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ABSTRACT

October 26, 1995 a snow avalanche hit a village in NW Iceland killing 20 people. Subsequently, extensive research on the properties and characteristics of avalanches and defence possibilities was instigated aiming at appraising preventive measures. Due consideration of the prevailing conditions showed training dikes (deflecting dams) of specific height and angles to be the most cost effective measures, provided that these could be constructed from materials available in the immediate vicinity. Additionally, the steeper the slope facing the avalanche (upstream) the more protective the dike. This was designed and constructed at 1 vertical to 1.25 horizontal upstream. The 1200 m long dikes extend from sea level to 60 m a.s.l. up a slope of 10 to 15°. The necessary height varied along the dikes' alignment from 20 m at the top to 15 m at sea level. Total volume in the dikes amounts about 700.000 m³.

The Flateyri fishing village is located in a fiord on a low, narrow promontory extending from a relatively steep mountain slope. The mountainside contains numerous circues and crevasses where appreciable amounts of snow may accumulate. The mountain, some 15 million years old, is built up from a succession of basalt lava flows, frequently intercalated with relatively thin sediments. The columnar core of each flow is typically adjoined by upper and lower scoriae. During the ice age the entire area was ice covered. The glacier left relics in the surroundings e.g. moraines. Thus the talus covering the slopes adjoining the village contains essentially eroded materials of glacial and erosional origin, with the angle of the talus gradually increasing with elevation from essentially zero to some 35°. The talus typically classifies on USCS as SM material, containing some 30 % fines, equal percentage of sand with the remainder being gravel and boulders. This constitutes the construction material.

PREAMBLE

Following the Oct 1995 avalanche the shocked and scared inhabitants of Flateyri, were acutely aware of the conditions they must endure if they wanted to keep on living here. With the strong psychological after effect of the avalanche prevailing in the village it was important that the whole nation show solidarity with the inhabitants. Support came from near and far and the government of Iceland pledged quick and decisive measures to avert such future occurrences. Location of the Flateyri village in NW Iceland is shown in *fig. 1*.

Investigations and studies of possible protection were instigated shortly after the avalanche with e.g. experts from abroad brought to Iceland for consultancy. Based on the results of these and additional studies it was determined that training dikes constructed upslope from the village should provide the best overall protection for the village.

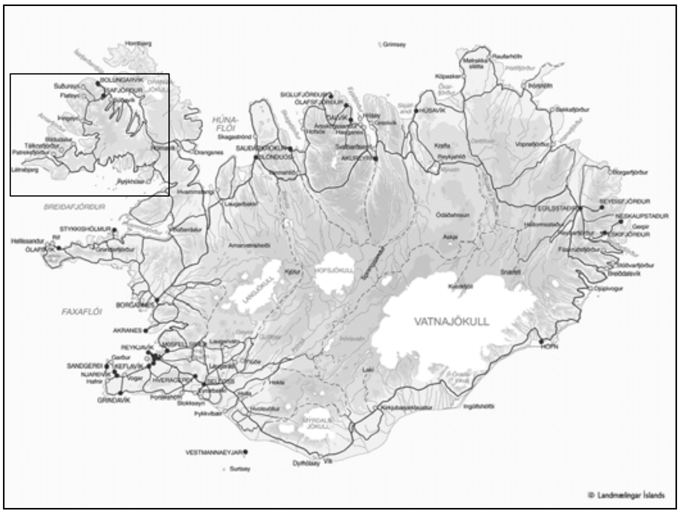

Fig. 1 A Map showing location of the village Flateyri in the Vestfirðir peninsula in Northwest Iceland.

The prevailing criteria in the design and construction of the snow avalanche training dikes at Flateyri were apart from the technical aspects to make to the extent possible use of the site specific geological and geo-technical conditions, given the topographic and environmental constraints. Furthermore to make the dikes as steep as possible on the avalanche side as in general it may be stated that the steeper the slope towards the avalanche, the more effective given a certain height, or conversely; a certain height will serve to divert ever greater avalanches the steeper the slope, at least up to a limit.

However, making use of the potential and readily available construction materials located relatively close to the dikes was a priority. Borrowing these immediately adjacent to the dikes should serve twofold:

- increase their effective height
- shorten the hauling distance

Both aspects are cost effective.

Needless to say, the construction of such "monster dikes" adjoining the village on slope were countless generations had enjoyed evening stroll of dreams was opposed by many, not the least earlier inhabitants. However, since the dikes were constructed, let alone proven their effectiveness, these voices have become silent.

In this paper we will not consider the snow avalanche specifics, the characteristics and properties of such avalanches, which both in general and as regards this specific avalanche have been detailed and discussed in a number of papers. The aim of this paper is rather to detail the conditions and main design criteria for the construction as well as to describe the execution.

SITE CONDITIONS

Flateyri is a small village of some 300 people who predominantly base their life on the obtaining and processing of fish. The village is located on a low, narrow promontory extending out into a fiord from a relatively steep mountain slope cf. *fig. 2.* The prevailing conditions are such that avalanche will originate in two separate crevasses overlying the village. With increasing population and the area close to the harbour restricted to industrial needs, the live-in houses were located ever closer to the mountain. The mountainside upslope from the village, although covered with vegetation in the lower elevations is barren further up, cut by numerous circues and crevasses where, given certain weather conditions, appreciable amounts of snow may accumulate.

The mountain, some 15 million years old, is built up from a succession of basalt lava- flows, frequently intercalated with relatively thin sediments. The columnar core of each lava flow is typically adjoined by upper and lower scoriae. During the ice age the entire area was ice covered. The glacier left relics in the surroundings e.g. moraines. Thus the talus covering the slopes adjoining the village contains essentially eroded materials of glacial and erosional origin, with the angle of the talus gradually increasing with elevation from essentially zero to some 35°. The talus typically classifies on USCS as SM material, containing up to 45 % fines, with about equal percentage of sand with the remainder comprising gravel and boulders *(Table 2).* This constitutes the construction material.

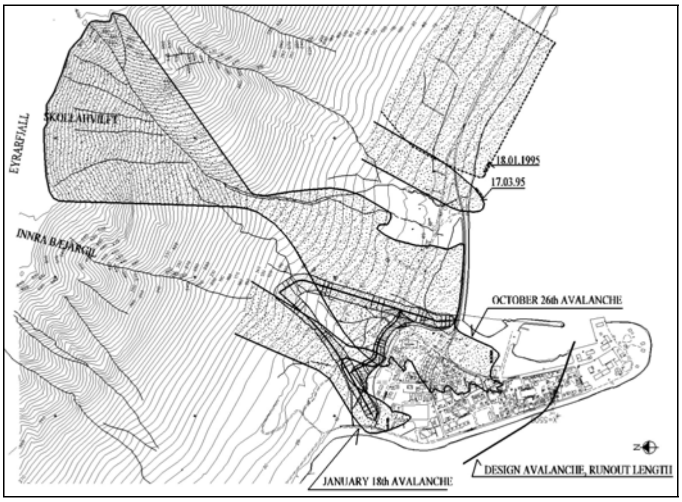

Fig. 2 The proposed defences, runout length of the design avalanche and the extent of the avalanches of 1995.

ENVIRONMENTAL ISSUES

It was acknowledged that the proposed avalanche defences would have considerable impact on the local environment at Flateyri both permanent and temporary during the construction period. Furthermore, that the dikes were likely to change the microclimate in the adjacent area, especially this inside the dikes. This has however produced favourable conditions for the development of certain plants and trees and the area inside the dikes has been turned into such for outdoor activities.

An environmental impact assessment study was prepared for the project, resulting in a positive ruling by the Icelandic Planning Agency on July 26, 1996.

Long term impact

The long-term positive impact of overwhelming importance is the increased safety for the population of Flateyri with the avalanche hazard for a large portion of the village brought down to an acceptable level. It could be argued, that the future of habitation in the village was questionable without substantial defence measures.

The greatest negative long-term impact was considered substantial reshaping of the mountainside above the village. The two-talus fans that dominated the slope were to a large extent removed in order to form a clearer path for avalanches emanating in the two above gullies and running along the proposed dikes. Additionally the talus materials should provide construction material. The view of the mountain changed substantially.

Still the impact was somewhat mitigated by vegetation on the surface of the dikes, and the shaping of these. A fairly successful effort was made to return the surface of the dikes and the adjoining excavation areas to earlier vegetation levels. Also, snow accumulation close to the dikes has increased.

The construction affected to some extent the surface runoff in the area, as well as the local groundwater levels. Still these effects have been minimal as measures were taken to ensure natural flow of surface water along the dikes and through these.

Short term impact

During the construction period the impact on the local environment was substantial with a significant number of workers being stationed in the area. Contrarily, local business profited somewhat.

In the short term vegetation was less and the use of the area for outdoor activities limited. Some soil erosion occurred and the local bird life was slightly disturbed.

THE TRAINING DIKES, LAYOUT AND SECTIONS

Extensive studies showed that two essentially 20 m high, about 600 m long training dikes, extending in a v-shaped manned down from about El. 110 m above sea level, connected by a 10 m high transverse dike (catching dam) at about El 10 m a.s.l. should provide the specified protection. The transverse dike is to retain snow that may spill over the training dikes. The height of the dikes should be partly achieved by excavation adjacent to the toe of the dikes. The routing of the design avalanches on each side showed that the height of the dikes could be linearly reduced to15 m in the lowest lying part. The layout is shown in *fig. 2*.

Excavations

The construction materials available from the talus fans beneath the two gullies was found essentially suitable for the construction of the dikes. Most of the material was preferably to be taken from the fan beneath the innermost gully Skollahvilft, a much larger fan and where it was most important to reshape the terrain to increase the effectiveness of the training dikes, since this side was expected to convey the largest avalanches. Thus, a large part of the corresponding fan was to be removed to channelise avalanches in the desired direction. The same is done down-slope from the outer gully Innra-Bæjargil, although to a lesser extent. The material was to be borrowed from the uppermost part of the fans, from around elevation 50 m a.s.l. to 120 m a.s.l., covering an area of some 210.000 m^2. The estimated volume of excavations in the fan beneath Skollahvilft was about 460.000 m^3, while excavation from the other fan was 210.000 m^3.

Typical transverse section of dike is shown in *fig. 3*.

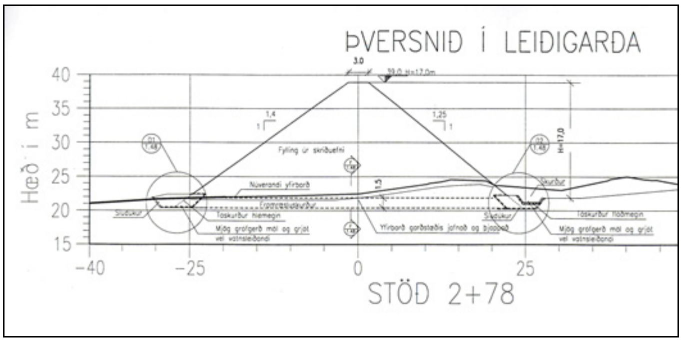

Fig. 3 Typical transverse section of dike.

INVESTIGATIONS

Prior to the final design of the dikes test pits were excavated in the mountain slope with samples obtained for classification and testing. The test pits excavated by a 25 t backhoe were scattered in the slope so as to best reflect the prevailing conditions, thickness of the overburden and the properties. A description of the layering and the soils in the test pits is detailed in *Table 1*. As the general layering and the materials were found to be similar in all the pits further investigations were not considered necessary. The material is a fairly typical talus with up to 45 % fines, cf. *Table 2*, common in the basalt regions of Iceland, which commonly classify as either SM or GM. The fines are non plastic, of fairly low density indicating volcanic origin. The natural moisture content was found to exceed Standard Proctor optimum by a considerable margin.

Altogether six triaxial tests were conducted on reworked samples. The samples were compacted in a mould to Standard Proctor compaction at close to optimum moisture content and placed in the triaxial cell. Three UU tests run at three different cell pressure values and three CIU tests also run at different cell pressure. The UU tests were conducted in order to check the pore pressure build up during construction and to measure the friction angle under such conditions whereas the CIU tests were performed to allow determination of the long-term stability. The main triaxial test results are detailed in *Table 3* and *4*. The sample size in the triaxial tests is about 1650 cm^3, the cross sectional area about 81 cm^2 and the height some 20 cm. The specific gravity of the mixture was found to be 30,04 kN/m^3. Note that considerable deformation was needed to fully mobilise the friction on one hand and also that a marked difference in both cohesion and friction angle was evidenced between the two types of tests.

Table 1. Description of soil in test pits

Test pit	Depth	Description
1	0-0,7 m	Brown, gravelly organic topsoil with stones
Elevation ≈ 40 m a.s.l Sample no. I	0,7-2,7 m	Brown, silty and gravelly sand w/stones. Increasing fines with depth. Increasing moisture w/depth
	2,7 m	Bottom of pit
2	0-0,5 m	Brown, gravelly organic topsoil rich in stones
Elevation ≈ 55 m a.s.l Sample no. II	0,5-2,6 m	Brown, sandy, silty gravel w/angular stones Less stones and increasing fines with depth. Stones rounded to semi rounded
	2,6 m	Bottom of pit
3	0-0,5 m	Brown, gravelly organic topsoil with stones
Elevation ≈ 70 m a.s.l Sample no. III	0,5-2,6 m	Brown, silty and gravelly sand w/ stones. Increasing fines and stones with depth
	2,6 m	Bottom of pit
4	0-0,4 m	Brown, gravelly organic topsoil with stones
Elevation ≈ 90 m a.s.l Sample no. IV.1 and IV.2	0,4-2,6 m	Brown, silty and gravelly sand w/ stones. Increasing moisture and fines with depth
	2,6 m	Bottom of pit (probably close to groundwater table)

Table 2. Properties of soil in test pits

Sample no	Moisture cont. %	Matr'l d <19 mm	USCS
I	28,5	30,4	GM
II	17,7	24,9	GM
III	26,9	29,2	SM
IV.1	19,1	21,0	GM
IV.2	35,0	43,1	SM

Table 3. Results from triaxial tests

Sample no.	Triaxial test	Moisture content %	Cell press. kPa	Density kN/m³ Wet	dry	Porosity %
II/III mix.	UU-1	28,4	50	20,34	15,91	47,0
"	UU-2	17,7	100	20,17	15,72	47,7
"	UU-3	26,9	150	20,16	15,70	47,7
"	CIU-1	27,7-26,0	50	20,60	16,35	45,6
"	CIU-2	28,0-25,9	100	20,62	16,38	45,5
"	CIU-3	28,4-25,7	150	20,65	16,43	45,3

Table 4 Results from triaxial tests

Sample no.	φ' °	c' kPa	ε %	c_v cm²/min
II/III mix.	35,2	15,3	4,3	
"	37,6	14,9	2,3	
"	35,5	17,2	3,5	
"	41,3	10,6	2,9	1,0
"	40,2	12,4	3,5	1,0
"	40,5	13,2	4,2	1,4

Based on the testing, economic and environmental constraints it was concluded to use the talus for the construction. It was however acknowledged allowing a low factor of safety difficulties might be encountered during construction. However, other potential construction materials, albeit limited, were available in the general vicinity. These comprising on one hand sandy gravel, and fairly uniform fine grained sand on the other, could at least be used for drainage layers in case of e.g. unfavourable weather conditions.

STABILITY ANALYSIS

A deflecting dike is believed to be most effective if it is steep on the upstream side. Increased steepness serves additionally to reduce the volume of the dams and should therefore be cost effective. With the dams located somewhat askew to the mountain slope cf. *fig. 2*, a probable failure surface, being perpendicular to the slope, will in reality have an inclination that differs from that perpendicular to the dam's axis. This was utilised in the design to the extent practicable. However, stability analysis showed, that considerable draining of the proposed construction material was at least desirable if not necessary to construct the dam to the designed slope and additionally to reduce the subsequent settlements. Thus in order for the dam to be constructed at a 1:1.25 slope, i.e. the effective failure plane sloping 1:1.3 to 1.35, the construction material should have to drain considerably. Otherwise measures should have to be taken to ensure drainage. The required long-term factor of safety of approximately 1.2 could only be achieved with this talus materials upon some drainage. To enhance this, trenches as deep as practicable into the fan were excavated in the proposed borrow areas at the earliest possibility.

Furthermore, the stability analyses indicated that an avalanche side slope of 1 vertical to 1.25 horizontal might be achieved, albeit with a calculated factor of safety by about 1,05 during the construction period. In this context it is important to note;

- the construction was to extend over two summers
- the constructor was at site to mitigate and amend possible damages.

Thus such a low F_S might be justified and tolerated in that period. The slope on the lee side was selected 1 vert. to 1.4 hor. favouring e.g. that "poorer" materials be placed there.

The dikes were to be constructed with a crest width of 3 m and a camber of 1 %. One of the possibilities considered to achieve the preferred slopes was to initially construct these to another and lesser inclination and steepen them when the necessary degree of draining of the construction materials has been reached. This however was not realised as e.g. the overall size of the work allowed certain distribution and flexibility.

Springs existing in the mountain slope in the proposed dikes' foundation were collected into trenches and the water conveyed down-slope beyond the dikes. Additionally, in order to further ensure the safety of the dikes, a trench was excavated in the toe on the avalanche side. This was refilled with free-draining materials and the water conveyed into existing springs beyond the dikes.

An additional concern was the construction of the "bow", i.e. the upslope connection of the two dikes, where the effective slope was 1:1,25. It was considered that this might be achieved through selection and the placement of boulders which could be furnished by screening in the borrow areas.

Finally in order to ensure acceptable safety during construction this might be partly achieved by selecting the materials in the borrow areas and place the coarser portions on the avalanche side.

CONSTRUCTION

The construction work of the dam structures began with the excavation of trenches adjacent to and in the dike foundation and the borrow areas, to drain these to the extent possible as well as to divert possible inflow of groundwater. This was followed by the stripping of some or all of the organic topsoil from the dams' foundation.
In order to ensure a stable structure at all stages, the foundation of the training dikes needed to be drained. The draining was achieved through longitudinal as well as transverse trenches, refilled with free-draining material, embedded in non-woven geo-textile as needed. These trenches reached into the relatively free-draining layer in the foundation, which however are somewhat discontinuous in the slope. As excavation in the borrow areas progressed the trenches initially excavated there were extended further and deeper into the fan. This potentially served to increase the stability of the dikes and favoured construction traffic, which at times was very difficult, even on foot. As it turned out, the two summers of construction were extremely wet, requiring measures to mitigate the effects.

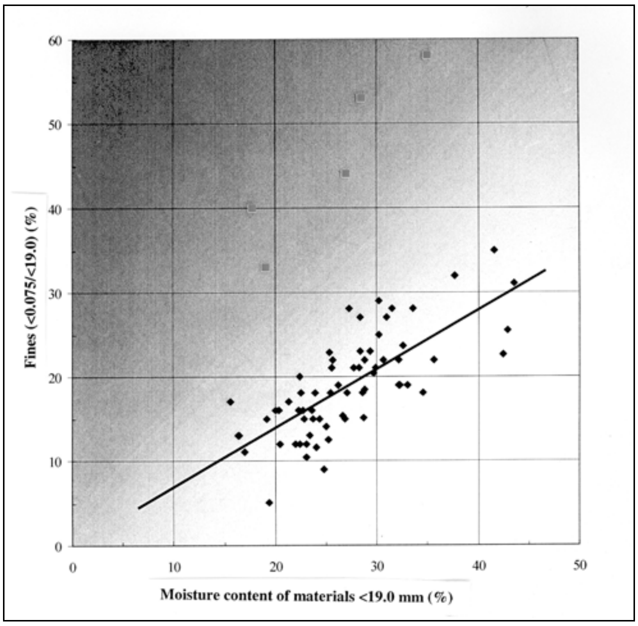

Fig. 4. Fines – moisture content relation in the fill.

During the construction it became evident that the pre-construction site investigation and testing had not been entirely conclusive inasmuch that variability in the borrow areas was greater than was concluded from the test pits, both as regards amounts of fines and the moisture content, with the first lower and consequently also the latter. *Figure 4* displays the fines – moisture content relation in the fill. Additionally, the amount of stones and boulders was higher than anticipated. This however affected the properties of the construction materials only to a minor degree as these were still governed by the fines. Still, the natural moisture content was at or very close to saturation and thus exceeded the Standard Proctor optimum by a considerable margin. The moisture content was even further accentuated by springs that emerged in the borrow areas. This resulted i.a. in that appreciable amounts of the materials in the borrow areas could not be utilized directly in the dikes and had to be substituted for by either the sandy gravel or the sand.

During construction the classification and moisture content was mostly regularly monitored. Additionally, Standard Proctor compaction tests were sporadically conducted with the coefficient of permeability measured at the corresponding densities. The difference in permeability coefficient between the gravel and the fill amounted some three to four orders of magnitude.

The moisture content of the talus materials ranged from 20 to 40 % but measured most commonly 30 to 40 %.

The total quantities in the construction of the training dikes and appurtenances are detailed in the following table.

Table 5.

Item	Estimated quantity	Executed quantity
Excavation in foundation	70.000 m³	83.000 m³
Fills	640.000 m³	727.000 m³
Trenches in foundation	1.600 m	2.400 m
Conditioning of borrow areas	210.000 m²	20.000 m²

The fills were excavated with large backhoes or pay-loaders in the talus adjacent to the dikes and hauled laterally into these to the extent practicable by some 35 t trucks. Upon emptying of the trucks, which at least at times only could maneuver to a limited degree on the dikes due to the very high moisture content, a relatively small dozer on wide belts was used to spread the fill. Additionally when possible, other heavy dozers on smaller belts were used to spread and drive on the fills. This traffic provided the only compaction of the fills in the dikes. Consequently, appreciable settlements, partly differential were expected although these should be somewhat counteracted by the relatively long construction period which allowed a considerable portion of the primary settlement to take place in that period and thus that the dikes to be constructed accordingly.

At the end of construction the dikes were covered with very large fishing nets for stabilisation and sprayed with grass seed mixed with fertilizer.

In summary; although weather conditions throughout the construction period proved to be relatively unfavourable with more than average amounts of precipitation, mostly rain and that during construction more water emerged in the borrow areas than presumed, the work was mostly completed on time. As it turned out the dikes were constructed mostly considerably higher, on the average about 0,7 m not counting the camber, than designed.

EXPERIENCE

The dikes are mostly covered with grass and blend favourably into the mountain slope although unquestionably prominent there. Trees have been planted somewhat randomly in the slopes of the dikes. The growing of these will however be a long-term process, given the prevailing climatic conditions.

Settlements of the dikes was measured about two years after their construction. The average total settlement then amounted 0,29 m i.e. about 1,5 % from the design height. The distribution of the settlement along the dikes was considerable as could be expected with the difference in conditions; materials moisture and composition, handling and foundation conditions.
A minor sloughing occurred at one location near the down-slope end of the inner dike. This covered an area of some 300 m² with a total volume of about 100 m³. Other smaller occurrences have been noted all however very minor and mostly in the lower lying portions of the dikes.

An avalanche of considerable proportions hit the eastern dike the 21 February 1999 and was deflected into the sea. Shortly thereafter snowing stopped allowing extensive evaluation of the avalanche, its origin, route and extent. In short, there were markings of the avalanche on the dike up to about 80 % of its height. Calculations on the predicted extent of the avalanche based on the observed information indicated that without the dike the flood should have reached the uppermost houses in the village.

Another avalanche of considerable proportions hit the western side of the dikes the 28 February 2000 and was deflected into the sea. That avalanche is also believed to have reached the uppermost houses in the absence of the dikes.

In view of the frequency of snow avalanches here it has been decided to establish a radar on the dikes in order to register the velocity of the avalanche and as may apply other properties.

SUMMARY

Following the catastrophic avalanche in the village Flateyri, 26 October, 1995, VST Consulting engineers Ltd. were asked to review its avalanche defences. In February 1996 NGI joined VST in the evaluation of the avalanche hazard and an appraisal of avalanche defences for the village.

Although the October avalanche was quite large with an estimated return period of 100-200 years, avalanches with longer run-out may be expected. The proposed defences were designed for an avalanche with about 150 m longer run-out than that of the October avalanche, corresponding to an estimated return period of 500-1000 years. It is believed that with these design criteria, the risk level in the village will be within $0{,}2 \cdot 10^{-4}$ per year.

The proposed defences consist of two deflecting dams, located just above the village and connecting at the top at an elevation of around 100 m a.s.l., together with a catching dam between them at an elevation around 10-15 m a.s.l. Additionally, extensive reshaping of the talus fans on each side of the dams was proposed to channelise avalanches away from the village.

The main inherent significant data are:

Length of training dikes:	1200 m
Length of catching dike:	350 m
Height of training dikes:	15 - 20 m
Height of catching dike:	10 m
Total volume of fill:	670.000 m^3
Total excavated area:	210.000 m^2

The engineers estimated total cost of the dikes amounted 394 MISK (million Icelandic krónur) inclusive contractor cost and contingencies, design and supervision. This corresponds to somewhat less than 6 MUSD. However the construction was tendered out and lowest bid proved to be considerably less than the engineers estimate.

The total value of all properties at Flateyri is estimated as 2200 MISK. It may be argued that all properties at Flateyri will be defended by the dams, as such a large part of the village is within the hazard zone that the remaining part would not be able to function independently.

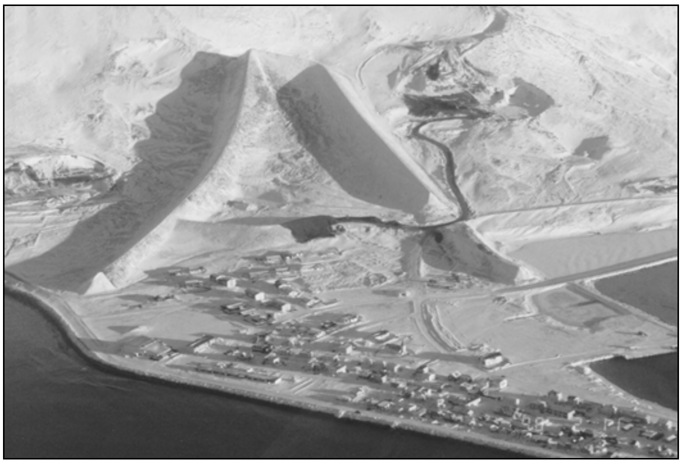

Fig. 5. A view of Flateyri during dikes´construction.

Fig. 6. A view of Flateyri with the defences near completion.

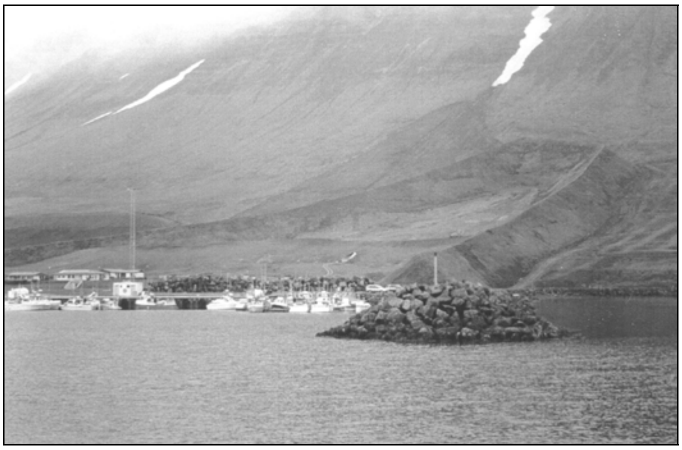

Fig. 7. A view of the training dikes after completion.

Fig. 8. Side view of downslope outer dike, note dam toe.

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