Avalanche defences for Flateyri, Iceland.
From hazard evaluation to construction of defences.

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ABSTRACT.

The village of Flateyri was hit by two major avalanches in 1995, with the latter one killing 20 of the 45 people caught in it. These, together with the catastrophic avalanche in the nearby Súðavík in January the same year, initiated a complete review of all government actions and regulations regarding avalanche risk and avalanche defences in Iceland. The government set a long term goal for the acceptable risk to people living in avalanche prone areas and increased funding for the construction of avalanche defences.

The avalanche situation in Flateyri is quite serious and the risk the inhabitants live with is very high. The town is threatened by avalanches from two gullies, Innra-Bæjargil in the north-west and Skollahvilft in the north-east, with several records of avalanches reaching well into the present residential area. To fulfil the safety requirements, an appraisal study was carried out and a proposal made for avalanche defences for the community, consisting of two earthfill deflecting dams and an earthfill catching dam. The proposal was accepted by the local authorities and the Icelandic government in the spring of 1996, design work was carried out in that summer and construction work started in September 1996. The construction of the dams is now close to completion, two years after the accident.

INTRODUCTION

Following the catastrophic avalanche in Flateyri on October 26th 1995, the township of Flateyri instigated a total review of its avalanche defences. In November 1995, VST Consulting Engineers were hired to evalutate the avalanche defence situation in the village and in February 1996, NGI joined VST in a co-operation on an evaluation of the avalanche hazard and an appraisal for construction of new avalanche defences for the village, based on the current experience and new safety requirements. The goal of the project was to protect the whole village against snow avalanches, or at least those parts of it that may be protected in a safe and economical way. The work has also been done in co-operation with representatives of the Icelandic Meteorological Office (IMO) and the Icelandic Ministry for the Environment. The results of this joint work of VST and NGI are described in this paper, together with the construction of the defences.

TOPOGRAPHIC AND CLIMATIC CONDITIONS

The town of Flateyri is situated on the northern side of the fjord Önundarfjörður (fig. 1) in Vestfirðir, a peninsula that extends Northwest from the mainland body of Iceland. Trade in some form is said to have started at Flateyri in the year 1792, but it was not until the end of last century that population started to grow at Flateyri due to the growing fisheries and fish industry. In the year 1900 some 200 inhabitants are registered there. As off December 1st, 1994, the inhabitants of Flateyri were 379, but on December 1st 1997, two years after the accident, the population had gone down to 289 inhabitants. Decline in population is at present a major problem of rural areas in Iceland, but the decline in population at Flateyri is far more than the general decline in the Vestfirðir region.

The town of Flateyri is situated on a sand and gravel reef by the same name that stretches out from the north into the fjord. Up from the reef, the southwest facing mountain

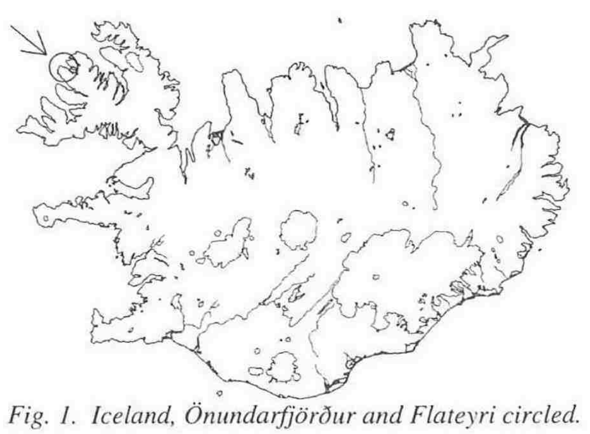

Fig. 1. Iceland, Önundarfjörður and Flateyri circled.

Eyrarfjall reaches up to an elevation of 660-670 m a.s.l., quite steep with numerous gullies, depressions and small valleys. Two separate starting zones, formed as open bowls, can be distinguished in the mountain above the village, Innra-Bæjargil directly above the reef and the larger Skollahvilft, a little to the east of the reef. The mountaintop is flat and formed as a plateau, a common feature in Vestfirðir.

The inclination of the terrain in the two bowls is between 38° and 40°, and both of them narrow down to gullies at an elevation of about 300-350 m a.s.l. Material transported by the two creeks flowing in the gullies and debris slides have built large fanshaped depositions apexing at the gully outlets. The Innra-Bæjargil bowl is about 250 m wide at the top with a total area of the avalanche starting zone of 4-7 ha. The Skollahvilft bowl is much larger, about 800 m wide at the top with a total area of the starting zone of 15-20 ha (150.000 to 200.000 m^2). The inclination in the uppermost part of the fans is 20-25°, decreasing down to 10-15° at their lower margins. The settlement of Flateyri starts close to the toe of the fans.

Snow accumulation in the Innra-Bæjargil starting zone occurs mostly by drifting snow associated with NW-ly to NE-ly winds, but possibly also with W-ly winds. The snow catchment area is the rather extensive flat mountain top adjacent to the starting zone. With winds blowing from the east, this bowl is to some extent protected from snow accumulation by the adjacent Skollahvilft. The accumulation of snow in Skollahvilft also occurs mostly by drifting snow associated with N-ly winds. The top of Eyrarfjall is extensive, with great potential for storing of snow. During strong winds from NW to ENE a huge amount of snow can accumulate in the bowl within a short period of time. Some snow accumulation may also occur in the gully during E-ly winds, whereas Skollahvilft is protected from W-ly winds by Innra-Bæjargil.

During the winter, gale force winds from northerly directions accompanied by heavy precipitation and air temperatures below freezing all the way down to sea level occur frequently in this part of Iceland. Consequently, the climate in Vestfirðir offers favourable conditions for frequent avalanche activity in slopes where the topographical conditions make sliding possible. The weather situation prior to the release of the avalanche in October 1995 was unusual, and analysis performed by the Icelandic Meteorological Office indicates that similar weather situations in October have a return period of about 30-50 years. Similar synoptic situations during the winter season can occur nearly every year, but usually the precipitation intensities are then somewhat lower (Jóhannesson & Jónsson, 1996).

AVALANCHE HAZARD AT FLATEYRI

Written records of avalanches from the two gullies above the village date back to the first part of this century and contain numerous records of avalanches from both gullies with runout length towards and into the presest residential area. The work presented here is based on records that date back to 1936, but recently IMO has gathered some new information and found avalanches dating back to 1910 [IMO, personal communication]. The reason for the avalanche records not dating further back in time is that the settlement on the reef was limited to its outer part until the turn of this century. Avalanches terminating in the upper part of the reef therefore caused no damage and were not recorded.

Calculation of runout distances is usually performed with statistical and dynamic models. To obtain a runout distance corresponding to the avalanche on October 26th 1995, quite unusual parameter values have to be used in the models compared to the experience from other countries for avalanches with long runout distances. This indicates that the runout of the catastrophic avalanche was very long. It is difficult to make accurate quantification of the frequency of avalanches with a specific runout distance. Based on the avalanche history, topographic and climatic characteristics of the area and the use of models for calculation of runout distance, the following deductions with respect to avalanche frequency in the Flateyri area can be made:

- Small avalanches with runout down to the lower part of the alluvial fan occur several times per decade.
- Larger avalanches reaching the margins of the settlement occur approximately every 10 years on average.
- Catastrophic avalanches reaching far into the settlement corresponding to the avalanche of October 26th, 1995 occur every 100-200 year on average.

The Innra-Bæjargil avalanche mainly threatens the western part of the settlement, while the Skollahvilft avalanche usually has its main direction towards the eastern part. However, in specific weather situations when great volumes of snow are involved, avalanches from both gullies can move more in the direction of the central parts of Flateyri. Avalanches from Skollahvilft have potential for greater volumes due to the larger starting zone, and thus the extent of the hazard zone is largely governed by the Skollahvilft avalanches.

PROPOSED DEFENCES

After considering several possible alternatives for avalanche defences we came to the conclusion that deflecting dams located directly above the village, as shown in Figure 2 were the most feasible alternative for avalanche defences for Flateyri. Supporting structures were ruled out because of the size of the two starting zones with consequent high cost, and difficult terrain with great danger of rock fall. A catching dam was ruled out because of the high speed of the avalanche at the possible location of the dam.

The dams reach from the outskirts of the village up to elevation around 100 m a.s.l., where they meet to form a wedge shaped structure, although not functioning as a typical splitting wedge, as all avalanches from Innra-Bæjargil will probably be deflected to the west of the dams, while all avalanches from Skollahvilft will be deflected to the east. Other layouts were considered, but this one was found to be the most feasible. Connecting the two dams in the upper part was deemed necessary to stop any small avalanches originating in the mountainside between the two gullies. Additionally, a smaller catching dam is proposed extending between the two deflecting dams at an elevation

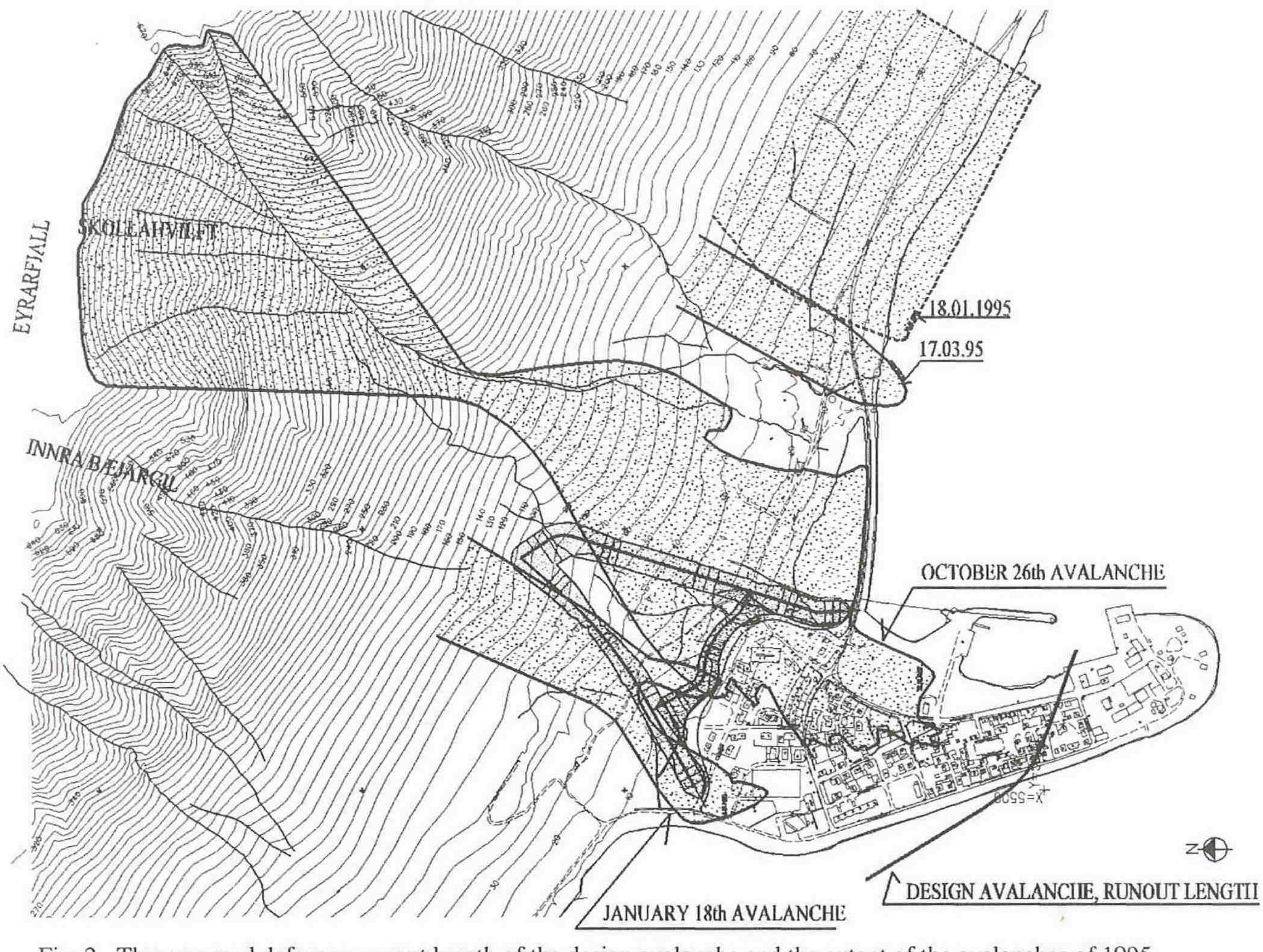

Fig. 2. The proposed defences, runout length of the design avalanche and the extent of the avalanches of 1995.

of 10-15 m a.s.l. Its purpose is to stop any avalanche mass that may spill over the deflecting dams when hit by a large avalanche comparable to the design avalanche.

DESIGN AND DIMENSIONING CRITERIA

Results of the Norwegian α-β model (Bakkehöi et al., 1983) calibrated for available data on Icelandic avalanches (α=0,92β, SD=2.55°, Jóhannesson, et al., 1996), show that the October 1995 avalanche went 1.5 standard deviations beyond the average α-value (After this work was completed, the above model was revised, based on a new and revised database for long Icelandic avalanches, and new parameters obtained, resulting in the model α=0,85β with SD=2,2°, Johannesson, 1998a). This result indicates quite clearly the high frequency of avalanches in Flateyri and how serious the avalanche situation is. The runout length of the design avalanche at Flateyri is taken to correspond to two standard deviations beyond the average value. Statistical methods indicate that the associated runout distance may correspond to an avalanche with a return period of 500-1000 years. This estimate is based on a Gumbel distribution fitted to the runout distances of the observed avalanches from Skollahvilft. Similar results have been obtained by other authors and results based on newly gathered information on previously unrecorded avalanches dated back to 1910 further strengthen this estimate (Johannesson, 1998b). The runout length of the design avalanche is shown in Figure 2.

Dry avalanches have the largest impact on the deflecting dams, and the design of the two wings is made on basis of a dry avalanche 150 m longer than the 1995 avalanche as discussed above. The necessary height of the deflecting dams is based on the following simple formula:

$$H = h_s + h_f + \frac{(v \cdot \sin\varphi)^2}{2g}$$

where

- v = avalanche speed (m/s)
- φ = angle between the avalanche direction and the centreline of the wall
- g = acceleration of gravity (m/s^2)
- h_s = maximum snowheight on the ground at the toe of the dam (m)
- h_f = flow height of the dense layer of the avalanche (m)

Back-calculations of the avalanche velocity profile based on the runout length of the design avalanche have been performed with different dynamic models, among them the PCM-model and the NIS-model. The results indicate that the speed of the design avalanche may be 50-60 m/s in the uppermost part of the construction area, but 30-40 m/s in the lower part. Construction of safety measures against such high velocities has to our best knowledge never been

Fig. 3. A view of Flateyri with the defences near completion. Picture taken Jan. 29th 1998

performed before. That lack of experience adds some uncertainty to the design of the dams.

The snow depth is difficult to estimate exactly, because wind drifting snow causes great differences in snow height close to the dams, especially in areas leeward to the prevailing wind directions. The existence of the dam will greatly influence the local wind directions close to the ground, and this may reduce the effective height of the dam. The prevailing winds with precipitation are from the north to east, indicating that the largest snow accumulation is likely to occur leeward of the western wing below Innra-Bæjargil. In the design we have assumed h_s=3 m for the Innra-Bæjargil track and h_s=2 m for the Skollahvilft track.

Measurements from the full-scale experimental Ryggfonn-avalanche in Norway indicate that the dense layer usually has a thickness of 1-3 m in the lower part of the track, the saltation layer 3-5 m, while the snow-cloud can extend to 30-50 m. The dense part of the Skollahvilft avalanche may attain a considerable height while flowing through the confinement in the gully system above the fan, probably more than 10 m. However, once the avalanche has exited the confinement the thickness will drop considerably. At the top of the construction area the dense flow depth is most likely to be h_d=3 m and the saltation layer depth about h_{sa}=5 m. The thickness will decrease downslope, and in the lower part of the construction area the thicknesses of the two layers are probably h_d=2 m and h_{sa}=2 m. Due to the lesser volume of the Innra-Bæjargil avalanche, the flowing height of this avalanche is somewhat lower, probably h_d=2 m and h_{sa}=3 m at the uppermost part of dams. In the lower parts these heights will have decreased to h_d=1 m and h_{sa}=1 m.

The thickness of the snow-cloud for big and dry avalanches can be up to 30-50 m adjacent to the top of the dam for Skollahvilft decreasing down to 20-30 m in the lower part. For Innra-Bæjargil the snow-cloud height is presumably 20-30 m adjacent to the top part of the dam decreasing to 10-15 m at the bottom part. This implies that only the dense part of the avalanche will be directly deflected by the dams in the upper part of the construction. The snow-cloud is by far too high to deflect, but the velocity of the snow-cloud will quickly retard if not fed by the dense layer. This applies to the saltation layer as well. To take care of the overflow of the saltation layer in this part an additional catching dam between the two wings is proposed. The height of the dam is chosen 10 m.

The height of dams necessary to deflect an avalanche is very sensitive to the angle of deflection. For the Flateyri defences it was found that the total volume of the dams decreased with decreasing deflection angle, in spite of the longer dams and higher estimated speeds. However, the layout of the dams is limited by other factors. In order to protect the whole village, the distance between the dams at the outskirts of the village has to be at least 450-500 m. Secondly, as the deflecting angles are decreased, the eastern and western wing of the dams will coincide at an ever higher elevation, making their design and construction more difficult due to the increasing slope of the terrain. Furthermore, as we move further up into the track, the estimated avalanche speeds increase, thus increasing the necessary height of the dams. The deflecting angles for an avalanche from Skollahvilft are estimated around 20° in the lower part and 18° in the upper part of the dam. The deflecting angles for avalanches from Innra-Bæjargil are estimated around 25° in the lower part and 18° in the upper part. The length of the eastern wing is about 650 m, while that of the western wing is about 600 m.

Based on these design criteria, the necessary height of the deflecting dams is found to be 20 m in the uppermost part and 15 m in the lowermost part of each wing. Their top width is 3 m and the embankment slope is 1:1.4 on the leeward side, but 1:1.25 on the avalanche side.

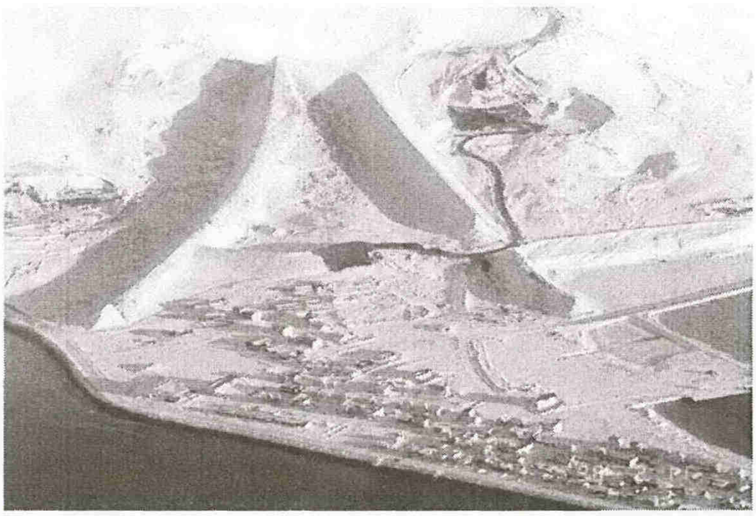

Fig. 4. A view of Flateyri. Picture taken Feb. 11th 1998

CONSTRUCTION OF THE DAMS

The proposal of VST and NGI was accepted in the spring of 1996 and a decision made by the municipality of Flateyri and the Icelandic government to build the proposed defences. The dams were designed and bidding documents prepared by VST in the summer of 1996. An environmental impact assessment was also made as well as a new master plan for the village, with the defensive structures included. A contractor was hired in August 1996 and the construction work started in September the same year. The work is now near completion and will be finished this spring. The total cost of the project is expected to be within the original cost estimate of US$ 5.5 million. The total value of property defended by the dams is estimated to be around US$ 27.5 million.

To lessen the impact of the dams on the local environment, an effort will be made to return the surface of the dams and the excavation areas to similar or better vegetation levels than prior to the construction. The shelter provided by the dams will be used to grow trees and create a friendly area between the dams for outdoor activities for the inhabitants of Flateyri. To provide access to the area, a pedestrian tunnel has been made through the catching dam.

DISCUSSION

Avalanche defences for the village of Flateyri in Iceland, consisting of two deflecting dams and a catching dam, are currently under construction and close to completion. The deflecting dams are about 600 m long each and 15-20 m high. The catching dam is 10 m high and about 350 m long. The total volume of fill in the dams is about 700.000 m^3.

The deflecting dams are designed for speeds associated with an avalanche with an estimated return period of 500-1000 years. If hit by a larger avalanche, the dams will still give considerable protection, as they may be expected to deflect the largest part of the avalanche, although some of it may pass over. The safety below the dams is thus believed to be considerably more than that corresponding to a return period of 500-1000 years. It is our belief that with these design criteria, the risk level below the dams is within the acceptable limits proposed by the Icelandic Government, i.e. less than $0{,}2 \cdot 10^{-4}$ per year.

Given the high frequency of avalanches in Flateyri, the deflecting dams are likely to be hit by an avalanche of considerable size within the next years or decades. The Icelandic Meteorological Office has made plans to set up equipment to measure the speed and runup of oncoming avalanches to verify the design and dimensioning criteria of the dams. Such data if obtained would make invaluable contribution to the determination of design criteria for avalanche deflecting dams.

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