HAZARD MAPPING FOR ICE AND COMBINED SNOW/ICE AVALANCHES - TWO CASE STUDIES FROM THE SWISS AND ITALIAN ALPS

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ABSTRACT: In September 1996 210'000 m³ of glacier ice broke off from the Gutzgletscher which is situated in the north-west face of the Wetterhorn above Grindelwald (Bernese Alps, Switzerland). The ice masses dropped down the 1000 m high rock face and formed two huge powder avalanches. The avalanche debris blocked a road and the air pressure injured 3 people. The avalanche history of the Gutzgletscher is well documented. The second case study we describe is situated below the top of the Grandes Jorasses in the Italian part of the Mont-Blanc massif. In January 1997, a part of the hanging glacier broke off. The time of the event could be predicted by displacement measurements at the front of the hanging glacier. Below the hanging glacier there are huge starting zones for snow avalanches. Because the break off was expected during a period with considerable avalanche hazard, it was assumed that the ice masses could release big snow-avalanches. For that reason we proposed to evacuate the valley below the hanging glacier. The breaking off occurred a few days after the important snowfall, so that the snowpack had stabilized and no snow avalanches were observed. There were no damages. For both cases the Swiss Federal Institute for Snow and Avalanche Research (SLF) prepared hazard maps and worked out corresponding safety plans in collaboration with the Laboratory for Hydraulics, Hydrology and Glaciology (VAW). The main principles and difficulties of hazard assessment for ice avalanches are described based on the two case studies.

KEYWORDS: avalanche run-out, hanging glacier, ice avalanche, hazard mapping

1. INTRODUCTION

Ice avalanches occur when a large mass of ice breaks off from a glacier, drops down slope driven by gravity and bursts into smaller pieces of ice. Ice avalanching is the normal ablation process of many high altitude, alpine glaciers on steep slopes. The effect of ice avalanches is comparable to that of snow avalanches, the big difference being that they can occur at any time during the whole year. The most destructive ice avalanches happen in winter, when the ice avalanche can release or entrain additional snow masses. Such combined snow/ice avalanches can cover very long run-out distances. In the Alps, ice avalanches occur less frequently than snow avalanches.

In this century the most catastrophic event happened at Mattmark in 1965. 88 people were killed by an ice avalanche from the Allalin glacier in a camp for workers building a dam for a hydro-electric plant. In the Alps hazard mapping for ice avalanches is becoming more and more important, because of intensive land use and development of tourism.

The present paper shows the method for hazard assessment for ice avalanches used for the cases of Gutzgletscher and Grandes Jorasses, where large ice avalanches occurred recently. For both cases the Swiss Federal Institute for Snow and Avalanche Research (SLF) was engaged in collaboration with the Laboratory for Hydraulics, Hydrology and Glaciology (VAW) to prepare hazard maps and to work out corresponding safety plans. VAW performed the glaciological investigations. SLF made the avalanche dynamics study and worked out the hazard maps.

2. ELABORATION OF ICE AVALANCHE HAZARD MAPS

The goal of a glaciological hazard study is to determine the extent of hazard zones of potential ice avalanches, to define the necessary safety measures to be taken and to propose monitoring systems for recognizing any dangerous evolution

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of the glacier in time. At present no universal avalanche model exists to calculate run-out distances of ice avalanches. In general, the application of sophisticated, but poorly calibrated models is severely limited. In parallel to scientific reasoning, expert knowledge and judgement and the comparison with similar ice avalanche problems are fundamental. For the hazard assessment, similar steps as for snow avalanches (Margreth and Gruber, 1998) were used:

2.1 Avalanche history

Information from former avalanche events is very valuable for the calibration of avalanche dynamic models. The starting zone, avalanche track and deposit zone should be mapped. In addition, the volume of ice and the failure mechanism should be determined. If there is a powder part, the influence zone should be mapped. Avalanche pressures may be derived from recorded damages.

2.2 Analysis of topography and terrain parameters

At first, the starting zone of ice avalanches has to be determined. If the terrain is uneven it can be difficult to define the correct initial flow direction. Often different tracks must be investigated. The inclination and extent of the slopes below the glacier have to be analysed to find secondary starting zones for snow avalanches triggered by the ice avalanche. If these starting zones are very large, the snow avalanches can be decisive for the extent of the hazard zones. If the track is very steep or if there are cliffs, a part of the avalanche mass can get in suspension and form a powder avalanche. Often, the powder part can take different tracks. Important losses of mass can occur on flatter terraces or in crevasse zones of glaciers. The fact that glaciers may change considerably in both extent and volume has to be paid attention for.

2.3 Glaciological analysis

At first the potential for ice avalanches of a dangerous glacier has to be identified. Often a slowly opening transverse crevasse appears behind the unstable ice mass. However, in many cases the potential avalanching ice mass can not be estimated long in advance. Therefore continuous observation of a dangerous glacier is necessary.

In a next step break off volumes have to be determined. Typical scenarios with variable ice masses for winter and summer conditions are established. Attempts have been made to determine unstable ice masses by numerical simulation of the glacier motion (Funk, 1995).

Finally, unfavourable developments of the glacier geometry can be detected by regular monitoring using aerial photographs and photogrammetry. An abnormally high ice avalanche activity may be interpreted as an early warning sign for a larger event. The most reliable method to predict the time of failure is based on glacier motion measurements. Pillars with target prismas are mounted at different locations on the glacier. They are periodically surveyed with theodolites and distometers. Analysing the acceleration of the surface velocity, the most probable time of breaking off can be calculated. This method has been used successfully for hanging glaciers on the Weisshorn (Röthlisberger, 1978) and on the Eiger (Funk, 1995).

2.4 Avalanche dynamics study

Beside the analysis of observed events, the results from avalanche dynamics calculations are used to quantify avalanche pressures or run-out distances for different ice masses and in particular for potential avalanches which were not registered in the avalanche history. Current avalanche dynamics models often fail with complex situations. The model calculations are based on the avalanche path profile and on the ice or snow input parameters. These parameters must be chosen very carefully. The volume and geometry of the falling ice masses, snow entrainment, possible suspension rates in the track and the friction coefficients in the track and run-out zone must be considered. The calculations have to be performed for winter and summer conditions. The roughness of the terrain in winter is much smaller and the snowpack constitutes a good sliding surface.

For the calculation of ice avalanches the same models as for snow avalanches were applied. During the initial fall the ice masses burst apart completely after a short distance so that the ice avalanche is flowing according to the laws of a dry flowing snow avalanche. As the physical processes of ice avalanches are largely unknown, no advanced calculation models exist. Therefore simple calculation models developed for snow avalanches were applied, which can be easily adjusted for varying situations by choosing different sets of parameter values. For the dense part the Voellmy-Salm model (Salm et al., 1990), a one-dimensional rigid body model, and for the powder part the French model AVAER (Rapin, 1995), a variable-size block model, were used. The most severe problems concerned the calibration of the models for ice avalanches and the definition of the initial conditions. In table 1 the most critical parameters are given.

Fortunately, the input parameters e.g. for the Wetterhorn situation could be calibrated with backcalculations of the well-documented glacier fall of the Gutzgletscher on 5 of September 1996. One of the most critical parameters to determine is the flow rate, which depends mainly on the initial flow height.

The initial conditions depend on the type of failure. According to Haefeli (1966) failure is divided into two categories: wedge failure (type I) and slab failure (type II) (Fig. 1).

- In the type I starting zone (wedge failure), the glacier develops a nearly vertical front, typically at a break in angle of the bedrock. When the icecliff becomes too steep or even overhanging, an ice segment can break off. It is assumed that at first a shear failure occurs at the foot of the ice segment and that the foot is the front of the resulting ice avalanche. A mean initial flow height d_o of 35 - 50% of the mean thickness of the ice segment seems to be reasonable. The mean thickness can be estimated by visual interpretation of the crevasse patterns. The width and the height of the front can be determined by surveys or photogrammetry. The resulting mass is limited by the thickness of the ice segment. The type I starting zones produce usually relatively small masses of ice.
- In the type II starting zone (slab failure), the so called ramp-type, very large volumes of ice of a hanging glacier can be released. The failure mechanism is due to gliding of an ice mass on the bed rock after reduction of adhesion. As the thickness of the gliding ice mass can be important, the resulting flow rate is much higher than in the case of starting zone type I. An initial flow height d_o reaching maximal 50% of the mean thickness of the gliding ice mass seems to be appropriate.

Table 1: Most critical parameters for ice avalanche modelling

Dense flow avalanche model (Salm et al., 1990):	Powder snow avalanche model (Rapin, 1995):
– Initial flow thickness: d_o	– Suspension factor
– Initital flow rate: $Q=W_o \cdot d_o \cdot [d_o \cdot \xi \cdot (\sin\Psi - \mu \cdot \cos\Psi)]^{1/2}$ W_o: width Ψ: mean slope angle	– Geometry of initial powder cloud: height, length and width – Initial average avalanche density – Snow entrainment in the track
– Dynamic friction coefficient: μ	
– Turbulence coefficient: ξ	
– Mass balance in the track	

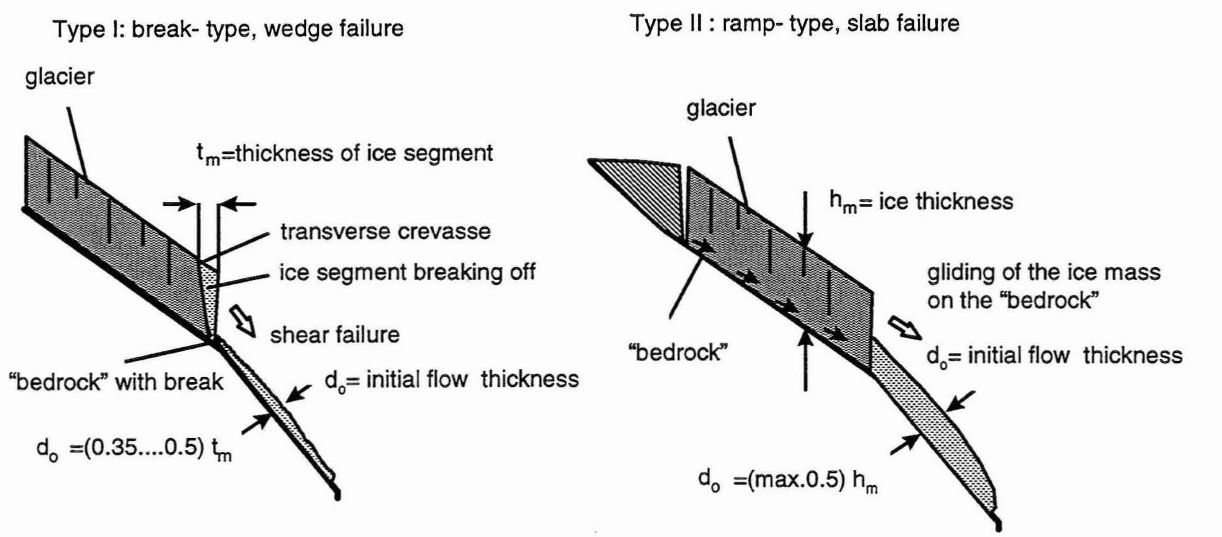

Figure 1. Types of starting zones

Alean (1984) related the average slope of ice avalanches to their volume and characteristic terrain parameters. The use of the average slope model proposed by Alean is only justifiable for short reaches or for overview studies. According to our experience the average slope model is not complete enough for detailed hazard mapping and the results are too conservative especially for steep tracks (too large run-out distances). In addition the powder part is neglected in this model.

2.5 Hazard mapping

Avalanche dynamics calculations alone are not sufficient for hazard mapping, but they are a useful tool to quantify the run-out distances for variable ice masses. Two types of hazard maps are common for ice avalanche problems:

- Firstly, there are the classical hazard maps which consider extreme events. These hazard maps are used for land-use planning. Normally the extreme winter event is decisive. The degrees of hazard are the same as given in the Swiss federal guidelines for hazard mapping (1984) for snow avalanches. The potential hazard is quantified in the guidelines by the frequency and intensity. It is difficult to assign a realistic frequency to the extreme ice avalanche event. For example at the Altels (Bernese Oberland, Switzerland) extreme ice avalanches with a volume of about 5 million m³ were observed in 1782 and 1895 (Heim, 1895). So within 113 years the glacier regenerated and again produced an extreme ice avalanche. On the other hand, it has been observed that extreme events did not repeat, even with a similar glacier extent.

- Secondly, the hazard map can be a tool for avalanche warning and evacuation during time periods of imminent glacier fall. These types of hazard maps are prepared for typical scenarios with different ice volumes and can only be applied provided the glacier is continuously monitored. Closures or evacuations are imposed according to the prevailing hazard situation. An avalanche pressure of 0.5 kN/m² is used in the run-out as a lower limit for non protected persons.

3. CASE STUDY I: GUTZGLETSCHER NEAR GRINDELWALD (BERNESE OBERLAND, SWITZERLAND)

3.1 Situation

The Gutzgletscher is situated in the north-west face of the Wetterhorn high above Grindelwald (Bernese Alps, Switzerland). In the northern sector the glacier flows from a relatively flat bowl into the 60° steep and roughly 1000 m high north face of the Wetterhorn (Fig. 2, 4). This is the starting zone of the ice avalanche called „Wätterlaui". On 5 September 1996 at 3 p.m. and

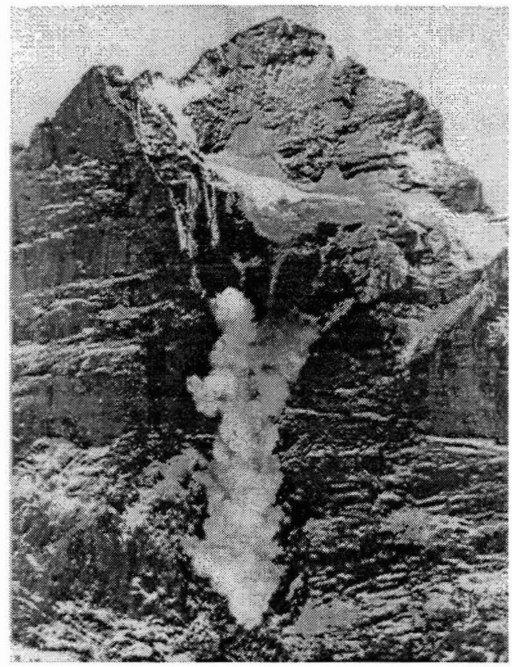

Figure 2. Wetterhorn with Gutzgletscher (Photographer unknown)

9 p.m. important ice masses broke off from Gutzgletscher and dropped down as powder and dense flow avalanche in the direction of the road from Grindelwald to Grosse Scheidegg. The closest distance between the road and the foot of the steep rock face is 500 m. The dense part flowed down along a small channel, which becomes gradually flatter, and finally blocked the road over a distance of 20 m. The powder part was not deflected by the terrain and moved from the foot of the rock face straight on for about 1 km (Fig. 3). Three persons were injured and some hikers were knocked down.

Consequently VAW and SLF were engaged to perform a glaciological and avalanche dynamics study. Especially the questions about the minimal ice masses which can fall and do not endanger the road and the maximal possible endangered perimeter have to be answered. Results are given in detail in two unpublished expert reports (Funk, 1997a; Margreth, 1997a).

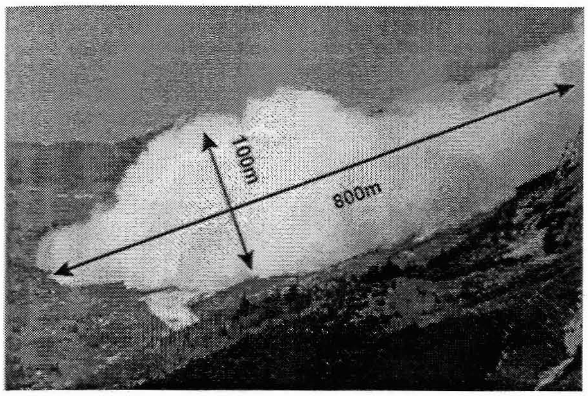

Figure 3. Powder part of the 3 p.m. avalanche of 5 September 1996 (Photo: U.Schiebner)

3.2 _Avalanche history of the „Wätterlaui“_

As falling ice is the dominating ablation process of the Gutzgletscher, ice avalanches have often been observed in the past. In the avalanche history 9 bigger events are recorded in the last 74 years. There have been severe damages to buildings, animals and forests. In Figure 5 the estimated extent of the different historical avalanches is shown. The maximal run-out of the powder part was more than 2.5 km from the foot of the steep rock face and the maximal historical run-out of the dense part was 650 m longer than in 1996. The ice avalanche of 1996 is not one of the biggest recorded avalanches in the past. Since 1924, 6 avalanches have been recorded in summer and 3 in winter. The mean return period for a bigger

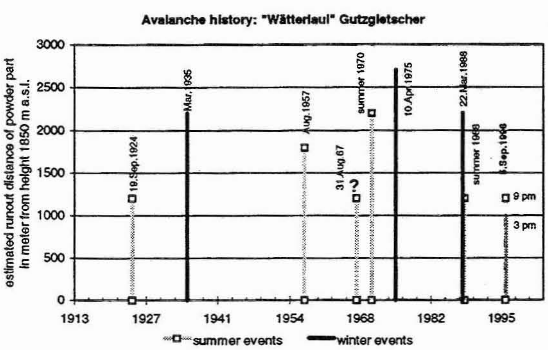

Figure 5. Avalanche history „Wätterlaui“

ice avalanche is about 8 years. Smaller ice avalanches have been observed almost every day. They are however harmless because they die out during the fall due to loss of mass.

3.3 _Analysis of the ice avalanches of September 1996_

The two ice avalanches of September 1996 were well documented with photographs and video films. As a basis for avalanche dynamics calculations and for estimation of possible suspension rates, an attempt was made to establish a mass balance. The area and the thickness of the deposit of the dense part were estimated according to the analysis of photographs. Before the 5 September 1996 there was a deposit of ice in the run-out zone of about 60'000-80'000 m³. The ice volume of the first avalanche on 5 September 1996 was estimated at 80'000-100'000 m³ and that of the second avalanche at 170'000-190'000 m³. The density of the glacier ice was estimated to be between 850 and 900 kg/m³ and the density of deposit between 400 and 500 kg/m³. We assumed that, due to the fall, the density of ice masses was nearly halved. It was more difficult to estimate the mass of the powder part.

Due to high summer temperatures, the deposit of the powder part of the first avalanche melted rapidly. The persons who were in the precipitation zone of the powder cloud were completely drenched by the ice dust. At the beginning of the run-out the powder cloud had approximately the following dimensions: length 800 m, width 200 m and height 100 m (Fig. 3). If we assume a mean density of 2.4 kg/m³, that means 1.4 kg ice per m³, a mass of 22'000 tons results. At the footpath where the 3 persons were injured, we estimated a mean avalanche pressure of 1.5 kN/m².

The deposit of the powder part of the 9 p.m. avalanche extended over an area of more than 35 ha with a mean thickness of about 20 cm. In front of obstacles it was thicker and in the avalanche shadow practically non existent. The powder avalanche entrained a lot of small stones. The vegetation was similarly affected as during a strong hailstorm.

A loss of volume of 220'000 m³ at the front of the Gutzgletscher was able to be determined with photogrammetry for the period between 26.7.1996 and 1.9.1996. The established mass balance shows that the probable suspension rate was between 30 and 70%, implying that 30 - 70% of the ice went down as a powder

Figure 4. Hazard map Gutzgletscher "Wätterlaui"

avalanche. If the two events of 5 September 1996 would have occurred as one big ice avalanche, the intensity would have been much more destructive.

3.4 Avalanche dynamics study

The two starting zones at the Gutzgletscher (left and right side of the glacier front) from where the ice avalanches on 5 September 1996 were released are so called break types (type I, Fig.1). The glaciological investigations showed that the height of the front was between 60 and 70 m and the length of each zone about 100 m. The thickness of the broken ice lamella was estimated to be between 10 and 30 m at the top and at the foot 10 m at the most. The maximal possible ice volumes which can be released in future from the two zones were determined as being 230'000 m³ and 130'000 m³ respectively. It was assumed to be very unlikely that the two masses would fall at the same time. The investigated tracks are shown in Figure 4. Table 2 compiles the avalanche dynamics calculations for the „Wätterlaui", and in Figure 6 the track profile with the run-out distances for the dense part is shown. For comparison also the average slopes are given. The run-out distances calculated with the average slope model proposed by Alean (1984) would be much longer.

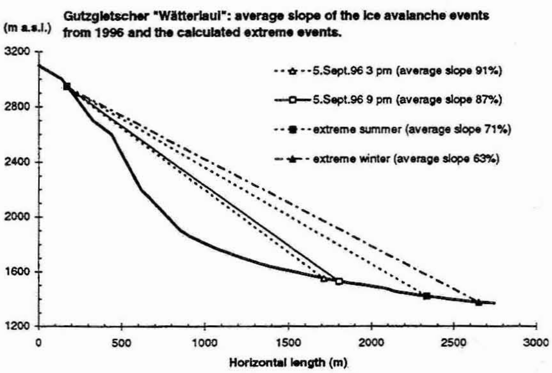

Figure 6. Track profile „Wätterlaui"

- The run-out of the dense part of the ice avalanche events from the 5 September 1996 was backcalculated using a turbulent friction coefficient ξ of 800 m/s^2 and a kinetic friction coefficient μ of 0.3. The flow rate was backcalculated to 10'000 respectively 20'000 m³/s. The run-out of the second avalanche was about 110 m longer. The avalanche pressure of the powder part for the two events results in 1.4 kN/m² and 2.2 kN/m² respectively at the footpath, were the 3 persons were injured.

- The minimal ice volume which can cause an avalanche pressure of 0.5 kN/m² at the footpath, was found to be between 15'000 and 25'000 m³. The powder part is relevant. The dense part does not reach the road.

- The extreme event was calculated with an ice volume of 230'000 m³. With a suspension degree of 35%, a volume of 150'000 m³ would fall as a dense flow avalanche and 80'000 m³ as a powder avalanche. It was assumed that in winter the powder avalanche would entrain additional snow. The transition from the steep rockface into the flatter terrain leads to a considerable enlargement and energy loss of the powder avalanche. As the avalanche masses are significantly bigger than on 5 September 1996, the dynamic friction coefficient μ was assumed to be equal to 0.25 for the extreme summer event and equal to 0.20 for the extreme winter event. The flow rate is 55'000 m³/s. The run-out distance of the extreme summer event is about 500 m longer than the one of the 5 September 1996 event. The extreme winter event is about 800 m longer. The avalanche pressure of the powder part on the footpath for the summer extreme event amounts to 3.7 kN/m² and for the extreme winter event to 5.3 kN/m².

3.5 *Hazard maps*

The hazard map of the extreme winter event is decisive for future landuse planning (Fig. 4). The extent of the area endangered by the powder part is comparable to the biggest observed event in winter 1975. In addition hazard maps were prepared for the extreme summer event, a medium event corresponding to the extent of 5 September 1996 and for the minimal event. According to glaciological investigations, the volume of an ice avalanche will not exceed 78'000 m³ in the near future. Additional recommendations were also mentioned in the expert report to prevent accidents by ice avalanches from the Gutzgletscher in the future.

Tab.2: Avalanche dynamic calculations Wätterlaui

Event:	5.9.96 3 p.m.	5.9.96 9 p.m.	Minimal	Extreme Summer	Extreme winter
Total ice volume [m³]	70'000	115'000	15-25'000	230'000	230'000
Avalanche type:	dense snow	dense snow	dense snow	dense snow	dense snow
Ice volume [m³]	45'000	80'000	<13'000	150'000	150'000
Falling lamella geometry: Width/Height/mean thickness [m]	120/60/6	120/70/10	60/40/6	120/70/18	120/70/18
Flow rate [m³/s]	10'000	20'000	-	55'000	55'000
Friction coefficient μ/ξ	0.3/800	0.3/800	-	0.25/800	0.2/800
Max. horizontal run-out distance [m]	1545	1660	ca. 1190	2165	2485
Max. vertical drop [m]	1400	1425	ca. 1300	1530	1575
Avalanche type:	powder snow	powder snow	powder snow	powder snow	powder snow
Suspension factor [%]	35	30	>50	35	35
Ice volume [m³]	25'000	35'000	12'000	80'000	80'000
Initial powder cloud: Width/Height/Length [m]	90/40/200	110/45/220	70/35/150	150/70/250	150/70/250
Initial mean density [kg/m³]	30	30	30	30	30
Snow entrainement	no	no	no	no	yes
Mean avalanche pressure after a horiz. reach of 1280 m (footpath) [kN/m²]	1.4	2.2	0.5	3.7	5.3
Width [m]	290	310	230	510	510
Horizontal run-out until mean avalanche pressure < 1 kN/m² [m]	1460	1610	1210	2060	2310
Horizontal run-out until mean avalanche pressure < 0.5 kN/m² [m]	1710	1910	1210	2460	2760

4. CASE STUDY II: WHYMPER GLACIER, GRANDES JORASSES (MONT BLANC MASSIF, ITALY)

4.1 Situation

The Whymper glacier is a hanging glacier at an elevation of 3950 m.a.s.l. situated just below the top of the Grandes Jorasses (Fig. 8). The front of the glacier has a width of about 90 m and the surface is about 25'000 m². Breaking off ice masses can fall along 4 different tracks (Fig. 7, 9). Because the terrain below the hanging glacier is partly steeper than 30°, it is likely that a primary ice avalanche can trigger secondary snow avalanches in winter. The total area of potential starting zones below the hanging glacier is more than 180 ha. The tracks consist partly of glaciers which are strongly crevassed. Smaller avalanches will stop in these crevassed zones because of mass loss. Cliffs in the tracks will cause powder avalanches. It is not possible to determine the most probable track in advance. It depends on the release mechanism, on the surface roughness of the glaciers in the tracks and on deposits of former avalanches or rockfalls. The village Planpincieux in the Val Ferret is endangered by the avalanches. The elevation difference between the hanging glacier and Planpincieux is about 2300 m and the horizontal distance is more than 4000 m. The valley is frequented by numerous tourists in summer and in winter.

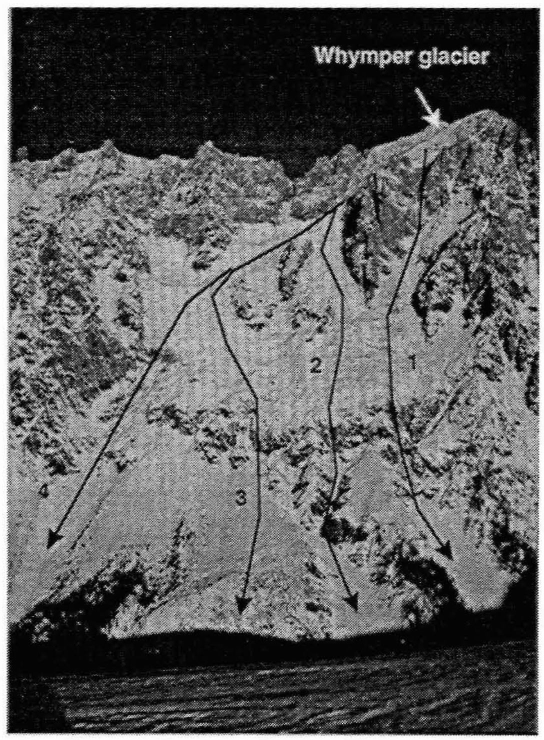

Figure 7. Grandes Jorasses (Photo: SLF)

VAW and SLF were engaged to check the ice avalanche and ice/snow avalanche danger, to work out a safety plan and to determine the endangered areas for different scenarios. Results are given in detail in two unpublished expert reports (Funk,1997b; Margreth,1997b).

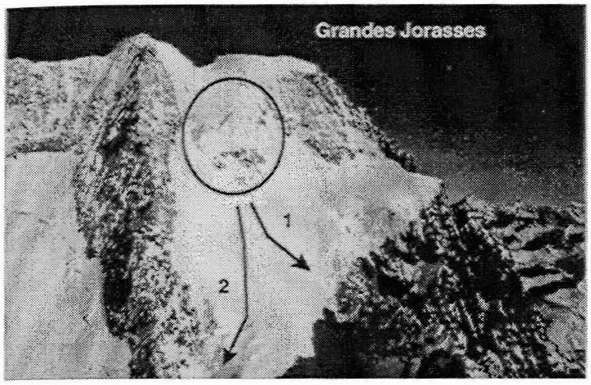

Figure 8. Whymper glacier (Photo: SLF)

4.2 Avalanche history

On 21 December 1952 after an intensive snow fall period a huge avalanche was released below the Grandes Jorasses which destroyed a 200 year old forest and blocked the bottom of the Val Ferret over a distance of more than 1 km. We estimate the avalanche volume to have been more than 1'000'000 m^3. It is not clear if the snow avalanche was triggered by an ice avalanche from the Whymper glacier.

In August 1993 and July 1996 ice avalanches with volumes of 80'000 and 24'000 m^3 respectively were released from the Whymper glacier. Both avalanches followed track 3 or 4 (Fig. 9) and stopped on a glacier terrace about 1500 m above the valley.

4.3 Avalanche dynamics study

The normal ablation zone of the Whymper Glacier is the glacier front where ice lamellas break off periodically. It is a so called break type (type I, Fig. 1). The height of the front is 40 m and the maximal width 100 m. The thickness of the ice lamellas has been established to be between 7 and 20 m. For a normal situation we assume an ice lamella with a volume of 30'000 (+/- 10'000) m^3. Glaciological investigations showed that the whole Whymper glacier with a volume of about 250'000 +/- 100'000 m^3 (width 90 m, length 70 m, height 40 m) might destabilise. In this extreme situation it is a not a single lamella but nearly the whole glacier which can slide on the bedrock (starting zone type II, Fig. 1). Because of the thickness of the ice mass, the flow rate of the resulting avalanche is higher than for a normal situation.

For the avalanche dynamics investigations it is necessary to distinguish between summer and winter conditions. In winter a primary ice avalanche can entrain a lot of snow or release secondary snow avalanches depending on the prevailing stability of the snowpack. The impact of falling ice masses on the snowpack is much bigger than methods of artificial avalanche release. If the snow pack stability is very poor, a small ice avalanche with a volume of several 1'000 m^3 can be sufficient to release a huge snow avalanche. On the other hand experience has shown that with a stable snowpack only a huge ice avalanche can release a secondary snow avalanche. As it is not possible to calculate the mass of snow that can be triggered by ice avalanches according to their size, different scenarios were distinguished.

It is very unlikely that during the short period (a few days) with imminent risk for ice avalanching intensive snowfalls with a return period of for example 300 years occur. Therefore we do not consider a combination of these two extreme events. For the avalanche dynamics calculations we have estimated that the fracture depth corresponds to the snowdepth increase in 3 days for a return period of 10 years. The data are taken from extreme value statistics of nearby weather stations. For an altitude of 3500 m.a.s.l. and a slopeangle of 35° the fracture depth is calculated to be 150 cm. The possible sizes of potential avalanches were chosen according to the international avalanche-danger degree scale. The five danger degrees depend on the avalanche release probability, the avalanche size and the local distribution of dangerous slopes. In table 3 the investigated scenarios are summarised.

For each scenario and for each of the 4 tracks (Fig. 9) avalanche dynamics calculations for powder and dense flow avalanches were performed to calculate the run-out distances and mean avalanche pressures. The increase of the flow rate caused by secondary release of snow avalanches was considered by adding the flow rate of the released snow avalanches to the flow rate of the ice avalanche. In table 4.1 and 4.2 a summary of the calculations is given.

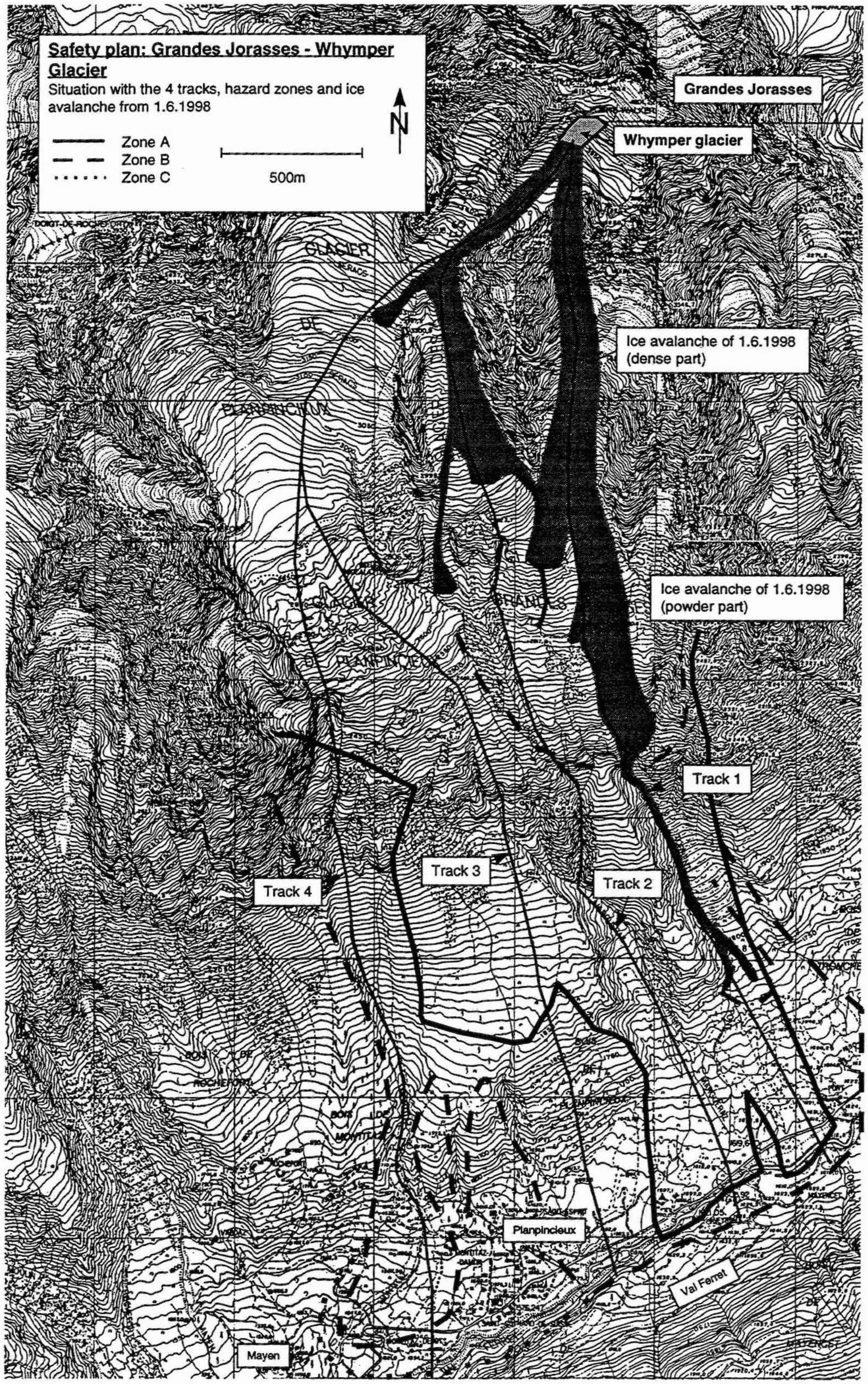

Figure 9. Safety plan Grandes Jorasses - Whymper glacier

Tab. 3: Definition of the investigated scenarios

Ice volume	summer -	winter: avalanche danger degree 1 (low)	2 (moderate)	3 (considerable)	4 (high)	5 (very high)
critical: summer	Scenario 1					
winter		Scenario 2				
normal: 30'000m³ +/- 10'000m³		Scenario 3	Scenario 4		Scenario 5	
extreme: 250'000m³ +/- 100'000m³	Scenario 6	Scenario 7				

Tab. 4.1: Dense snow avalanche dynamics calculations Whymper glacier along track 1

Scenario:	1	2	3	4	5	6	7
Starting zone:	ice avalanche from Whymper glacier						
Ice volume [m³]	<40'000	<20'000	30'000	30'000	30'000	300'000	300'000
Falling lamella geometry: Width/Height/mean thickness [m]	-	-	90/40/7.5	90/40/7.5	90/40/7.5	100/40/75	100/40/75
Flow rate [m³/s]	-	-	7'500	7'500	7'500	75'000	75'000
Volume of released snow avalanches in track 1 [m³]	0	0	0	120'000	500'000	0	>500'000
Total flow rate [m³/s]	-	-	7'500	15'000	21'000	75'000	>90'000
Friction coefficient μ/ξ	-	-	0.3/800	0.2/1000	0.155/1000	0.25/1000	0.155/1000
Avalanche flows over road	no	no	no	yes	yes	yes	yes

Tab. 4.2: Powder avalanche dynamics calculations Whymper glacier along tracks 1 and 3

Scenario:	1	2	3	4	5	6	7
Starting zone:	ice avalanche from Whymper glacier						
Suspension factor [%]	>50	>50	30	30	30	40	50
Ice volume [m³]	<25'000	<12'000	12'000	12'000	12'000	125'000	158'000
Initial powder cloud after a fall of 600 m: Width/Height/Length [m]	150/50/250	100/50/200	90/40/200	90/40/200	90/40/200	150/70/350	150/90/350
Initial mean density [kg/m³]	11	11	11	11	11	30	30
Snow entrainment	no	yes	yes	yes	yes	no	yes
Mean avalanche pressure on the road along track 1 [kN/m²]	0.6	0.5	-	-	-	-	-
Mean avalanche pressure on the road along track 3 [kN/m²]	-	-	0.5	1.1	2.1	1.3	8.1
Width [m]	>150	>150	220	270	270	320	500

For the safety plan a hazard map with 3 different zones (A, B, C) was established (Fig. 9). Because the entire situation is very complex, many assumptions have to be made. Results from avalanche dynamics calculations are only a small part in the final hazard assessment.

- The powder part is relevant for defining the ice volume (called critical ice volume) above which persons are endangered (mean avalanche pressure greater than 0.5 kN/m²). The most critical track is number 1, where the average slope between the Whymper glacier and the road at the bottom of the Val Ferret is 65 % (Fig. 10). The investigations show that in summer the critical ice volume is 40'000 m³ (scenario 1).
- In winter the critical ice volume is smaller because of snow entrainment. For scenario 2 it is 20'000 m³.
- In scenario 3, persons on the road are endangered by track 1. The village of Planpincieux is considered to be safe. We propose to evacuate the hazard zone A.

- In scenario 4 dense avalanches do not reach the centre of the village, the destruction of houses is unlikely, but persons outside buildings might be endangered. We propose to evacuate hazard zones A and B and to advise the people in zone C to stay in their houses.
- In scenario 5 and 6 important destructions will occur mainly around the village. Damages in the village can not be excluded. Persons in the buildings might also be endangered. The extent of scenario 5 and 6 is comparable to the event in 1952. We propose to evacuate the hazard zones A, B and in winter additionally C.
- Scenario 7 is catastrophic for the Val Ferret. The destructions surpass scenario 5 by far. We propose to evacuate the hazard zones A, B and C and the hamlet of Mayen.

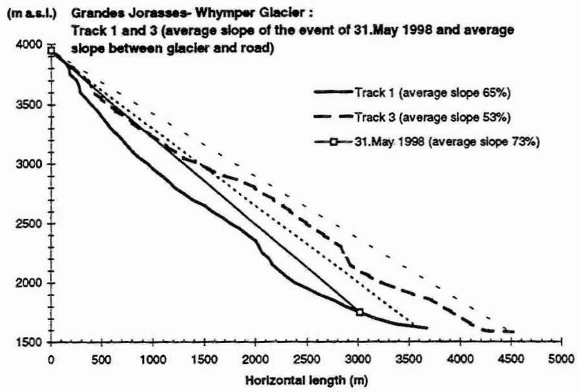

Figure 10. Track profile Grandes Jorasses

4.4 _Assessment of actual glacier fall risk: situations of January 1997 and May 1998_

The Whymper glacier has been monitored since 1994. In spring 1996 local people observed a slowly opening transverse crevasse behind the front and in the rear part of the Whymper glacier (suggesting that the whole glacier could break off). A survey instrumentation consisting of 11 pillars with target prismas was installed on the glacier to measure the surface velocity. Additionally, every month photographs were taken and the hanging glacier was observed periodically. The proposed safety measures can only be effective if the glacier is monitored, so that a dangerous development can be recognised in advance.

The displacement measurements on 17 January 1997 showed clearly a progressive acceleration of the front part. The daily displacement increased from about 7 to more than 14 cm/day. The fall of 10'000-25'000 m^3 of ice was predicted to occur between the 20 and 22 January. At the same time in the Val Ferret a snow storm brought about 70 cm of fresh snow. Before the snowfall the stability of the snowpack was good. The avalanche danger degree after the snowfall was considerable. After discussions with VAW and SLF the local authorities evacuated the village of Planpincieux on the 21 January and closed the road into the valley. Between the 23 and 25 January about 25'000 m^3 +/- 10'000 m^3 ice from the Whymper glacier broke off and the avalanche stopped high above the bottom of the valley. The ice avalanche did not release a snow avalanche because the snowpack had stabilised in the meantime.

In the night of 31 May 1998 to 1 June 1998 a huge ice avalanche was released from the Whymper glacier. An important part of the glacier sheared off. The released ice volume was estimated to be about 150'000 m^3. The ice masses dropped down mainly along track 1 and 2 and stopped at a distance of 500 m from the houses and the road. The avalanche did not surpass zone A. The extent was somewhat smaller than estimated in advance. With a vertical drop of 2200 m and a horizontal run-out distance of 3000 m the corresponding average slope is 73% (Fig. 10). Because the terrain was snowfree on the second half of the track, an important loss of mass occurred. The ice avalanche entrained a lot of boulders and developed an important powder part. There were no fatalities and only light damages to the vegetation.

5. CONCLUSIONS

The accuracy of the presented hazard maps for ice avalanches is of course somewhat limited because many parameters are unknown. An important point is that the expert explains the consequences of the uncertainties. Uncertainties exist in the analysis of the glaciological process (ice volume, ice stability, ice velocity, moment of break off, periodicity of events) and in the analysis of the avalanche process (initial conditions, suspension rate, friction values, flow direction, mass balance, release of secondary avalanches). The best approach is to describe the hazard situation for different scenarios. In the presented studies we have investigated three scenarios:

1. A minimal scenario, where the ice mass is too small to produce an avalanche which can endanger persons in the run-out.
2. A medium scenario, where an ice mass breaks off, which is typical for the glacier in question.
3. An extreme scenario, where the maximal possible ice mass breaks off.

For ice avalanche problems two types of hazard maps were distinguished. Firstly, classical hazard maps, which are used for land-use planning. For this type of hazard maps the scenario of the extreme winter event is decisive. The other type of hazard maps is based on the above mentioned three scenarios and is combined with a so called safety plan. This is used for avalanche warning and evacuation during times of imminent glacier fall. However they can only be applied provided the glacier is continuously monitored.

In the two case studies the use of avalanche models was a support to determine the endangered zones. For the calculation of ice avalanches the same models as for snow avalanches were used. The model calculations are useful if the input parameters can be calibrated from well documented events. The avalanche dynamics calculations are especially appropriate to figure out the run-out distances and the avalanche pressure for the different scenarios.

The collaboration between glaciologist and avalanche dynamics experts allowed many stimulating discussions on the topic of ice avalanches.

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