR.

16.7 Gróuskarðshnjúkur, northern part

16.7.1 Description
The east facing mountain side of the northern part of the Gróuskarðshnjúkur mountain is rather steep with cliffs near the top.

The width of the inhabited area is about 250 m. The runout zone above the uppermost buildings is essentially non-existent.

There are many residential and some other buildings in the area.

No defense structures have been proposed to date.

16.7.2 Avalanche hazard
The avalanche danger is considered low. The mountain slope above this area usually collects little snow, but buildings are located very close to the slope.

16.7.3 Proposed action
The area must be closely monitored during winter.

17. RECOMMENDATIONS FOR AVALANCHE SAFETY IMPROVEMENTS

Although the purpose of the trips was mainly to collect information about the conditions for avalanche protection, some more general ideas for improvements in the avalanche safety in Iceland were discussed during the trips. They are summarized here.

1. Snow stakes or observation points must be placed or marked in potential avalanche starting zones and the snow depth monitored regularly during the winter.
2. Specific sites should be chosen in each town for photographing potential avalanche slopes. Photographs should be taken at the end of every winter and after exceptional accumulation of snow on the slopes.
3. The local avalanche observer should make a yearly report about the winter snow and avalanche conditions.

4. Standards need to be established for the observations performed by the local avalanche observers and the observations need to be systematized in a data base at the IMO in Reykjavík.
5. Different possibilities for direct defenses of individual buildings should be investigated and requirements for new buildings in avalanche prone areas should be revised with avalanche safety in mind. These possibilities include the construction of direct defense structures above the many single family houses which are located near the bottom of the slope in areas where avalanches are rare, but where the potential for avalanches cannot be ruled out.
6. Research on the effectivity of snow fences in Iceland should be initiated.
7. Automatic weather loggers should be placed on several mountain plateaus to collect wind data for preparing the possible construction of snow fences on these plateaus.
8. The possible use of earth profiles and scattered boulders which are often transported by avalanches for the evaluation of the runout and frequency of avalanches should be investigated.
9. The effect of avalanche defence works should be monitored systematically as such constructions are built.

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19. APPENDIX I: Dimensions and cost of proposed dams and deflectors

The parameters characterizing the deflectors (denoted by "L"), catching dams (denoted by "G") and breaking mounds (denoted by "K"), proposed in the report are given in the following tables. The cost category I, II, III, IV or V of the dams is given in each case (see section 5.6.1). Thus a dam of type "LI" is a deflector in cost category I. The parameters are defined as follows.

Param	Definition
L	length of dam (m)
ψ	surface slope perpendicular to the dam axis at the location of dam (°)
ϕ	deflecting angle (°)
v	design velocity (m/s)
H	height of dam above the surroundings upstream from the dam (m)
D	excavation depth in the dam site (m)
Vol	volume of the dam (m^3)
Cost	building cost of the dam (mi IKR)

The thickness of snow on the ground on the upstream side of the dam before the avalanche falls, H_s, and the thickness of the flowing part of the avalanche, H_f, are assumed to be 2 m each unless otherwise stated (*cf.* eq. (1)). The parameter λ in eq. (2) is assumed to have a value of 2 for dams with a steep upstream side unless otherwise stated.

ÍSAFJÖRÐUR

Holtahverfi

Western wing of catching dam (type GI).

Param	Value
L	220 m
ψ	0°
v	22 m/s at the eastern end, 17 m/s at the western end
H	15 m at the eastern end, 10 m at the western end
D	1-2 m
Vol	35000 m^3
Cost	40 mi IKR

Eastern wing of catching dam (type GI).

Param	Value
L	220 m
ψ	10°
v	22 m/s
H	15 m
D	1-2 m
Vol	73000 m^3
Cost	90 mi IKR

The modelled speed of the design avalanches at the location of the dams is between 25 and 30 m/s for most of the length of the dams. A flow height of 1 m is chosen because small flow rates with little concentration of the avalanche flow are expected here. The construction of a dam higher than 15 m is not practical at the site. This corresponds to a speed of 22 m/s. The modelled speeds are about 5 m/s lower near the western end of the area where the dam can be placed further away from the foot of the slope compared with the middle and eastern part of the area.

The western wing of the catching dam is situated somewhat to the side of the path of the avalanches which fell in 1981 and 1983.

It is expected that avalanches hitting this wing will be the inner or western margin of avalanches whose center would hit the eastern wing of the catching dam. The impact and runup of the avalanches is therefore expected to be less on the western wing than on the eastern wing. The design speed for the western wing was reduced by 5-10 m/s due to this reason. This needs further study in the appraisal phase of a dam in this place.

The 15 m high eastern wing of the catching dam is not properly dimensioned according to the modelled speed of the design avalanche. It is nevertheless a significant improvement in the safety of the site. Supporting structures in the starting zone above the eastern part of the area are a preferable solution to the avalanche hazard there, but they are more expensive than a dam.

Both dams are assumed to be of type GI. There is sufficient space to build the western wing as a dam of type GII (*i.e.* gentle upstream slope) in which case it would be built somewhat higher in order to obtain the same effectivity. This does not substantially change the cost estimates derived here and should be considered during the design of the dams.

A 1.5 m deep test pit was dug at the foot of the slope near the place where the two wings meet. The material visible in the pit was mostly topsoil with scattered stones and boulders. The material at the bottom of the pit appeared to be of better quality. The grain size distribution of a sample from the pit was analyzed. The USCS class of the sample was determined to be GM or GW-GP-GM and the fraction of clay and fines was about 10%. There appear to be sufficient quantities of usable material for dam construction immediately to the west of the site of the dam, but the grain size of this material was not analyzed.

Seljalandshverfi

Deflecting dam to the west of Seljaland (similar to type LI).

Param	Value
L	700 m
ψ	0-10°
ϕ	28-50°
v	18-33 m/s
H	13.5-16 m
D	1-6 m
Vol	240000 m^3
Cost	320 mi IKR

The dimensions and the cost of the dam are taken from HNIT and NGI (1996). They are therefore not computed according to the same methodology as for other dams in this report.

Seljalandshlíð

Plough at Steiniðja and Netagerða Vestfjarða (type LII).

Param	Value
L	2x250+150 m
ψ	0
ϕ	20°
v	33 m/s
H	10 m for the wings, the top can be somewhat lower, the average height of the top is taken to be 9 m.
D	2 m
Vol	70000 m^3
Cost	50 mi IKR

The wings are 250 m each. In addition the wings are connected at the top by somewhat lower dams.

There is abundant material of reasonable quality for the construction of the dam near the site.

Gleiðarhjalli

Dams for catching debris flows (type GII).

Param	Value
L	1500 m
H	5 m
D	2 m
Vol	59000 m^3
Cost	40 mi IKR

Funi

Plough above the garbage burning plant Funi (type LII).

Param	Value
L	190 m
ψ	0°
ϕ	15°
v	35-40 m/s
H	9-10 m
D	0 m
Vol	23000 m^3
Cost	30 mi IKR

The dimensions and the cost of the plough are supplied by Gunnar Guðni Tómasson from VST (personal communication). They are therefore not computed according to the same methodology as for other dams in this report. The plough is an earth fill construction with a top made of concrete. This explains the rather high per m^3 price. The above description of the plough is based on initial proposals that have been put forward in an appraisal of defense structures for Funi and may change during the course of the work.

HNÍFSDALUR

Bakkahyrna

Catching dam in the western part of the area (type GI).

Param	Value
L	340/480 m
ψ	8°
v	19-22 m/s
H	12-15 m, 13 m is chosen here
D	2 m
Vol	71000/101000 m^3
Cost	90/120 mi IKR

Two lengths are given. The shorter dam would be combined with a more extensive area defended by supporting structures and the longer dam with a smaller area defended by supporting structures.

The choice of a design avalanche is difficult for the site. The design avalanche was chosen relatively small compared with more frequent avalanche paths because an extreme avalanche is thought to be unlikely here.

The modelled speed of the design avalanches at the location of the dams is approximately 30 m/s. A flow height of 1 m is chosen because small flow rates with little concentration of the avalanche flow are expected here. The construction of a dam higher than 12-15 m is not practical at the site. This corresponds to a speed of 19-22 m/s. A 12-15 m high catching dam is not properly dimensioned according to the modelled speed of the design avalanche. It is nevertheless a significant improvement in the safety of the site.

The dam is assumed to be of type GI due to the limited available space above the area to be protected.

Búðarfjall

Plough at the location of Heimabær (type LII).

Param	Value
L	200 m
ψ	0°
ϕ	30°
v	21 m/s
H	10 m
D	2 m
Vol	23000 m^3
Cost	20 mi IKR

Plough above apartment buildings (type LII).

Param	Value
L	280 m
ψ	0°
ϕ	30°
v	21 m/s
H	10 m
D	2 m
Vol	32000 m^3
Cost	20 mi IKR

Plough at the farm Hraun (type LII).

Param	Value
L	70 m
ψ	0°
ϕ	30-45°
v	16 m/s
H	5-6 m
D	0-0.5 m
Vol	3500-4100 m^3
Cost	3 mi IKR

The modelled speed of the design avalanches at the location of the ploughs at Heimabær and above the apartment buildings is about 26 m/s. The ploughs are located somewhat to the side of the main avalanche paths and it is expected that the impact and runup of the avalanches will be less than near the center of the paths. The design speeds were reduced by 5 m/s due to this reason.

The farm Hraun is also located somewhat to the side of the main avalanche path and has been standing there for centuries without documented avalanche damage. The design avalanche for the plough at Hraun was chosen to have a speed of about 16 m/s. The dimensions of the plough were not only determined by explicit velocity computations as it is assumed that potential avalanche tongues reaching the farm would be the sidewards margins of avalanches so that the impact toward the farms would be relatively small. This question should be addressed during the appraisal of a plough in this place.

A 2 m test pit was dug at the foot of the slope between Traðargil and Hraunsgil. The material visible in the pit appeared to be usable for dam construction. The grain size distribution of a sample from the pit was analyzed. The USCS class of the sample was determined to be GM and fraction of clay and fines was about 22%.

FLATEYRI

Skollahvilft/Innra-Bæjargil

Deflectors (type LII).

Param	Value
L	1250 m
ψ	0°
ϕ	18-25°
v	55 m/s near the top, 35-40 m/s near the bottom
H	20 m at the top, decreasing to 15 m at the bottom
D	0-6 m
Vol	530000 m^3
Cost	350 mi IKR

Catching dam (type GII).

Param	Value
L	350 m
ψ	9°
v	–
H	10 m
D	–
Vol	50000 m^3
Cost	50 mi IKR

The dimensions and the cost of the dam are taken from VST and NGI (1996). They are therefore not computed according to the same methodology as for other dams in this report.

The total estimated cost of the deflectors and the catching dam is 390 mi IKR according to VST and NGI (1996) and 310 mi IKR according to a revised cost estimate.

SÚÐAVÍK

Súðavíkurhlíð

Plough above the harbour area (similar to type LII').

Param	Value
L	560 m
ψ	0°
ϕ	20-40°
v	32 m/s near the top
H	13 m
D	1-2 m
Vol	135000 m^3
Cost	140 mi IKR

The dimensions and the cost of the dam are taken from HNIT (1995a,b). They are therefore not computed according to the same methodology as for other dams in this report.

BOLUNGARVÍK

Gullies in the western part of the town

Catching dam below the two gullies (type GI).

Param	Value
L	450 m
ψ	9°
v	22 m/s
H	15 m for 175 m at the western end, 15 m decreasing to 10 m for next 275 m
D	2 m
Vol	110000 m^3
Cost	130 mi IKR

The modelled speed of the design avalanches at the location of the dam is approximately 30 m/s. A flow height of 1 m is chosen because small flow rates with little concentration of the avalanche flow are expected here. The construction of a dam higher than 15 m is not practical at the site. This corresponds to a speed of 22 m/s. A 15 m high catching dam is not properly dimensioned according to the modelled speed of the design avalanche. It is nevertheless a significant improvement in the safety of the site. The dam height is lowered linearly to 10 m toward the eastern end where the conditions are judged to be less dangerous than below the gully above the western part of the dam.

Two 2.5-3.0 m deep test pits were dug, one below the gullies and the other to the west of the gullies. The material visible in the pits appeared to be good for dam construction. The grain size distribution of four samples from the pits was analyzed. The USCS class was determined to be GM or GW-GP-GM for one sample and SM for three sample and fraction of clay and fines in the samples was between 10% and 25%.

Ernir

Plough above the buildings of the Vestfirðir Power Company (type LII).

Param	Value
L	175 m
ψ	0°
ϕ	30°
v	25 m/s
H	11 m
D	2 m
Vol	25000 m^3
Cost	20 mi IKR

The modelled speed of a design avalanche in the main gully above the stables is approximately 40 m/s. The buildings of the Vestfirðir Power Company are located to the side of the main gully. Avalanches released from the hill directly above the buildings are expected to be significantly smaller than avalanches from the gully. Design runout and consequently design speeds were reduced due to this reason. The design avalanche was chosen to have a speed of about 25 m/s. A flow height of 1 m was chosen because small flow rates with little concentration of the avalanche flow are expected here.

There is abundant material for of reasonable quality for the construction of the plough near the site.

PATREKSFJÖRÐUR

Vatneyri

Deflectors on both sides of the main avalanche path (type LI).

Param	Value
L	2x50 m
ψ	0°
ϕ	10-20°
v	35-38 m/s
H	15 m at the top, decreasing to 10 m at the bottom
D	2 m
Vol	15000 m^3
Cost	20 mi IKR

Catching dams close to the main avalanche path (type GI). The longer dam is on the western side.

Param	Value
L	125+90 m
ψ	10°
v	22 m/s
H	15 m
D	2 m
Vol	66000 m^3
Cost	80 mi IKR

Catching dams further away from the main avalanche path (type GI). The longer dam is on the eastern side.

Param	Value
L	100+150 m
ψ	$\approx$10°
	>10° to the east
v	–
H	15 m near the main path, decreasing to $\approx$8 m away from the path
D	2 m to 0 m
Vol	49000 m^3
Cost	60 mi IKR

The modelled speed of the design avalanches in the main path at the level of the catching dam is 35-38 m/s. The deflectors can be dimensioned for this speed by keeping the deflecting angle below 20°. The construction of catching dams higher than 15 m is not practical at the site due to limited space for the dams. This corresponds to a speed of 22 m/s. 15 m high catching dams are not properly dimensioned according to the modelled speed of the design avalanche although impact and runup at the location of the dams may be expected to be smaller than in the main path.

A flow height of 4 m was chosen for the deflectors in the main path but a flow height of 1 m was chosen for the catching dams because the avalanches are expected to be thinner there than in the main path.

The catching dams could possibly be combined with retarding mounds to reduce the speed. The retarding mounds are not included in the cost estimate presented here.

The height of the deflectors should increase from 10 m at the lower end to 15 m at the top where they meet the 15 m high catching dams.

The proper design speed for the outer part of the catching dams is difficult to determine and there is very little space for the outer catching dam on the eastern side. The height of the outer dams is assumed to decrease from 15 m to 8 m or to whatever is practical to build at the site. This suggestion for dam height is not computed from explicit velocity assumptions and needs to be addressed during the design of defense structures for the site.

There is little space for the defense structures at the site and the present location of buildings makes the design of the structures quite difficult. The defense structures are nevertheless a significant improvement in the safety of the site.

Four test pits ranging from 3.5 m to 4 m in depth and one 2.5 m deep pit were dug below the slope. The material visible in the pits appeared to be good for dam construction. There is abundant material for an earth fill dam.

Klif

Catching dam above the hospital and the school (type GIII).

Param	Value
L	250 m
ψ	$\approx$12°
v	–
H	6-10 m, 8 m is chosen here
D	0 m
Vol	25000 m^3
Cost	50 mi IKR

There is little space for the dam. The dam height should be between 6 and 10 m depending on what is practical to build at the site.

Stekkagil

Guiding dam along the slush path (type LV).

Param	Value
L	2x400 m
H	3-4 m
Cost	10 mi IKR

Litladalsá

Guiding dam along the western bank of the river (type LV).

Param	Value
L	550 m
H	3-4 m
Cost	7 mi IKR

Sigtúnssvæði

Catching dam (type GI).

Param	Value
L	375 m
ψ	≈11°
v	22 m/s
H	15 m in the middle, decreasing to 10 m near the ends
D	1 m
Vol	100000 m^3
Cost	120 mi IKR

The modelled speed of the design avalanche at the location of the dam is approximately 25 m/s. The construction of a dam higher than 15 m is not practical at the site. This corresponds to a speed of 22 m/s if a flow height of 1 m is chosen because small flow rates with little concentration of the avalanche flow are expected here. Due to lack of space it will not be possible to reduce the height of the dam by much excavation on the upstream side, especially near the western end. The excavation depth D is reduced to 1 m due to this reason.

BÍLDUDALUR

Búðargil

Deflector down the fan below Búðargil (type LII).

Param	Value
L	325 m
ψ	0°
ϕ	20-30°
v	40 m/s at the top
H	15 m or more at the top, 15 m for next 150 m, decreasing to 10 m along the lowest 175 m
D	3 m
Vol	65000 m^3
Cost	40 mi IKR

The flow height of the design avalanche was chosen to be 3-4 m near the opening of the gully and 2 m away from the gully.

Milligil/Gilsbakkagil

Dams for catching and deflecting debris flows (type GII).

Param	Value
L	1000 m
H	6 m
D	2 m
Vol	60000 m^3
Cost	40 mi IKR

Guiding dams along the debris flow paths (type LV).

Param	Value
L	2x350 m
H	3-4 m
Cost	9 mi IKR

NESKAUPSTAÐUR

Dams at Neskaupstaður are designed with the thickness of snow on the ground on the upstream side of the dam before the avalanche falls, $H_s = 2$ m, and the thickness of the flowing part of the avalanche, $H_f = 2$ m (the default values).

The parameter λ in eq. (2) is assumed to have a value of 1.5 for dams with a steep upstream side with a slope of 1:0.5 because there is a potential for large avalanches hitting the dams.

The quality of the material on the site is rather bad and one must assume that building material of reasonable quality for a part of the fill must be transported several kilometers to the dam site. We assume that some local material can nevertheless be used and reduce the slope of the fill to 1:1.8 to accommodate this material mixed with material of better quality from further away. Dams of type GI' for Neskaupstaður therefore have a fill slope of 1:1.8. Unit cost per m^3 of dams in Neskaupstaður is assumed to be an average of the unit cost of dams of type GI and GI' as described in section 5.6.1.

The modelled speed at the dam sites is quite high in several of the areas (see tables below) and we propose to build breaking mounds in two rows above the catching dams to reduce the speed before the avalanche hits the dam. The breaking mounds are assumed to have steep upper sides and be elongated along the slope. The length of the top of the breaking mounds is chosen to be 10 m, the width of the top is chosen to be 5 m, the uphill slope is chosen to be 1:0.5 and the slope of the sides and the fill is chosen to be 1:1.5.

There do not exist accepted guidelines for computing the impact of rows of breaking mounds on the speed of dry snow avalanches. We have here arbitrarily assumed that a single row of sufficiently high breaking mounds of the type described above will reduce the speed of an avalanche by 25%.

Two test pits were dug above the town of Neskaupstaður, a 4.5 m deep pit below Tröllagil and a 5.5 m deep pit below Nesgil to the east of the reforestation area. The material visible in the pits was mostly soil with 10% to 30-40% stones and boulders. The grain size distribution of two samples from the pits was analyzed. The USCS class of the samples was determined to be SM and the fraction of clay and fines was 12-22%.

Many relevant questions regarding the proposed dams were not discussed in any detail by the work group. Brooks in the mountain must be allowed to pass through openings in the dams or through culverts under the dams. The design of such openings or culverts must be considered in the appraisal stage in the design of the dams and their effect on the cost of the dams is not considered here.

Stóralækjargil

Catching dam (GI').

Param	Value
L	450 m
ψ	5°
v	18 m/s at the western end, 10 m/s at the eastern end
H	15 m at the western end, 10 m at the eastern end
D	2 m
Vol	92000 m^3
Cost	120 mi IKR

Nesgil/Bakkagil

Catching dam (GI').

Param	Value
L	525 m 100 m long connection to the west
ψ	7°
v	21 m/s at the western end, 18 m/s at the eastern end
H	19 m at the eastern end, 15 m at the western end, the connection is 10 m high
D	2 m
Vol	221000 m^3 (dam) 13000 m^3 (connection) 234000 m^3 (total)
Cost	290 mi IKR

Drangaskarð

Catching dam and breaking mounds (GI'+KI').

Param	Value
L	400 m 15 breaking mounds 12 m high
ψ	10°
v	31 m/s
H	17 m
D	2 m
Vol	194000 m^3 (dam) 128000 m^3 (mounds) 322000 m^3 (total)
Cost	410 mi IKR

The breaking mounds are assumed to be arranged in two rows.

Urðarbotnar

Catching dam and breaking mounds (GI'+KI').

Param	Value
L	250 m 9 breaking mounds 12 m high, 50 m long connection to the east
ψ	11°
v	30 m/s
H	17 m
D	2 m
Vol	128000 m^3 (dam) 80000 m^3 (mounds) 8000 m^3 (connection) 216000 m^3 (total)
Cost	280 mi IKR

The breaking mounds are assumed to be arranged in two rows.

Between Tröllagil and Urðarbotnar

Catching dam (GI').

Param	Value
L	250 m
ψ	11°
v	–
H	10 m
D	2 m
Vol	42000 m^3
Cost	60 mi IKR

The avalanche hazard in this area is considered much lower than in the neighbouring areas and the recorded avalanche history shows no avalanches approaching the inhabited area. The dam is not designed on the basis of explicit velocity modelling, but rather intended to connect the higher dams below Tröllagil and Urðarbotnar in order to provide defense against smaller avalanches that might be released in the area under extreme circumstances.

Tröllagil

Catching dam and breaking mounds (GI'+KI').

Param	Value
L	625 m
	25 breaking mounds 12 m high
ψ	11°
	12.5° at the breaking mounds
v	24 m/s
H	17 m
D	2 m
Vol	321000 m^3 (dam)
	241000 m^3 (mounds)
	562000 m^3 (total)
Cost	710 mi IKR

The breaking mounds are assumed to be arranged in two rows.

The dam described in the above table is not based on the same safety assumptions as for other dams in this report as mentioned in the main text. Design avalanches based on similar assumptions as elsewhere in the report lead to a modelled velocity of about 35 m/s near the dam site and the work group judges it impractical to design a dam for such a high velocity. There is less space for breaking mounds than above the other dams further to the east and the dam would have to be significantly higher than 20 m. The dam described in the table is based on a design velocity corresponding to the longest recorded avalanches (or perhaps somewhat shorter because these avalanches terminated in the sea and the actual runout distance is therefore not known). The dam must be combined with an evacuation plan in order to provide acceptable safety to the inhabitants of the area as mentioned in the main text.

SEYÐISFJÖRÐUR

Bjólfur

Catching dam at 650 m a.s.l. in Bjólfur (type GII)..

Param	Value
L	425 m
ψ	≈0°
v	20/30 m/s
H	22-41 m,
	25/35 m are chosen
D	5 m
Vol	265000/575000 m^3
Cost	150/270 mi IKR

The design of a dam on the shelf at 650 m a.s.l. must be addressed in the appraisal phase after more avalanche modelling has been performed. The slope above the dam reaches to 800-1000 m a.s.l. and may be expected to be one large starting zone under extreme circumstances. The speed of an appropriate design avalanche must be computed with a model which takes due account of entrainment of snow along the track.

Since large avalanches are expected here and because the proposed dam has a slope of the upstream side equal to 1:1.3, determined by the angle of repose of the building material, we assume a rather low value of the parameter $\lambda = 1.3$ in eq. (2) (*cf.* subsection 5.5.1). We further assume a high value for the thickness of snow on the ground on the upstream side of the dam before the avalanche falls, $H_s = 4$ m, because large amounts of drifting snow have been observed to collect on the shelf where the dam would be built and deposits from previous avalanches may be expected to be present above the dam when an avalanche falls. The large value $D = 5$ m for the excavation depth upstream from the dam is chosen because the local conditions favour extensive reshaping of the terrain near the dam.

We choose two dam heights, H = 25 m and H = 35 m in order to give an idea of the size and cost of a dam which we judge to be realistic based on our current examination of the conditions, but we are not at the present time able to tell which of them represents a better choice. This will have to be answered by a more extensive future analysis. Both dams are realistic in the sense that no technical problems should prevent their construction, they do not present a significant environmental problem and their cost is much less than the value of the properties which they would defend. We have chosen to use the more expensive dam in our table of cost estimates, but a smaller dam is certainly a possibility which must be addressed in the appraisal phase of a dam in this place.

A catching dam at the shelf at 650 m a.s.l. in Bjólfur was suggested by the engineer Þorsteinn Jóhannesson of Verkfræðistofa Siglufjarðar to the town engineer of Seyðisfjörður, Sigurður Jónsson, in a letter dated 27 November 1995. Sigurður forwarded this suggestion to the work group which made the above computations based on this suggestion. The higher volume derived above is similar to the dam volume suggested by Þorsteinn Jóhannesson in his letter.

Catching dam at the foot of the slope (type GI).

Param	Value
L	375+225+250=850 m
ψ	5°
v	19 m/s
H	12 m
D	2 m
Vol	59000+35000+39000=133000 m^3
Cost	70+40+50=170 mi IKR

It is believed that the most catastrophic avalanches that endanger the area would be released in the higher part of Bjólfur above the high catchment dam which would be located on the shelf at 650 m a.s.l. The modelled speed of a design avalanche starting below 600 m a.s.l. (*i.e.* below the dam on the shelf) at the location of the dam is more than 30 m/s. Gullies in the southern part of the slope may be expected to divert potential avalanches away from buildings below that part of the slope and the convex shape of the slope in this area reduces the risk of dangerous accumulation of snow. The danger of avalanches which are released from the lower part of the slope is difficult to determine, but there is a clear potential for the release of avalanches in the Kálfabotnar in the northern part of the slope where supporting structures are proposed (see the main text).

The work group proposes the 12 m high dam described in the table to reduce the risk associated with avalanches from the lower part of the slope. The proposed catching dam is not properly dimensioned according to the modelled speed of design avalanches. It is nevertheless a significant improvement in the safety of the site. The dam must be combined with an evacuation plan, especially for the industrial buildings under the northern part of the mountainside in order to provide acceptable safety to the inhabitants of the area as mentioned in the main text.

It is possible that near the southern and northern ends, the lower dam should be built as a deflector rather than a catching dam. This would improve the protection against avalanches which come from the Fálkagil gully and from the northern and more dangerous part of the slope. A deflector with a deflecting angle $\phi \approx 25°$ may be located below Fálkagil. This would increase the total length of dams in the lower part of the slope by about 125 m. The lengthening of the dams arising from a deflector shape at the northern end is more difficult to estimate without further study. Modelled velocities of avalanches from Fálkagil depend to a large extent on assumptions regarding the concentration of flow in the gully and a determination of the height of a deflector was not made by the work group. The cost increase arising from the possible deflector shape at the southern and northern ends of the dam is not expected to have a large impact on the total cost of avalanche protection for the Bjólfur area and it is not included in the cost estimate given in this report.

Strandartindur/Botnar

Guiding dams along slush and debris flow paths (type LV).

Param	Value
L	2x2250 m
H	3-4 m
Cost	60 mi IKR

SIGLUFJÖRÐUR

Jörundarskál/Strengsgil

Deflector below Ytra-Strengsgil (type LII).

Param	Value
L	825 m
ψ	7°
ϕ	15°
v	45 m/s near the top
H	18 m at the top and for the uppermost 600 m, decreasing to 15 m at the bottom
D	3 m
Vol	413000 m^3
Cost	260 mi IKR

A flow height of $H_f = 4$ m is assumed because of the confined track. Furthermore, the thickness of snow on the ground and the thickness of previous avalanche deposits are assumed to be 5 m and 2 m, respectively, giving $H_s = 7$ m. Adding the thickness of snow on the ground to the thickness previous avalanche deposits is a conservative assumption since accumulation of drifting snow after an avalanche falls may not be independent of the presence of previous avalanche deposits. This should be addressed in a further study in the appraisal phase.

The configuration of the southern end of the deflector needs further study. It depends to a large extent on the proposed reshaping of the opening of the gully from Jörundarskál and the short deflector which is proposed there (see below). Three possibilities should be considered: (1) a long deflector that defends all current buildings. (2) a short deflector which does not provide defense for between 10 and 15 buildings in the southern part of the area. (3) a long relatively straight deflector which requires the elimination of between 10 and 15 buildings in the southern part of the area. It is not possible to recommend one particular choice at the present time, but configuration (1) corresponds to the dams described in the tables in this section. This must be further studied in the appraisal stage in the design of the dams.

Three 3.3-3.7 m deep test pits were dug below Strengsgil. Much of the material visible in the pits appeared good for dam construction. There is abundant material for an earth fill deflector.

Deflector below Jörundarskál (type LII).

Param	Value
L	150-200 m, choose 200 m
ψ	<5°
ϕ	<10°
v	45 m/s near the top
H	15 m
D	3 m
Vol	61000 m^3
Cost	40 mi IKR

As for the deflector below Strengsgil, a flow height of $H_f = 4$ m is assumed because of the confined track. The thickness of snow on the ground and the thickness of previous avalanche deposits are assumed to be 5 m and 2 m, respectively, giving $H_s = 7$ m.

This short deflector is intended to divert avalanches toward the south so that they do not hit the deflector under Strengsgil with an unfavourable deflecting angle. The deflector should be combined with a widening of the opening of the gully by blasting of the bedrock to the south of the gully. This directs avalanches away from the Strengsgil deflector so that its lower part can be designed with a higher deflecting angle.

The estimated cost of the deflectors below Strengsgil and Jörundarskál given in the tables does not include the cost of relocation of water supply lines, electricity cables and other such cost components. This cost has been roughly estimated to be about 20 mi IKR by Þorsteinn Jóhannesson from Verkfræðistofa Siglufjarðar.

20. APPENDIX II: Cost assumptions for dams

The cost estimates for dams which are listed in section 5.6.1 are based on several simplifying assumptions:

1. The slope of the hill where the dam is built is ψ=10°.
2. Transportation distance for material that needs to be transported to the site is 5 km.
3. Transportation distance for material that can be obtained at or near the site is less than 1 km.
4. Excavation of overburden in the dam site is 1 m.
5. Unforseen costs are taken to be 20%.
6. Design, management and control before and during the building phase is taken to be 8%.
7. Prices include VAT of 24.5%.

Dam cost is expressed as unit price per m^3 of fill and assumed to decrease linearly with dam height. The unit price is of a dam is computed from the price of a 12 m high dam, c_{12}, and the price of a 17 m high dam, c_{17}, by linear interpolation/extrapolation from these values. The adopted unit prices c_{12} and c_{17} for dam types I, II and III are given in the following table

Dam type	c_{12} (IKR/m^3)	c_{17} (IKR/m^3)
I	1200	1100
I'	1400	1300
II	650	600
II'	850	800
III	1800	1700
III'	2000	1900

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