Veðurstofa Íslands
Report

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Minutes from a meeting about avalanche protection for Neskaupstaður held at Hótel Egilsbúð on 4 and 5 September 1997

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1. General

The people who attended the meeting were Flosi Sigurðsson and Gunnar Guðni Tómasson from VST Consulting Engineers Ltd. (VST), Francois Rapin from Cemagref in France, Karstein Lied from Norges Geotekniske Institutt in Norway (NGI), Stefan Margreth from Eidgenössisches Institut für Schnee- und Lawinenforschung in Switzerland (EISLF), Josef Hopf from Austria, Tómas Jóhannesson and Sigurður Kiernan from the Icelandic Meteorological Office (IMO), Óskar Valdimarsson from the Government Construction Contracts and Guðmundur Helgi Sigfússon, the local community engineer in Neskaupstaður, who participated in a part of the meeting.

The purpose of the meeting was to discuss possible avalanche protection measures for Neskaupstaður, in particular preliminary protection ideas of the VST/Cemagref work group which is working on an appraisal of avalanche protection measures for Neskaupstaður, especially for the Drangagil area. Presentations were given about the avalanche problems and avalanche history of Neskaupstaður, the supporting structure experiment in Siglufjörður, the overall protection plan of VST/Cemagref for the whole town, results of geological investigations, protection measures for Drangagil proposed by VST/Cemagref, proposed design assumptions including design avalanches, design snow depth for supporting structures and determination of dam height from computed avalanche velocities (see attached agenda for meeting). The first half of the second day of the meeting was used for field examination of conditions in the lower part of the mountain and in the starting zone above Drangagil. The discussions following the presentations and discussions during the examination of field conditions will not be described in detail here, but a summary of the main points brought up by the participants will be given.

2. Avalanche conditions / avalanche history

Tómas Jóhannesson started the meeting by summarising the avalanche problems and the avalanche history of Neskaupstaður. His main points were the following:

The scale of the problem

1. The main residential area in Neskaupstaður is approximately 2.7 km wide along the shore.
2. There are 5 main gullies with large potential starting zones directly over the main residential area (not counting the Urðarbotnar area).
3. The recorded avalanche history includes several large events with estimated volumes of many hundred thousand m^3.
4. Highlights of the avalanche history:
    - An avalanche from the Tröllagil gullies reached into the ocean in 1894 in an area where there are currently 4 rows of residential and other buildings.
    - An avalanche from Drangagil in 1894 reached 300 m into the currently populated area
    - An avalanche from Nesgil in 1974 reached within 80-150 m of the town and an avalanche from Bakkagil in the same year almost reached the uppermost houses.
    - Avalanches from Miðstrandargil and Bræðslugjár in 1974 claimed 12 lives. These avalanche paths are to the west of the main residential area of Neskaupstaður and outside the area where protection measures are now being considered.

Comparison with other endangered towns in Iceland

The number of inhabitants/buildings in several Icelandic town threatened by avalanches is given in the following table.

Town/village	approx. total # of inhabitants, in 1994	# of "endangered" residential apartments	width of "endangered" resid. area (m)
Neskaupstaður	1600	514	2700
Siglufjörður	1700	455	1750
Patreksfjörður	900	172	1450
Ísafjörður/Hnífsdalur	3500	146	1850
Flateyri[1]	400	≈100	450
Seyðisfjörður	900	89	800
Bolungarvík	1100	53	450
Bíldudalur	300	52	450
Súðavík[2]	200	?	?

The number of apartments and the width of the residential areas are derived from data collected for the "overview report" published by IMO in 1996. Only residential areas where explicit defences were proposed in the report are included. Areas where low dams, primarily intended for slush flow or debris flows, that were proposed in the report are not included.

The situation in Neskaupstaður compared with other endangered towns in Iceland

1. The frequency of avalanches with comparable size appears to be much lower in Neskaupstaður than in the main avalanche paths in Vestfirðir (by a factor on the order of 5-10).
2. In spite of this, the location of the uppermost buildings close to the mountain leads to avalanche risk which is on the same order as for the more dangerous areas of the other towns.
3. The characteristics of the different avalanche paths in the other towns are usually to some extent different from path to path so a combination of several different avalanche protection solutions may be expected to be appropriate.
4. The main avalanche paths in many of the other towns are near the margin of the town making deflecting dams an option for avalanche defences without the need to sacrifice buildings to make "corridors" through the populated area.
5. The situation in Neskaupstaður is, however, more uniform along the length of the entire town, although there are substantial variations in the degree of danger.
6. The total size of the starting zones above Neskaupstaður and the width of the area of the town that is exposed to the main avalanche paths is larger than in any of the other towns.
7. Evacuation of buildings under extreme avalanche conditions is more problematic for Neskaupstaður than for any of the other towns.

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1 Avalanche protection measures consisting of deflecting dams are currently under construction at Flateyri.

2 Endangered residential buildings in Súðavík have been purchased by the government and a new residential area has been developed further to the south in Álftafjörður.

Climate of Neskaupstaður, 1975-1995

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average temp. (°C)	-0.31	0.42	0.58	1.91	4.66	8.01	9.92	9.67	6.77	4.06	1.64	0.43	4.00
Accumul. precip. (mm)	193	149	190	92	93	75	89	110	169	255	182	168	1765
Snow (mm)	49	28	42	16	10	0	0	0	0	9	23	44	221
Sleet (mm)	99	61	69	45	27	3	0	0	17	55	55	53	484
Mxdpr. (mm)	116	59	66	104	88	98	186	96	119	154	91	88	186

Mxdpr is the maximum recorded precipitation during one day.

The meteorological station in Neskaupstaður has only been in operation since 1974. For comparison the following table lists the climatology of the standard 30 year period 1961-1990 for the nearby meteorological station Dalatangi.

Climate of Dalatangi, 1961-1990

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average temp. (°C)	0.3	0.6	0.1	1.4	3.3	6.2	8.0	8.3	6.6	4.5	1.8	0.6	3.5
Precip. (mm)	135	103	116	87	93	87	97	114	160	169	129	121	1410
Snow (mm)	30	28	33	22	13	0	0	0	1	6	28	37	198
Sleet (mm)	75	53	55	43	37	4	0	1	33	64	51	57	473
Mxdpr. (mm)	84	86	66	71	78	74	149	100	160	200	87	45	200

Snow depth measurements in the mountain above Neskaupstaður

Snow depth has been measured since the winter of 1993/94. Maximum vertical snow depth at the stakes is estimated between 3.5 and 4 m. The 3 m high stakes used in the initial years were oversnowed at the time of maximum snow depth. They have been replaced with longer stakes.

3. General discussion of design assumptions, avalanche risk and return periods

Acceptable risk and design criteria of avalanche protection measures in different countries were discussed during the meeting. Óskar Valdimarsson asked what where the main hazard mapping and design principles in other countries. The following summary is in part based on additional information from the participants after they returned home after the meeting.

Icelandic authorities have decided that avalanche hazard maps shall be based on an acceptable risk of 0.2 fatal accidents per year per 10000 persons. This decision has not yet been formalised in a law or a regulation and it is possible that it will be changed when a formal regulation is worked out by the authorities. The goal of avalanche protection measures is to reach the same risk level after the construction of the protection measures. Explicit or detailed computation of avalanche risk after the construction of protection measures is, however, in general not possible with current scientific knowledge of avalanches. Therefore, the design of the protection measures must in part be based on subjective judgement of avalanche experts with the official risk goal in mind. A general decision has not been made whether the risk level can partly by reached by evacuations after protection measures are implemented, but this possibility has not been excluded and must be considered on a case by case basis during the design of protection measures.

3.1 Norway (Karstein Lied)

Avalanche hazard maps and avalanche protection measures in Norway are based on a classification of buildings into three classes according to the following table.

Safety Class	Consequences of Structural Failure	Highest Nominal, Annual Probability of Natural Hazards	Categories of Buildings
1	Less serious	10^{-2}	— Garages for max. 2 cars, boat houses etc. — Storage sheds occasionally in use — Halls of plastic-based fabrics — Agricultural buildings etc., if frequently used class 2 or 3
2	Serious	10^{-3}	— Buildings not exceeding two storeys of moderate span and in normal use — Industrial and storage buildings of one storey not accessible to general public, with ≤ 5 persons per 100 m². Distance to other buildings, roads etc. ≥ height of the facade — Tall masts, independent towers, silos and chimneys outside of built up areas
3	Extremely serious	$< 10^{-3}$	— Buildings not included in class 1 & 2.

Table 1: Safety requirements for the location of Buildings

"The tolerated nominal annual probability for hazards to buildings in safety class 3 ($<10^{-3}$) should be decided on according to the stipulated total risk due to natural hazard. The higher the consequences the lower the probability of hazard should be allowed. The Municipal Building Committees shall approve the highest nominal annual probability of hazard in these cases. Buildings of safety class 2 and 3, which already exist within hazardous areas, may be rehabilitated or rebuilt. However, the highest nominal annual probability of hazards should not exceed $3x10^{-3}$ in class 2 and 10^{-3} in class 3. As indicated in the general clause, buildings and their outside areas may also be dimensioned or otherwise secured so that the specific safety standard is fulfilled."

In the case of snow avalanches, these regulations are interpreted such that the lower limit of the hazard zone is defined as a line where the nominal probability of an avalanche reaching beyond the line at a particular location is 10^{-3} per year for ordinary residential houses. Design avalanches for determination of the dimensions of protection measures for such buildings are furthermore defined to be avalanches with a 1000 year return period. The word "nominal" indicates that it is not always possible to compute the indicated probability in an explicit way and both the hazard map and the design avalanches must be determined in part by a subjective evaluation. The height of supporting structures in Norway is based on a subjective estimate of an appropriate snow depth. The total amount of supporting structures in Norway is small compared with Switzerland and Austria.

3.2 Switzerland (Stefan Margreth)

Avalanche hazard maps in Switzerland are mainly based on avalanches with a 300 year return period. Zones where the 300 year avalanche has a impact pressure over 30kN/m² or which can be reached by avalanches with a return period of less than 30 years are coloured red. Zones within the reach of the 300 year avalanche are coloured blue. In addition, zones may be coloured yellow based on estimated risk due to powder snow avalanches. New buildings are prohibited in the red zone. New buildings in the blue zone must be reinforced to withstand the avalanche pressure. The return period of the Swiss regulations refers to an avalanche which reaches a certain runout distance within an avalanche path irrespective of the width of the path. This is different from the definition of the return period in the Norwegian regulations which is based on the probability of an avalanche reaching a fixed location in the runout zone. Since the tongues of avalanches often have a pointed shape and do not overrun the entire width of a typical avalanche path, the Swiss definition of a 300 year avalanche corresponds to an avalanche with a somewhat longer return period according to the Norwegian definition. The hazard zones in Switzerland are, furthermore, based on the runout distance of an avalanche with a fracture depth equal to the three day snow fall with a 300 year return period. This extreme snow depth does not necessarily lead to the release of an avalanche every time. The effect of the different definitions of return periods can be large enough to substantially reduce the difference between the Swiss and the Norwegian regulations.

The height of supporting structures in Switzerland is based on an estimate of the 100 year snow depth in the starting zone. Official guidelines specify the appropriate 100 year snow depth for different regions in Switzerland as a function of height above sea level and the aspect of the starting zone. Hazard maps are sometimes revised after the construction of supporting structures by estimating the runout distance of an avalanche with a fracture line thickness equal to the difference between the estimated 300 and 100 year snow depths. Another possibility which is also sometimes used is to modify the hazard map based on an estimate of the runout distance of an avalanche with a fracture line thickness equal to a three day snow fall with a three year return period. Hazard maps are in general not revised until several years after the construction of protection measures.

Deflectors and catching dams in Switzerland for the protection of residential houses are dimensioned on the basis of design avalanches with a return period of 300 years, Defence structures for other constructions may be designed on the basis of shorter returns periods, *e.g.* ≈50 years for electrical power lines.

3.3 Austria (Josef Hopf with additional information from a paper by Siegfried Sauermoser)

Avalanche hazard maps and avalanche protection measures in Austria are based on design avalanches with roughly a 150 year return period where the return period is defined in the same way as in Switzerland. Zones where the 150 year avalanche has a impact pressure over 25kN/m^2 and also areas with small but frequent avalanche events are coloured red. Thus, the Red Zone is endangered to such an extent that its permanent utilisation for settlements and infrastructure is not possible. Zones within the reach of the 150 year avalanche with pressures below 25kN/m^2 are coloured yellow. Here, new buildings and infrastructures are allowed in areas which are already partly settled but they have to be protected by reinforcement and special architectural designing. In non-settled yellow areas, the avalanche danger has to be eliminated by technical protective measures before dedication as a settlement area but public funds are not available for this purpose. In addition to snow avalanches, hazard maps in Austria take into account risk due to floods and debris flows in Red and Yellow Zones. Brown Zones are used to characterise areas with other natural hazards such as rock fall and landslides. Blue Zones have a special importance with regard to current or possible future avalanche protection measures.

The height of supporting structures in Austria is based on estimated snow depth with a return period of "more than" 100 years. Deflectors and catching dams are also dimensioned on the basis of a design avalanche with a return period of "more than" 100 years, that is in practice essentially the same assumption as used in the hazard zoning.

3.4 France (Francois Rapin)
Hazard zones in France are outlined by subjective evaluation of avalanche experts based on the recorded runout of historic avalanches. The height of supporting structures in France is also based on a subjective estimate of an appropriate snow depth, sometimes using the design principles of the Swiss Guidelines.

3.5 Avalanche risk in hazard zones in other countries (all participants, additional information compiled by Tómas Jóhannesson and Stefan Margreth)
Considerable time during the meeting was used for discussing the real risk (*e.g.* in terms of number of fatal accidents per year per 10000 persons) which the population of hazard zones and defended areas in Austria, France, Norway and Switzerland are exposed to. The central question in this discussion is whether the 100-300 year avalanches on which hazard zones and defence structures in Austria or Switzerland are based are systematically biased so that the safety of the people is in fact higher than would be expected if avalanches overrun the zones with the implied frequency. This question is relevant for the interpretation of the decision to use an acceptable risk of 0.2 fatal accidents per year per 10000 persons as a basis for hazard maps and defence structures in Iceland.

According to information compiled by Stefan Margreth after the meeting, there are 10000-15000 residential houses in red and blue hazard zones in Switzerland. Between 3000 and 4000 of these residential houses are located in red zones. Including farm buildings, vacation houses and other buildings without inhabitants or with only part time occupation during winter one may estimate that on the order of 50000 buildings are located in red and blue hazard zones in Switzerland. These number include the majority of approximately 8500 residential houses, which have been "protected" by avalanche protection measures, *e.g.* supporting structures, dams, *etc.*, but where the hazard map of the area has not been revised so that the houses are still considered a part of a hazard zone. The number of people living in these areas during winter is not available, but it may be expected that tens of thousands occupy the areas in wintertime. All these buildings should be exposed to a frequency of avalanches corresponding to a return period shorter than 300 years (according to the Swiss definition) and many of the buildings in the red zones should be exposed to avalanches corresponding to return period shorter than 30 years. Additionally, an unknown number of buildings and people outside the red and blue zones may be expected to be exposed to avalanches with a longer return period than 300 years but shorter than say 1000 years. If it is assumed that the return period of avalanches hitting particular predetermined buildings in red and blue zones in Switzerland is three times longer than the return period of avalanches reaching a predetermined runout in the avalanche paths (*cf.* the discussion in section 3.2 about the difference between the Swiss and Norwegian definitions of a return period), then the 50000 houses in the zones should be exposed to a frequency of avalanches well in excess of 10^{-3} per year (since the zones include areas where the Swiss return period is shorter than 300 years and down to shorter than 30 years in some red zones). Since avalanche warnings and evacuations have no effect on the number of buildings hit by avalanches and taking into account the short return period in red zones and that a number of buildings must be located in areas just outside the blues zones, it can be estimated that on average over 40 residential houses and in excess of 100-200 buildings should be hit by avalanches per year. According to the records, however, about 15 residential buildings per year on average were damaged by avalanches in the period 1973-1995, and in the period 1981 to 1988 about 107 buildings (residential and other buildings) per year on average where damaged by avalanches. These numbers are not easily interpreted since avalanches hitting reinforced buildings without causing damage are not recorded in Switzerland. The estimated number of residential houses hit by avalanches seems rather high though, being higher than the number of recorded damages by a factor of three. Average yearly damages to buildings in Switzerland due to avalanches in the period 1950-1993 are about 3.5 million SFr, *i.e.* 175 million IKR.

Evacuations, occupation of safe basements of residential buildings during dangerous periods and reinforcement of whole buildings are an integral part of the Swiss preparedness for avalanches. Evacuations are mainly practiced for buildings in the red zones and the more dangerous parts of the blues zones although an evacuation of the entire blue zone in an area under exceptional circumstances is conceivable. Furthermore, a large part of the population (say on the order of 50%) in the less dangerous parts of the blue zones (where the Swiss return period is nevertheless shorter than 300 years) does not live in reinforced buildings and only rarely moves to the basement during times of avalanche danger. Assuming that the probability of a fatal accident is 10-20% for each inhabitant when a non-reinforced building is hit by an avalanche, one would expect the risk of a fatal accident to be around 1-2 fatal accidents per year per 10000 persons on the border of the hazard zones, *i.e.* 5-10 times higher than the risk goal adopted in Iceland, and perhaps even higher on average within the hazard zones. This estimate is not much different from risk estimates at the lower limit of the Blue Zone in Switzerland that have recently been published (yearly risk of 1.6 per 10000 according to "The development of avalanche risk in Switzerland" by Christian Wilhelm). Large areas with tens of thousands of inhabitants outside the blue zones, where buildings are not reinforced and evacuations hardly occur, may furthermore be expected to be exposed to a risk of about 1 fatal accident per year per 10000 persons. Assuming that avalanche warnings and evacuations do not substantially alter the situation beyond what is described above (*i.e.* that inhabitants in large parts of the Blue Zones and the areas just outside the Blue Zones are still at risk), this leads to the expectation that on average on the order of 10 persons per year should be killed in populated areas in Switzerland,

Fatal avalanche accidents in residential areas in Switzerland in the past decades tend to be concentrated in particularly "bad" winters with high avalanche activity, *i.e.* the winters of 1967/68, 1970/71, 1974/75, 1983/84 when between 10 and 40 people were killed in populated areas in Switzerland in each winter. The number of fatalities in other winters than the "bad" winters is typically lower than 5 and only one person was killed in the entire decade from 1986 to 1995. The average number of fatalities during the 20 years from 1976 to 1995, which included the "bad" winter 1983/84, was 0.7 fatal accidents per year in houses and 1.8 fatal accidents per year in residential areas (both inside and outside houses). The number of accidents per year appears do have gone down with each decade in recent decades parallel with the construction of avalanche protection measures on a large scale together with an effective avalanche warning system. Since about 1970 the use of avalanche prone terrain for new buildings in Switzerland has become smaller than the area protected by the construction of avalanche protection measures each year. The very low number of fatalities in the last decade, may, however, partly be due the fact that no "bad" avalanche winter occurred in this decade.

Considering that

1. Tens of thousands of people in Switzerland live in hazard zones where estimated return periods of avalanches are shorter than 300 years (Swiss definition).
2. Evacuations, reinforced buildings, avalanche protection measures, avalanche warnings and artificial release of avalanches reduce the danger in the most dangerous parts of the zones, *e.g.* the red zones and the upper parts of the blue zones, but can nevertheless not be expected to reduce the average risk facing the inhabitants of the hazard zones below the risk at the lower limit of the blue zone.
3. Avalanche defence structures are designed with the aim of lowering the return period of avalanches reaching the uppermost defended buildings to 300 years. If this design is unbiased then one may expect a large number of populated buildings to be exposed to avalanches with a

return period close to 300 years even after the construction of defence structures is completed.

4. Additional tens of thousands of people in Switzerland live in areas where return periods of avalanches may be expected to be shorter than 1000 years (but longer than 300 years) where neither evacuations nor reinforcement of buildings can be expected to reduce the risk.
5. During the last 20 years the average number of fatal accidents in populated areas in Switzerland is below 1-2 per year and the construction of defence structures during this period may have decreased the frequency of fatal accidents below this average although this is not certain.

it appears likely that *in practice* hazard zoning and avalanche protection design principles in Switzerland lead to avalanche risk at the border of the hazard zones that is considerably lower than 1 fatal accident per year per 10000 persons. It is, however, not possible to say whether the risk is as low as 0.2 fatal accident per year per 10000 persons, which is the Icelandic goal. This may be possible if the large drop in the number of fatal accidents in Switzerland in the two recent decades reflects a permanent change as a consequence of the buildup of avalanche protection measures and an improvement in avalanche warnings. In any case it is clear that the combined Swiss system of hazard zoning, avalanche protection measures, reinforced buildings *and* avalanche warnings have during the last two decades resulted in a risk which is well below 1 fatal accident per year per 10000 persons for the tens of thousands of inhabitants in avalanche hazard zones in Switzerland. The Swiss Guidelines from 1984 estimate the current (*i.e.* 1984) level of risk for fatal accidents due to avalanches in hazard zones in Switzerland as roughly 10^{-8} per hour (equivalent to about 10^{-4} per year). The guidelines then say "Die jeweilingen Reaktionen der Oeffentlichkeit zeigen, dass dieses Risiko nicht toleriert wird".

Similar information about the population of hazard zones and the number of fatal accidents in populated areas in Austria, France and Norway was not available at the meeting. Fatal avalanche accidents in populated areas in Austria and France are equally rare as in Switzerland, *i.e.* on the order of 1 per year. The number of people in hazard zones and zones which are defended with avalanche defence structures in Austria may be expected to be smaller but on the same order of magnitude as in Switzerland, whereas these zones are much smaller in France and Norway.

Another way to view the question of acceptable avalanche risk in populated areas in Alpine countries is to consider the hypothetical situation if it were to turn out that the risk in the hazard zones and defended areas in Switzerland was in fact on the order of 1 fatal accident per year per 10000 persons. In this case one could for example discover after 10-20 years from now that the period 1976-1995 had an abnormally low number of avalanche accidents in populated areas and the situation would turn to a "more normal" rate of accidents similar to or slightly lower than was the case in the period 1956-1975. Assuming that tens of thousand of people in Switzerland were exposed to this risk and considering the spiky distribution of avalanche accidents, this could mean that several people, say 1-4, would be killed in an ordinary year and "bad" years with 10-15 fatalities might occur approximately once per decade. In Austria, one would probably be looking at somewhat lower numbers. The question of acceptable avalanche risk in the Alpine countries can then perhaps be considered in terms of the probable response of these societies to such a situation. Both Stefan Margreth and Josef Hopf expect that this situation would be considered untolerable and the response would be an intensification in the construction of protection measures and/or evacuations to reduce the number of accidents. In both countries one may expect a willingness to make a substantial financial contributions or other efforts to improve such a situation if it were to occur. This is equivalent to saying that an acceptable level of risk in these countries may be expected to be substantially lower than 1 fatal accident per year per 10000 persons, which is also implied by the above quote from the Swiss Guidelines from 1984. One must, nevertheless, realise that acceptable avalanche risk for populated areas is not a well defined mathematical quantity which can be derived by arguments as presented above. It is a political decision of each country which may in part be based on the above considerations.

3.6 Supporting structures and avalanche frequency (all participants)
The relation between the design snow depth and the height of supporting structures and the rest risk of the defended area after structures are built was discussed after the foreign participants had described the hazard mapping and design principles of their corresponding countries. It was noted by Karstein Lied that extreme avalanches are typically only released from some avalanche paths in an area during avalanche cycles. It was also noted that avalanche cycles do not necessarily occur in years of extreme snow depth although this may of course happen. For these reasons, the return period of extreme avalanches from a particular path is much longer than the return period of snow depth exceeding the height of supporting structures in the starting zone of the path. Quantitative computation of the frequency of avalanches from a starting zone after the construction of supporting structures is, however, not easy, although such computations are used in the revision of hazard maps in Switzerland as described above. Supporting structures in Austria, France, Norway and Switzerland are designed with respect to snow depth with a return period on the order of 100 years. As discussed above this practice seems to reduce the frequency of avalanches to the extent that the risk after the construction of defence structures is as low as described above for Switzerland.

3.7 Fatal accidents in Iceland
For comparison with the above statistics a total of 52 people were killed by avalanches in buildings, at work sites or within towns in Iceland in the 22 year period between 1974 and 1995 and a total of 107 persons have been killed during this century.

3.8 Avalanche risk in Neskaupstaður
Computations by Kristján Jónasson and Þorsteinn Arnalds of IMO indicate that the risk due to avalanches below Drangagil is around 20 per year per 10000 persons at the uppermost houses and around 5 per year per 10000 persons near the coast. Gunnar Guðni Tómasson presented risk computations which indicated similar risk.

4. Overall protection plan
Francois Rapin described the ideas of the VST/Cemagref work group for a protection plan for the whole town. The protection would consist of a complex of catching dams along the entire slope from Bakkagil to Tröllagil, breaking mounds arranged in two or three rows above the dams below Drangagil and Tröllagil and supporting structures covering a part of the starting zones in Drangagil and Tröllagil. After the meeting the possibility of breaking mounds in combination with dams below Nesgil and Bakkagil has also been mentioned. Additionally, a deflector would possibly be constructed below Stóralækjargil at the eastern margin of the town. Rapin explained that inhabitants in Neskaupstaður have expressed the wish that, if possible, they would prefer a solution consisting of supporting structures with as little modification of landscape and vegetation in the lower part of the slope as possible. Because of the level of the Icelandic protection goal, he said that the work group had nevertheless come to the conclusion that dams would be a necessary part of an avalanche protection for Neskaupstaður because of the large starting zones and difficult foundation conditions in a part of the mountain, *e.g.* Urðarbotnar and parts of Drangagil.

Óskar Valdimarsson mentioned that some inhabitants were appalled by the first ideas of the size of the proposed dams and asked whether it would be practical to decrease the dams by accepting somewhat higher rest risk and possibly by using evacuations in order to reduce the risk of fatal accidents. There was general agreement around the table that catching dams would necessarily have to be quite high, *i.e.* minimally 15 m as a rough estimate, and dams much lower than this would not be considered a valid part of a solution of the problem in other countries unless supporting structures were constructed in the entire starting zones.

Óskar also asked whether it would be possible to combine a lower dam with reinforcement of the existing houses to increase the safety of inhabitants in the case the dam would be overrun by an avalanche. This was not considered a viable solution. The reinforcement of the buildings may be expected to be on a similar cost level as the construction of new houses. If an essentially new house is to be built it makes more sense to move it to a safer location than to build it in a location of high avalanche risk. Stefan Margreth mentioned that the additional cost of reinforcing a house at the time of initial construction is 10-20% of the total building cost according to Swiss experience. Such buildings are designed to withstand an impact pressure of 10-30 kN/m^2. This cost is much higher if an existing poorly constructed building is to be strengthened. Flosi Sigurðsson mentioned that VST had, in a report for "Ofanflóðanefnd" two years ago, estimated the additional cost of strengthening some selected buildings at the time of initial construction, for withstanding an impact pressure up to 30 kN/m^2. The total cost increase due to the strengthening was estimated to be about 3-5% for a typical Icelandic one story (above ground) residential house, 7-10% for a three story apartment building and around 10% for a one story industrial building. These computations apply to reinforced concrete houses. The cost increase resulting from the choice of houses made of concrete in preference to other possible types of houses, *e.g.* wood frame houses, may be higher.

Karstein Lied questioned the necessity of the deflector below Stóralækjargil. Flosi and Rapin replied that it was just mentioned as a possibility and further evaluation of this area would be needed to judge whether it was necessary or not.

Josef Hopf stressed the necessity of a formal hazard map of Neskaupstaður as a part of the design of protection measures. The proposed protection measures should be presented in the context of the possible revision of a hazard map.

Stefan Margreth remarked that the idea of *rest risk* is an important component of Swiss avalanche protection design principles. It is assumed in the design of protection measures that evacuations will provide an additional margin of safety after the construction of defence structures. He questioned whether it was practical to construct protection measures which would obtain the required level of safety without evacuations. The practical difficulties of extensive evacuations in Neskaupstaður were discussed.

The danger of repeated avalanches in the same path during the same avalanche cycle or the same winter was discussed. An initial avalanche might fill the space above a dam and a later avalanches would then be able to overrun the dam. Stefan Margreth remarked that the danger of many events in the same path within a short interval was especially relevant in paths with complex and partly separated starting zones. This is not the case for Neskaupstaður. It was agreed that it was most sensible to plan for evacuations under these conditions rather than design dams that could possibly store more than one avalanche.

Francois Rapin described the idea of VST/Cemagref of planning for the possibility that the dams below Drangagil would be hit by an avalanche larger than the design avalanche. The idea is to control any snow mass that would spill over the dam and direct it into the small gully below the dam instead of it spilling over the dam in an uncontrolled fashion. This idea received a mixed response. If the tongue of an avalanche overriding the dam is 50 m wide and extends 150 m down the creek one may estimate the volume of a 3 m thick tongue of avalanche deposits to be roughly 20.000 m^3. This is not much in comparison with the total volume of recorded avalanches. The safety improvement obtained by trying to contain a possible spillover by some measures along the banks of the creeks was, however, not much discussed.

5. Protection plan for Drangagil

Francois Rapin described the ideas of the VST/Cemagref work group for a protection plan for the area of the town below Drangagil. The previously mentioned combination of supporting structures, breaking mounds and a dam would involve 1200 m of supporting structures in the starting zone, three rows of breaking mounds with very steep upper sides and roughly a 15 m or higher catching dam with a steep upper side located about 100 m above the uppermost houses. The dam would have a curved shape in a plane view such that the ends are located somewhat further away from the houses than the middle part of the dam. The purpose of curved shape of the dam was questioned. Rapin replied that the suggested shape was partly for environmental reasons in order to avoid long straight lines in the design of the dams and also to control the lateral spreading of the avalanche masses.

Flosi Sigurðsson described the results of geological investigations in the starting zone and in the area of the proposed dam/mounds below Drangagil, Tröllagil and Nesgil. There are areas of difficult foundation conditions and rock fall danger in parts of the starting zone. In the area of the proposed dam site, the depth to a firm ground, bedrock or tillite, is about 2-5.5 m. The uppermost 2 m were mainly of highly organic material and peat below which there is a stony material mixed with sand, gravel and peat. The material below the uppermost organic soil had over 30% fines with humidity over 30% which makes the material very poor for the construction of earth structures. A great amount of mass, the peat, would have to be removed and cannot be used in a dam except for distributing it over the excavated area after the construction of structures for environmental purposes to speed up the growth of vegetation. The bedrock is close to the surface in the uppermost part of the mound site. Flosi Sigurðsson also discussed further geotechnical investigations that haven't been finished but need to be carried out, *e.g.* further search for possible fill material and rocks for the dams/mounds, soil investigations in the area of the mounds and geotechnical studies in the area of questionable soil conditions in the starting zone. Regarding the questionable area in the starting zone he asked the other participants for their comments on what they considered most important for further studies.

Karstein Lied stressed the need for a thorough geotechnical investigation, both in the starting zone and in the dam/mound site. Stefan Margreth remarked that experimental drillings and pullout tests would be carried out in Switzerland as a part of preparations of supporting structures in difficult conditions as in the starting zone above Drangagil. He did, however, not recommend such a study unless one had already made a decision to use supporting structures as a part of the protection measures.

6. Design criteria

Gunnar Guðni Tómasson described an estimate of extreme snow depth in the starting zone based on a correlation between measured snow depth in the mountain since 1993/94 with maximum monthly snow depth recorded at the meteorological stations Dalatangi, Hvannstóð and Neskaupstaður. The record from Dalatangi starts in 1964 but the other records are shorter. The computations indicate that the 50 year vertical snow depth in the mountain is between 4 and 4.5 m and the 100 year snow depth between 4.5 and 5 m, but these computations are quite uncertain. Contemporary sources from Neskaupstaður indicate that snow depth in the mountain during some winters early in the century, *e.g.* in 1910, was much higher than in recent decades, but it is impossible to interpret these reports in quantitative terms.

The formation of cornices extending from edge of the mountain was discussed. Observations in 1974 indicate that such cornices were formed in that year. Karstein Lied expressed the opinion that cornices only seldom fall down and in general do not pose a threat by themselves unless there is a sufficient amount of unstable snow in the starting zone to produce an extreme avalanche without the contribution of the cornice itself.

VST/Cemagref propose to base the dam/mound design on a design avalanche which reaches about 150 m into the ocean below Drangagil. This design avalanche corresponds to $\alpha - 1.25\sigma$ in the Norwegian α/β model (using parameters corresponding to a data set of Icelandic avalanches) and Gunnar Guðni estimates that an avalanche reaches this runout with a 2000 year return period.

Josef Höpf found a several thousand year return period hard to grasp and questioned the presentation of the design principles in these terms.

Francois Rapin presented velocity computations performed with the Swiss VSG model which indicate a velocity of 25-35 m/s between the top row of mounds and the dam for the design avalanche if no supporting structures are constructed in the starting zone. Other participants thought this velocity was lower than expected for such a large event. Rapin also presented computations that indicated the reduction of the design event through the use of supporting structures covering only a part of the starting zone. Gunnar Guðni presented velocity computations with the PCM model giving velocities for the design avalanche between the top row of mounds and the dam in the range 37-44 m/s without supporting structures and 25-32 m/s with supporting structures based on Rapin's approach for computing the resulting from the supporting structures. He noted that the assumptions behind the reduction in the size of the design event due to the supporting structure are very uncertain. The effect of the mounds on the velocity is also highly uncertain and there are neither good observational nor theoretical arguments for the current assumptions regarding this effect. With supporting structures reducing the size of the event at the top of the mounds and a velocity reduction due to the passage of the avalanche through two rows of mounds he estimated velocities at the location of the catching dam to be in the range 13-22 m/s. Assuming snow depth on the ground in the range 2-3 m and flow depth in the range 3-4 m, this yields a dam height of 9.5-19.5 m. The storage volume above a 15 m high steep dam is found to be approximately 400000 m^3 which is similar to the estimated volume of the design avalanche. This volume was thought to be reasonable by the other participants. There was not full agreement among the participants whether one should assume that avalanche deposits above the mounds would make a significant contribution to the storage volume of the combined dam/mound system.

Karstein Lied asked Stefan Margreth whether there was a consensus in Switzerland that velocities computed with the VSG model are too low compared with field measurements. Margreth confirmed this and said that speeds computed with the VSG model are increased before they are used in the design of dams by some but not all experts in avalanche protection in Switzerland. Margreth remarked that the line of thought used by Rapin to compute the reduction in the size of the design event due to the supporting structures was similar to what he had used for modelling avalanches from paths with complex starting zone geometry.

Stefan Margreth presented modelled speeds of 36 m/s at 100 m a.s.l. for an event from Drangagil reaching approximately 100 m into the ocean. The modelling was carried out with a newly developed model from Davos which is called FEM. This model yields higher velocities for the same runout distance compared with the traditional VSG model. Margreth expected that a runout roughly this far into the ocean would be considered an appropriate design avalanche in Switzerland according to Swiss design practices.

Karstein Lied presented modelled speeds of 35-44 m/s at 50-100 m a.s.l. for an event from Drangagil reaching approximately 140 m into the ocean, which he had estimated to be the $\alpha - 1\sigma$ runout (using model parameters corresponding to Norwegian avalanches). The speeds were computed with the PCM model, but the Norwegian NIS model may be expected to produce similar speeds. Lied expected that an avalanche with approximately this runout would be considered an appropriate design avalanche in Norway according to Norwegian design practices.

Francios Rapin described that the dam would be constructed with a very steep upper side using geotextiles to reinforce the slope. There was not full agreement among the participants whether steepness beyond 1:1 was cost effective compared to a higher dam with a more gentle slope. The increased effectiveness of a dam which is steeper than the internal friction angle of snow was discussed without the discussion reaching a definite conclusion. It was remarked that the very lowest part of the dam, which is assumed to be below the snow lying on the ground before the avalanche is released, would not need to be steep. Therefore, the upper part of a steep dam should perhaps be made steeper than the lower part.

Josef Hopf remarked that the danger of debris flow should also be considered in the protection plan. It was agreed that a solution involving a catching dam had the advantage that such a dam would also solve the problem of debris flows. Care would have to be taken to ensure adequate flow of water through the mounds and under the dam in such a way that problems due to erosion would not arise, but this should not pose a technical problem. Hopf recommended that the inclination of the avalanche exposed slope of the dam should be as steep as possible in order to reduce the dynamic impact of the avalanche, using stones and rocks from the excavation. The height of the dam should be at least 20 m (including the depth of the excavation) and the shape of the excavation should be such that the angle between the remaining terrain and the dam is minimised.

7. Discussion of breaking mounds

Uncertainty regarding the effect of breaking mounds on the velocity of large, dry snow avalanches was discussed, including the possibility to perform experiments to shed some light on this problem. Little real information exits on the effectiveness of breaking mounds to reduce the speed of dry snow avalanches. There is evidence from real avalanches, *e.g.* Flateyri, that low conical mounds have no effect on the speed of large, dry avalanches. The avalanche experts agreed that they would nevertheless recommend mounds above a catching dam under the conditions in Neskaupstaður, but the mounds would have to be large and wider in the transverse direction than conical mounds.

The shape and size of mounds was discussed in some detail. There was agreement that mounds should be somewhat wider than indicated on the schematic sketches of VST/Cemagref. Width in the range 10-15 m at the top was mentioned. The height should be on the order of 10 m. Josef Hopf recommended a similar distance between the mounds as the width of the mounds and a chequered placement of the mounds. He also recommended that at least 3 rows should be made and that the distance between the rows should not be more than 50 m. The avalanche exposed side of the mounds should be made as steep as possible using stones and rocks from the excavation. For environmental and technical reasons, he recommended that the mounds are made mainly from excavation in the neighbouring terrain without the use of external material. Karstein Lied recommended that the mounds in each row should be close together, *i.e.* the separation of the mounds should only be what is needed for access of vehicles through the row. He did not think very steep upper sides were crucial for the effectiveness of mounds, but mounds in the Alps are, however, often built with very steep upper sides using concrete, rocks or other methods to strengthen the upper side.

Gunnar Guðni Tómassson and Tómas Jóhannesson asked whether it would be meaningful to perform some laboratory experiments to evaluate the effectiveness of mounds. The foreign experts did not think this would be practical. Stefan Margreth mentioned that there is a laboratory "avalanche path" outside of EISLF in Davos. He did not think it was large enough to give meaningful data on the flow of large, dry avalanches through a field of breaking mounds. Josef Hopf said that this idea should, nevertheless, but followed up considering the options described above for the size and shape of mounds.

8. Discussion of powder snow avalanches

The danger of powder snow avalanches in Neskaupstaður and the extent to which this should be taken into account in an evaluation of the avalanche danger was discussed. Powder avalanches are more frequent in the high mountain in Switzerland and Austria where the snow is cold and light compared with lower lying areas in these countries. The experts thought powder avalanches are likely to be less of a threat in the temperate climate of Iceland than in the Alps. With the possible exception of the Þrastarlundur avalanche in Neskaupstaður in 1990, there are no records of damages by the powder part of an avalanche to buildings in Iceland which were not hit by the dense flow part of the avalanche. The shape of the mountain in Neskaupstaður is in general not likely to produce powder avalanches, but Stefan Margreth remarked in the field trip that powder could be generated when avalanches "jump" from the cliffs at the lower end of the starting zone in Drangagil.

The experts were of the opinion that protection measures in Neskaupstaður should focus on dense flow avalanches and dimensioning of structures should be done on the basis of such avalanches. Stefan Margreth noted that in Switzerland one would in general define a red zone of the width of at least 50 m immediately below a catching dam due to pressure effects that may be expected on the leeward side of the dam when it is hit by an avalanche.

9. Layout of supporting structures

Francois Rapin showed the other participants his suggestions for the placement of supporting structures in the starting zone in Drangagil. This involved the installation of structures in the upper part of the starting zone only, with some gaps where foundation conditions are especially difficult. The experts agreed that foundation conditions are indeed difficult in the openings where Rapin had decided not to install structures. Rapin's location of rows outside these zones of special difficulties were similar to the ideas of the other experts, but the "Swiss Guidelines" have to be considered according to Josef Hopf. Stefan Margreth and Josef Hopf remarked that they advised against the open gaps in the supporting structures. Margreth noted that one should not in his opinion rule out the installation of supporting structures there. If supporting structures will be a part of avalanche protection for Neskaupstaður he recommended that careful investigations of these areas should be performed and every effort made to install structures there.

Stefan Margreth and Josef Hopf noted that installing supporting structures in only a part of the main starting zone would not be recommended in Switzerland or Austria. They and Karstein Lied were nevertheless of the opinion that if structures could be installed in the open areas in Rapin's suggested layout then such installation of structures in the upper part of the starting zone could be a worthwhile part of avalanche protection for Drangagil. Josef Hopf was concerned about rock fall danger, especially in the uppermost part of the starting zone where supporting structures would often be damaged and maintenance would therefore be expensive. Snow nets should be used there in preference to stiff constructions, but the danger of corrosion appears to be a serious obstacle for the use of the existing types of snow nets in Iceland. These facts and the bad soil conditions in some parts of the starting zone lead to special caution concerning supporting structures in the starting zone in Drangagil according to Hopf.

10. The supporting structure experiment in Siglufjörður

Tómas Jóhannesson described preliminary results from the supporting structure experiment in Siglufjörður which was initiated last year by IMO. The main results after the first winter are the following:

1. The snow depth in the gully became very high and the structures were partly overfilled, by between 1 and 2 meters perpendicular to the slope. Therefore the structures experienced high loading in the first winter.
2. The snow density is close to 400 kg/m^3 during the winter except in the top meter. It increases to close to 500 kg/m^3 after the snow pack has become isothermal in the spring.
3. The gliding is low. Two measurements yielded 2 and 10 cm after the winter.
4. The maximum loading of the structures occurs around the time of maximum snow depth. The onset of melting leads to a sharp decrease in the loading. There are no indications of an increase in the loading due to deformation or gliding introduced by melting.
5. The galvanised wires of the nets are not sufficiently protected against corrosion. There are already indications of the onset of rusting in the wires in Siglufjörður.
6. Austrian-type ground plates need to be anchored.
7. There are problems with lateral forces in the micropile anchoring of the posts in the Geobrugg nets in loose material.

11. Other ideas

The VST/Cemagref work group mentioned the possibility of using structures other than breaking mounds to retard the speed of an avalanche. One idea is to construct jumps similar to ski jumps that the avalanche would have to jump over and in the process loose some of its energy. Such jumps are well know from spillways where they are used to disperse the kinetic energy of water flowing down the spillway (ski jump spillway). The loss of energy through such a jump may be up to 70%. Lied, Margreth and Hopf did not find it likely such a structure would have much effect on the flow of avalanches, but the idea was not discussed much further.

12. How would a similar problem be addressed in Austria/Norway/Switzerland?

The meeting was closed by each expert describing how he thought a similar problem would be attacked in his own country.

Lied, Margreth and Hopf all said they thought their countrymen would conclude that there was a danger of an avalanche that could reach all the way to the ocean under Drangagil and that such an avalanche would be used as a design event for the planning of defence measures.

Lied said he expected NGI would suggest a solution consisting only of dams and mounds, but this could be influenced by the fact that supporting structures are not much used in Norway. He said that he was more concerned about problems with supporting structures in the Drangagil area after the field inspection than he had been before, in particular the difficult foundation conditions, the rock fall problem and the uncertainty about an appropriate design snow depth. He explicitly recommended against the use of supporting structures.

Margreth and Hopf said that supporting structures and dams/mounds would both be considered and such solutions compared with each other. There are even occasions where the inhabitants of towns in Switzerland decide by voting which solution they choose when more than one possibility is on the table. They said that mixing supporting structures and dams/mounds as suggested by VST/Cemagref would according to their opinion not be used in Austria or Switzerland, but they did not directly recommend against it. They did, however, recommend against the open spaces in the supporting structures as mentioned above. They thought the natural situation in Neskaupstaður was favourable for retarding structures in the runout zone because of the extensive area for earth structures above the uppermost buildings, especially east of Tröllagil. On the other hand, there are relatively difficult foundation conditions and problems related to rock fall in parts of the starting zone. Therefore, they thought that a dam/mound solution would be favoured in both countries after a comparison of the two options on the basis of a general project with estimated costs for both options. In Austria the "supporting structure option" would be based on the "Swiss Guidelines for supporting structure in the fracture zone". Josef Hopf commented after the meeting that the "mounds and dam option" could possibly be investigated by laboratory experiments in order to clarify the two principal unresolved questions regarding the effectiveness of mounds, *i.e.* the breaking up of the energy of the avalanche and the mass deposition on the upstream side of the mounds. The Austrian Institute for Avalanche Research in Innsbruck could possibly be contacted about the possible setup of such an experiment according to Hopf.