

# **SNOW AVALANCHES, ICE AVALANCHES AND GLACIER SURGES**

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## **1. Introduction**

This paper concerns the fast motion of snow and ice in the terrestrial environment and the associated hazards. These hazards tend to be very localized in mountain areas that are mostly sparsely populated. Historically their direct impact on people has been relatively small. However, with increased human activity in mountain terrain including habitation, resource extraction, transportation and recreation, it is necessary to recognize the potential impacts from moving ice that could be very serious.

Seasonal snow is wide spread in mountain environments and avalanches of snow from slopes can cause considerable damage to property and loss of life. In mountain areas where human activity is present, considerable effort goes into assessing where and when hazard is high and designing means to mitigate the impact through various control measures. The mechanical stability of snow on a slope depends on the amount and rate of snow deposition, the structural evolution of the snow after deposition and characteristics of the slope; snow slope stability depends on interactions between the terrain and weather. Relevant time scales range from seconds during the actual release and down slope acceleration of an avalanche, to minutes and hours during times of precipitation or rapid change in temperature, to days and weeks associated with snowfall history and gradual metamorphism of the snow pack.

In contrast perennial ice masses are more localized and respond to longer-term changes in climate. Nevertheless, parts of glaciers on steep slopes can sometimes fall as ice avalanches that devastate valley floors far below the level of the glacier. The exact timing of such icefalls may be related to recent weather or other environmental stimuli such as earthquakes or volcanic eruptions. More importantly, these falls are associated with a mechanical threshold that is approached through relatively slow evolution of the glacier over months to years in response to climate forcing. Mitigation requires hazard mapping based on past events and ongoing monitoring changes of potentially hazardous glaciers.

Surges of glaciers present another kind of mechanical instability leading to increased speed of motion. However, the ice remains in a state of quasi-static equilibrium. While the speed may be enhanced by a few orders of magnitude compared to typical glacier speeds, significant redistribution of the ice by the motion takes weeks or months. The direct hazard from surging glaciers is thus quite different than for snow or ice avalanches, which once initiated, can overwhelm people and structures in a few seconds or minutes. Nevertheless, surges can produce substantial changes in terrain and devastate vegetation and structures. A particularly important consequence can be the formation of ice dams across tributary valleys resulting in ice-dammed lakes. Such lakes can drain catastrophically with potential for extensive, down-stream flooding and associated impacts.

This paper focuses on these three land-ice processes. We emphasize that there are many other ice-related hazards of significance in the terrestrial environment. Examples are ice jams in rivers, ice on volcanoes, tidewater glaciers, and floods from ice-dammed lakes or water stored inside of glaciers. Furthermore, glaciers affect global sea level and all coastlines to some extent. There is particular concern about potentially large sea level change from polar ice sheets in Antarctica and Greenland.

## **2. Snow avalanches**

### **2.1 Description of snow avalanches**

Snow avalanches are ubiquitous in regions where snow accumulates on slopes. However, they become hazardous only when they affect human activity. Charlie Douglas, an early explorer in New Zealand recognized the hazard from avalanches and wrote "*... avalanches, like wild pigs, are only dangerous when you foolishly get in their way...*" In Europe, tales of terror and disaster about avalanches increased during the Middle Ages when people first started to inhabit the Alps. It was not uncommon for an entire village consisting of tens or hundreds of people to be overwhelmed and killed by avalanches. The toll has been even higher during times of war; more than 40,000 Austrian and Italian troops died from avalanches during the First World War. About 3,000 Austrian troops were killed in one 48-hour period by Italian troops who released avalanches above them with artillery. Although mountain communities continue to suffer occasional avalanche disasters, the hazard to villages and transportation corridors has been mitigated by the development of hazard maps, avalanche defense structures, avalanche forecast and control programs. Now, with increased usage of the mountains by snow-mobilers, climbers, skiers and snow-boarders, more than 65% of avalanche

victims are recreationists. On average, about 150 people are killed each year. The majority of the victims trigger the avalanches that bury them.

Avalanches normally recur in the same location or *path*. A path consists of a *start zone* at the top of the path where the avalanche initiates and accelerates, a *track* in the middle of the path where the speed reaches a maximum, and a *run-out zone* below the track where the flow decelerates and deposits. The average time between occurrences is the *return period*.

Snow stability is controlled by the geometry of the start zone and the mechanical properties of the snow pack. The starting characteristics of an avalanche depend on the relative cohesiveness of the snow. *Loose-snow* or *point-release* avalanches initiate when snow accumulates on slopes that are steeper than the angle of repose. Angles of repose usually increase as the snow temperature approaches 0°C but decrease considerably when the snow contains liquid water. *Slush* avalanches, containing up to 30% water, have been observed to initiate on slopes <10°. Although loose-snow avalanches initiate from a small volume (< 1 m<sup>3</sup>), additional snow entrained from the sides during down-slope motion has potential to develop an avalanche of hazardous proportions. Potential *slab* avalanche conditions occur when a relatively cohesive slab of snow overlies an extended plane of weakness. Slabs are typically ~ 0.5 m thick, but slabs up to 10 m thick have been measured. Slab width depends strongly on the geometry of the terrain; fractures have been known to propagate more than 1 km across unconfined slopes. Slab avalanches are particularly hazardous because of the large volume of the initial failure, and also because it is difficult to predict the evolving stability of buried weak layers.

The dynamics as the snow moves down slope depend on the relief and roughness of the avalanche track as well as the properties and volume of entrained snow. The flow disaggregates and the smaller particles may diffuse turbulently into a spectacular dust cloud that often travels more than 60 m s<sup>-1</sup> (Fig. 1). The flow near the ground is generally slower and consists of a high-density mix of snow and air.

The impact pressure  $I$  from an avalanche depends on the density  $\rho$  and the speed  $v$  of the flow:

$$I \approx \rho v^2 \quad (1)$$

The density of the flowing component near the ground ranges from about 200-550 kg m<sup>-3</sup>; impact pressures from the flowing component of a large avalanche (traveling at 20 m s<sup>-1</sup>) are expected to range from about 80 to 250 kPa. The density of the powder component of an avalanche is much less (~10-20 kg m<sup>-3</sup>) but the speed is faster and the cloud usually travels farther, thereby having a larger area of influence. The impact pressure from a dust cloud traveling at 60 m s<sup>-1</sup> is ~35 kPa. Measurements indicate that impact pressures of ~ 30 kPa will destroy a wood-framed structure, while pressures of 100 kPa will destroy a mature forest.



Figure 1. A large snow avalanche triggered by explosives crosses the Milford Highway in the upper Hollyford valley, New Zealand. *Photo by W. Carran, Works Infrastructure, N.Z.*

## 2.2 Release mechanisms and prediction

Field observations and physical models indicate that a necessary condition for slab avalanche release is that the gravitational stress from the overburden exceeds the strength of a buried weak layer. This condition can be met if the applied stress increases (for example, from additional loading by new snowfall, a skier or explosives), or if the shear strength of the weak layer decreases (for example by recrystallization of the snow grains). Loss of shear support at the base causes stresses around the remaining boundaries of the slab to increase, which may lead to failure. Sharply defined fracture

surfaces outline the slab boundaries after avalanche release (Fig. 2). Tensile failure occurs at the up-slope boundary (the *crown-wall*) of the slab, while stress at the lower boundary (the *stauch-wall*) is compressive and it fails in shear. A combination of shear and tensile failures occur at the sides and consequently the *flank-walls* often have a saw-tooth shape (Fig. 2).



Figure 2. Crownwall and flankwall fracture surfaces are clearly visible in the start zone of Murrells avalanche path that threatens the Milford Highway, New Zealand. The *stauchwall* at the toe of the slab has been over-run and is not visible. Photo by W. Carran, Works Infrastructure, N.Z.

A simple force-balance of an inclined slab can be used to estimate stress concentrations caused by localized reduction of the basal shear support. For example, a loss of basal shear support of just 50% over a distance of 10 times the slab thickness would increase the stress at the upper edge of the zone of stress relaxation by a factor of 5. Such stress concentration tends to propagate shear failure over a wider area, which can initiate release. Typical values for the mechanical properties of snow indicate that failure can initiate from a relatively small zone of basal weakness (order of 1 to 10 m length). Actual conditions in the snow pack are not likely to be accurately represented by such a simple analysis because snow is a visco-elastic material and the mechanical properties depend on strain and strain rate. However, more rigorous model calculations that include realistic boundary conditions and possible strain softening of the basal layer confirm that shear failure may initiate from such small zones of weakness.

Most natural avalanches release during storms, because gravitational stress from new snow often increases faster than the strength of buried layers. The timing of these *direct-action* avalanches can often be predicted to within a few hours or less by making

use of real-time weather and snow data relayed from remote sites (Fig. 3). Prediction of avalanches that release on buried weak layers that typically consist of surface hoar, faceted crystals or depth hoar (sometimes referred to as *persistent* weak layers) is more difficult, and requires rigorous modeling of the spatial and temporal evolution of thermal and mechanical conditions within the snow pack.

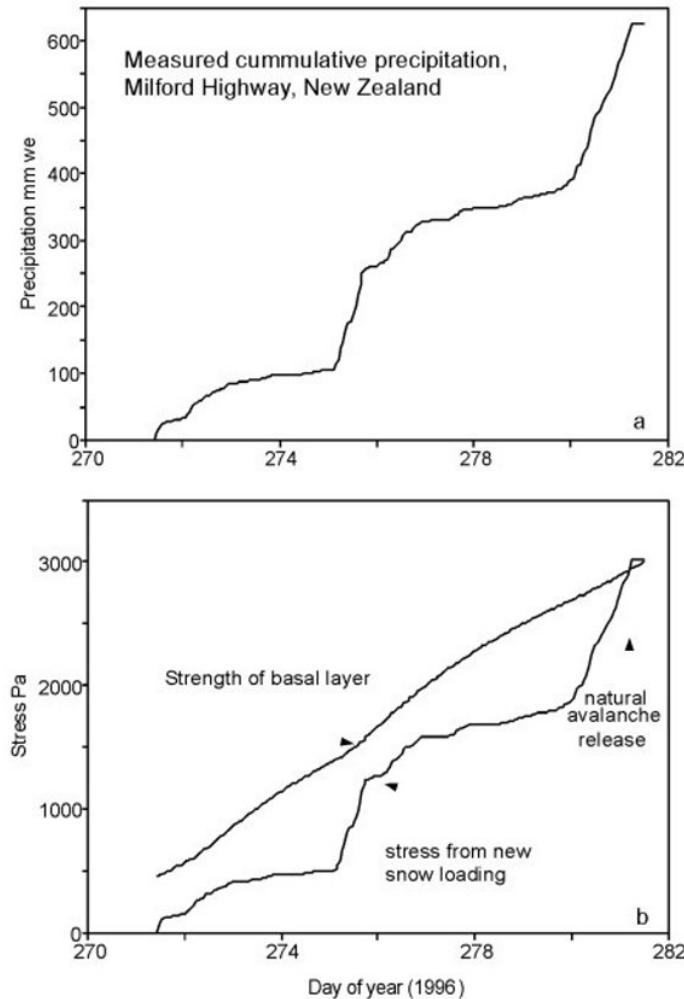


Figure 3. Hourly measurements of precipitation (upper figure) yield an estimate of the stress from the new snow. For a slope of angle  $\theta$  and cumulative precipitation  $P$ , the down-slope stress from the new snow at time  $t$  is  $\sigma_{xz}(t) = g \sum_0^t P \cos \theta \sin \theta$ , where  $g$  is the gravitational constant. Strength of the basal layer depends on density, which increases with time and the overburden stress. Slab failure is predicted soon after the stress from the overburden exceeds the strength of a buried layer.

Accurate prediction of slope stability and timing of slab avalanche release is still problematic because it is difficult to adequately define the spatial and temporal distribution of such small-scale zones of weakness. The potential for abrupt changes associated with changes in weather, especially strong melting or rain, and mechanical disturbance, for example from skiers or explosives, further complicates the problem. Avalanche activity on adjacent slopes is a clear indication that conditions are unstable,

while field tests of snow strength such as shear tests, ski-tests, or disturbance with explosives are useful but equivocal, because such tests may not detect a small zone of weakness that could be critical to slope release. Experience with the response of specific avalanche paths to actual weather conditions is still paramount for predicting the time of avalanche release.

### **2.3 Run-out distances and return periods**

Avalanche run-out distances and return periods are best determined from historical records and/or observations of damage to vegetation or structures supplemented with results from models. However estimating dates by counting annual rings of broken stumps and trees in a path is subject to considerable uncertainty, and historical records of sufficient quality or direct observations are not always available. Further, new or larger avalanches might occur during an extreme storm or if human activities such as logging have altered the terrain. In such cases, run-out and return periods can be estimated using deterministic or statistical models.

The deterministic approach uses a dynamic flow model to calculate the velocity profile down a slope. The run-out position is defined when the speed of the flow reaches zero. Information about the volume of the avalanche, the shape and angle of the track, and the resisting forces are required input for the flow model. The volume can be estimated from the amount of new snow accumulation during a storm; return periods for extreme avalanches can be estimated from the expected frequency of extreme storms. The resisting forces, which include friction underneath the avalanche, air drag at the front and upper boundary, and ploughing at the front and base are not well known. Although models of this type are useful, they are not yet sufficiently definitive for hazard mapping.

Statistical models are developed from run-out data measured from other paths in the region. The premise of this approach is that the angle  $\alpha$ , measured from the position of maximum run-out to the top of the start zone, is regionally similar. A probability distribution of  $\alpha$  angles is developed from measurements (at least 30 are recommended) for each region of interest, and used for paths where run-out has not been measured. In most regions however, values of  $\alpha$  vary from about  $15^\circ$  to  $50^\circ$ , and this wide range of values limits the accuracy of prediction. When good historical information about activity of a path is lacking, model derived run-out distances and return periods must be applied conservatively and with considerable caution.

### **2.4 Strategy for mitigation**

Snow avalanches affect people directly by causing injury or death, restricting transportation, destroying structures, limiting access to areas of activity and altering the natural environment. Impact craters have been observed at the bottom of some avalanche paths, and large avalanches can destroy concrete structures, mature forests and villages. The cost of avalanches to society is difficult to determine. In addition to direct damage, there are indirect costs associated with mitigation, loss of travel and business opportunity, litigation and insurance. Although on average the number of avalanches has not changed over the past century, the hazard has increased as more

people travel and build structures in mountainous regions. During the extraordinary winter 1998-99 in Switzerland, direct damages from avalanches, snow pressure and snow loads amounted to 440 million Swiss francs, and indirect damages due to financial losses in tourism, commerce, industry, power supplies etc. were about 180 million Swiss francs.

Although understanding of avalanche occurrence and run-out is improving, models are not yet sufficient to accurately predict the size and time of avalanche release. Accidents and damage can be prevented either by controlling the avalanches or by regulating the presence of people and structures in the avalanche path. Hazard maps containing information about avalanche run-out distance, frequency and potential impact pressures are a first step to guide land-use. Hazard zones are typically defined in terms of the return period and the potential impact pressure. In a zone of high hazard (red zone), an avalanche with impact pressure  $\geq 30$  kPa is expected in less than 300 years. New structures and buildings are not allowed in a red zone. Existing buildings must be protected and an evacuation plan is required. In a zone of moderate hazard (blue zone), impact pressures are expected to be  $< 30$  kPa with a return period between 30 and 300 years. New houses are allowed provided they are protected, but schools, lodges or other buildings that attract large crowds are not allowed. Avalanches are rare (return period  $\geq 300$  years) in a zone of low hazard (yellow zone) but structural measures against powder avalanches may be recommended. No avalanches are expected to reach a white zone and there are no restrictions to development.

Passive control methods such as avalanche warning, temporary closures of roads or ski areas, and evacuations are effective during times of high hazard. Active control of potential avalanche slopes using hand charges and/or explosives deployed by artillery, trams or helicopters is common at ski areas and highways. Engineering structures that retain snow in the start zones and retard flow in the track and run out zone are used widely to protect structures and villages, especially in Europe. All these control techniques minimize but do not eliminate the risk from snow avalanches.

### **3. Ice avalanches**

#### **3.1 Description of ice avalanches**

Unlike snow avalanches, ice avalanches originate from perennial ice masses and can occur at any time of the year. In most cases they are the normal means of mass wastage of steep, alpine glaciers or *hanging glaciers*. Although ice avalanches are relatively rare, in some cases they do threaten settlements and other fixed installations. Several avalanches consisting of more than  $10^6$  m<sup>3</sup> of ice have occurred in the Alps; the destructive power of an ice avalanche increases during winter when snow may be entrained by the flow. Particularly destructive avalanches may be generated when rock and soil is entrained into the flow; such mixed-flow avalanches can run long distances.

The most destructive avalanches on record occurred in the Peruvian Andes in 1962 and 1970. In 1962, a large snow and ice avalanche from Mount Huascarán traveled 16 km into the Santa Valley, destroying 9 small towns and killing more than 4,000 people. In



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## Biographical Sketches

**Howard Conway** became interested in snow avalanche release mechanisms while working at Mount Cook National Park in New Zealand. His Ph.D. thesis (1986 from the Department of Chemical Engineering at the University of Canterbury, N.Z.) focused on the spatial variability of snow strength. He came to the University of Washington, Seattle, U.S.A. in 1987, and is now Associate Professor of Geophysics. Recent research interests include: snow avalanche release mechanisms; response of glaciers to climate; basal processes at sub-freezing temperatures; and remote sensing of glaciers and ice sheets.

**Charles Raymond** started the study of glaciers when he was a graduate student in Geophysics at the California Institute of Technology. Since graduation, he has been on the faculty of the University of Washington in the Geophysics Program. One of his major research activities has been the examination of glacier surge behavior based on long-term field observations. His research also examines more generally the relation between glacier fluctuations and climate. Controls on the speed of fast moving Antarctic ice streams and the stability of the West Antarctic Ice Sheet have been his major research foci during the last decade. Teaching has included courses on continuum mechanics, glaciology and the physics of ice.

**Martin Funk**, after graduating from the Swiss Federal Institute of Technology of Lausanne (EPFL) with a civil engineering diploma in 1979, became a Swiss Mountain Guide in 1982. He attained a doctorate in glaciology from the Swiss Federal Institute of Technology of Zurich (ETHZ) in 1984 on *Mass balance on Rhonegletscher and its relationship to climate elements*. From 1979 - 1985 he worked as a research scientist at the Institute of Geography of the ETHZ. Since 1986 he has worked at the Laboratory for Hydraulics, Hydrology and Glaciology (VAW) of the ETHZ, and since 1992 he has been head of the glaciology department. Today his work includes management, research, consulting and teaching. Martin has been involved in many national and international research projects including ice dynamic modeling, determination of ice temperatures, deformation rates and internal layering of ice streams (Jakobshavn Isbrae, western Greenland), determination and parameterization of calving rates (Nordbogletscher, southern Greenland) and examination of the stability of steep glaciers. He has many years of experience in radio echo sounding on different glaciers in the Alps, Canadian Arctic and South America as well as in mass balance investigations on Swiss glaciers. He consults hydro-power companies (investigating the glaciology and hydrology of catchment basins), municipalities and mountain railways (surveying natural hazards such as ice avalanches and floods from glacier-lakes). At the ETHZ he lectures "Applied Glaciology" and supervises Ph.D. as well as Diploma theses.

**Stefan Margreth**, who has a civil engineering diploma from the ETH Zurich, works in the field of avalanche protection. Since the early nineties, he has performed consulting tasks all over the world, among them hazard mapping of ice and snow avalanches, design of protection measures for endangered objects as well as risk analysis. He is leader of the avalanche protection team of the Swiss Federal Institute of Snow and Avalanche Research at Davos (Switzerland). At present, his research focuses on snow pressure measurements on different snow supporting structure types. Besides that, he validates the effectiveness of avalanche protection measures. Since 1989 he has been a member of the Swiss avalanche and rock fall expert group.