Snow Avalanches

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9.1
Introduction

Snow avalanches represent a threat to societies in many countries of the world. In America, Asia, Australia, and Europe, several mountainous countries are affected by this type of natural hazard. People, housing areas, communication lines, ski areas, animals, and woodland are subjected to the threat of snow avalanches.

On a world basis, snow avalanches do not represent the most serious natural hazard, but in many mountainous areas of the world, snow avalanches are the most frequent and most serious natural hazard.

Every year in Europe, all the Alpine countries including Switzerland, Austria, Italy and France report fatal accidents and major material damage caused by snow avalanches. Other countries like Spain, Russia, Iceland, Sweden and Norway are also affected.

The best known country with snow avalanches is probably Switzerland, not only because of many disasters, but also because of the extensive snow avalanche research that has been performed for more than 60 years. Statistics from Switzerland indicate that about 25 persons per year are killed in snow avalanche accidents, and about twenty living houses are damaged each year on average. Nearly 100 other kinds of buildings are affected each year. In addition, several roads are closed each winter. Apart from the loss of lives, the total material damage in Switzerland added up to SFR 10 million in 1972, or ECU 6 million. The corresponding value for 1998 might be about ECU 40–50 million, which is a considerable amount of money.

Presently, Switzerland uses SFR 26 million (ECU 15 million) per year in research and snow avalanche protection (Føhn 1998, personal communication).

In Austria, snow avalanches are a major natural hazard. Every year, Austrian society spends about 1 200 million Austrian Shillings, (ECU 100 million) on avalanche and torrent control, and 250–300 million Austrian Shillings, (ECU 22–26 million) on snow avalanche control. Like in Switzerland, 20–25 persons are killed by avalanches on a yearly basis. Most of these are ski tourists (Hopf 1998, personal communication).

The most serious avalanche winter in the Alps in this century was in the winter of 1950/51. In Switzerland, 100 persons were killed, and in Austria, 135 lost their lives. Another catastrophic winter occurred in 1954 when 143 persons were killed in Austria, most of them in Vorarlberg.

In Iceland, another heavily affected country, 64 people have been killed in snow avalanches and slush floods since 1974, two persons per year on average. Fifty-two of these people were killed in buildings, most of them in three major disasters (Johannesson et al. 1996). In one of these accidents, twenty persons were killed in the small town of Flateyri by one single avalanche. The total material loss is estimated to be ECU 50 million since 1974. When the loss of lives is included in the costs, the cost increases to ECU 130 million. The estimated value of one human life is set to ECU 1.25 million. This value is based on figures from different countries in western Europe of what society is willing to spend on life-saving operations.

In Norway, about five persons are killed every year in snow avalanches. In this country, major avalanche winters seem to occur every thirteen years on average. In such major avalanche winters, ten to twenty persons are killed, and material damage is on the order of NOK 100–200 million (ECU 12.5–25 million).

In 1868, 161 persons were killed by avalanches in Norway. In the winter of 1986, 22 persons were killed; sixteen of these were soldiers taking part in a military exercise.

In conclusion, one may summarise the effects and consequences of snow avalanches on society to:

1. Loss of human lives
2. Material damage
3. Forest damage
4. Illness, sickness, and reduced physical health
5. Traumatic effects and reduced psychological health
6. Evacuation costs
7. Rescue and preparedness operations
8. Traffic delay and detours.

Who are affected by avalanche accidents? In brief, the following categories can be included:

- People dwelling in houses
- Persons in huts and other kinds of buildings
- Road and railway users
- Maintenance personnel
- Construction workers
- Military personnel
- Ski tourists
- Climbers
- Hunters
- Snow vehicle drivers
- Domestic and wild animals

In earlier years, most of the avalanche victims were hit in their homes or in other kinds of buildings. In the later decades, an increasing percentage of ski tourists have been killed, and presently the majority of accidents include ski tourists.

9.2 Avalanche Formation

In avalanche formation, three factors are important:

- Topography
- Snow pack
- Weather conditions

9.2.1 Avalanche Topography

Avalanche topography shows a great diversity in land forms. The vertical height of avalanche slopes ranges from more than 2 000 m down to 10 m. An avalanche may be more than 1 000 m broad and 3 000 m long, and contain more than 1 million m^3 of snow. On the other hand, avalanches released from slopes with vertical drop less than 10 m may be lethal.

An avalanche path is usually divided into three zones (Fig. 9.1):

1. Starting zone
2. Track
3. Runout zone

9.2.1.1 *Starting Zone*

Normally, avalanches that are big enough to create danger and damage are released in slopes with inclinations between 30 and 50° (Fig. 9.2). If the slope is gentler than 30°, the friction forces are big enough to hold the snow cover in place; if it is steeper than 50°, the snow glides off in small portions or sloughs during the accumulation.

For practical purposes, one may say that all slopes and mountain sides within the mentioned limits of inclination are potentially dangerous, if the slope is not covered by dense tree growth or big boulders and other kinds of rough topography that is not covered by snow during the winter.

The starting zone may be more than 1 000 m wide, and down 20–30 m. The starting zones are usually found in terrain formation where abundant snow is collected. This usually includes all kinds of depressions where snow deposition is heavier than elsewhere because of the lee effect. As the wind blows across a mountain slope, snow is eroded away from wind-exposed areas and deposited in areas where the wind velocity is low. The most common types of starting zones are:

- Cirques, formed by earlier glaciation
- Open, shallow depressions
- Deeply incised scars and gullies
- Plane rock faces
- Convex land forms

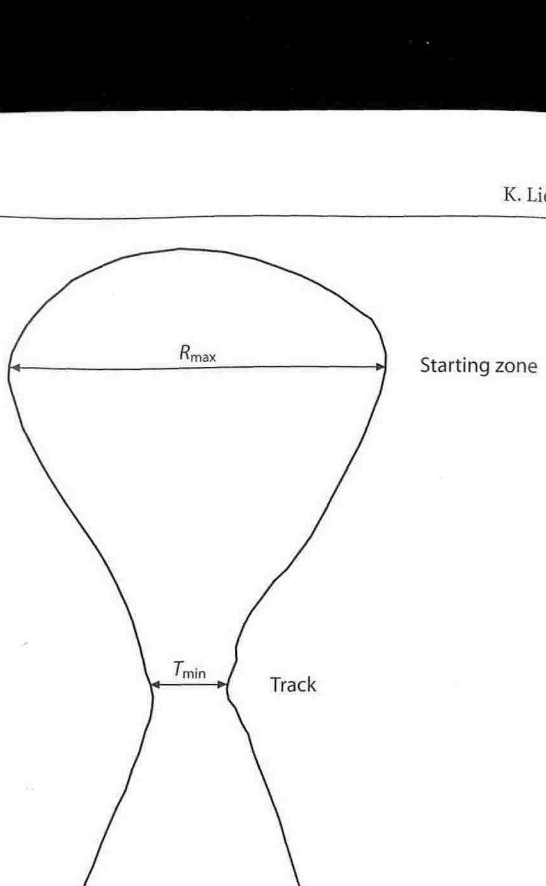


Fig. 9.1. Zones of an avalanche path

9.2.1.2
Track

When the terrain inclination is between 30° and 10–15°, the part of the path is defined as the avalanche track. The track is usually more narrow than the starting zone, as the avalanche normally starts in a relatively wide area and is confined into a narrow track. The track is often a river course, a scar or some kind of depression, but open flat portions of slopes are also seen. Many avalanches are unconfined, as they run in a constant width from start to stop.

9.2.1.3
Runout Zone

In the runout zone, the terrain inclination is less than the friction angle of the snow, and the avalanche is slowed down and gradually comes to rest. Many runout zones are found on river fans, others in flat valley bottoms. The runout lengths of major avalanches are usually several hundred metres, and sometimes big avalanches have

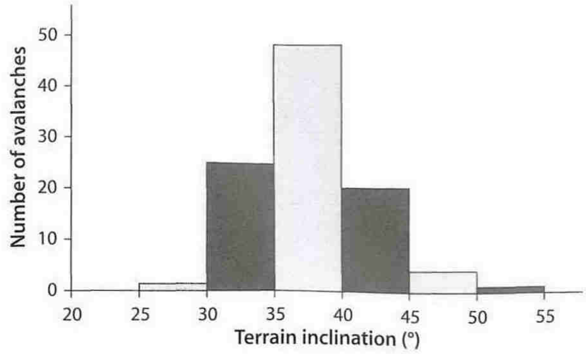


Fig. 9.2. Relation between avalanche frequency and terrain inclination

their runout on the opposite mountainside. Major dry avalanches usually obtain the longest runouts on gentle inclined terrain, mostly less than 10°. In wet snow avalanches, the friction resistance is higher, and such avalanches usually come to rest at inclinations between 10° and 20°, depending on the roughness of the terrain and the volume of the avalanche snow.

9.2.2 Snow Pack

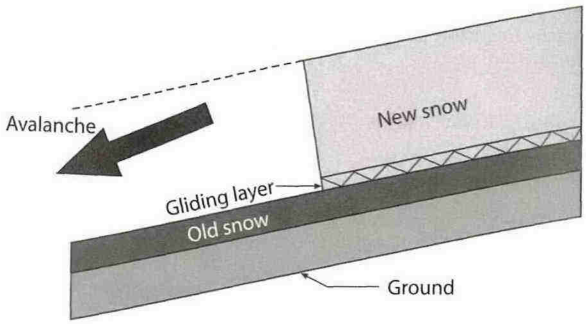
The typical snow-pack structure related to an avalanche situation is the following:

1. Older snow with high density and strength near the ground.
2. Thin weak-layer with little strength covering the old snow.
3. New snow, moderately wind packed, 0.5–1.5 m thick at the top.

The rupture is commonly thought to occur as a shear failure in the weak layer, followed by a tension failure at the top of the snow slab (Fig. 9.3). Experience has proved that high intensities of snow accumulation in the rupture zone increase the possibility for a failure. Based on a Coulomb-friction criterion for the slab and measured figures for cohesion, it is difficult to obtain a failure for evenly distributed shear stress values. The deformation velocity of the uppermost layer is of vital importance for the stability, as the shear strength will drop to residual values, which are pronounced lower than the peak strength for high deformation rates (Fig. 9.4). In nature, the deformation rates are found to be too low to create a failure without the existence of stress concentrations in the snow cover. Such stress concentrations must be located to superweak spots in the weak layer where the rupture is initiated. The stress concentration increase with the size of the superweak spot or layer, and is inversely proportional to the thickness (Fig. 9.5).

Access to the starting zones with measurements of the weak layers in an avalanche situation is hazardous and for practical purposes not possible. All measurements and evaluations must therefore be performed in areas with different snow and terrain conditions than in the actual rupture area. The evaluation of the snow-pack stability is therefore even today based on subjective methods and practical experience.

Fig. 9.3. Principle layering of snow cover



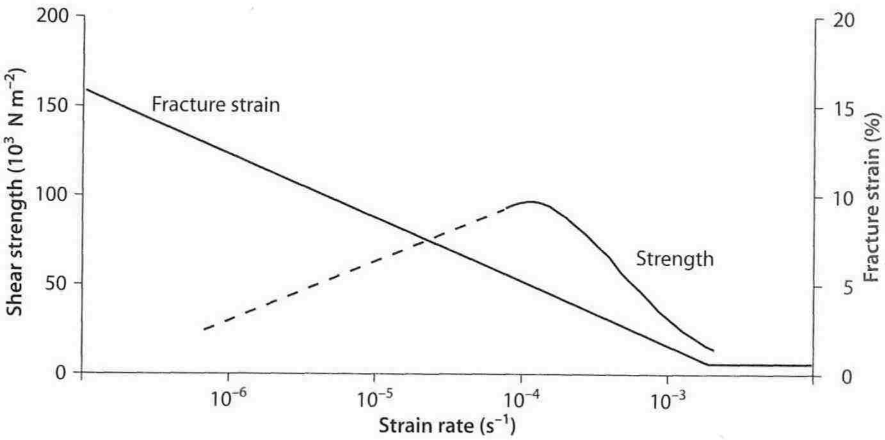


Fig. 9.4. Relation between strain rate and deformation

9.2.3
Weather Conditions

The main weather factors that control avalanche formation are:

- Snow precipitation and intensity
- Wind speed and wind direction
- Air temperature

Many models and methods have been used to predict and forecast avalanches (Føhn 1998, personal communication), but no method exists today that can predict exactly where and when an avalanche is going to occur.

The amount and rate of new snow that is accumulated in the starting zone is the most important factor concerning the immediate avalanche hazard. Table 9.1 gives an indication of the avalanche hazard compared to the amount of new snow.

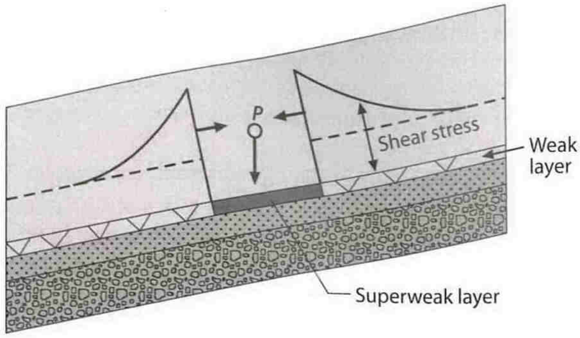


Fig. 9.5. Shear stress maxima in super weak layer

Table 9.1. Indication of avalanche hazard compared to amount of new snow

New snow depths in 3 days (cm)	Avalanche hazard
10	Small local sloughs
10 – 30	Minor slab avalanches; loose snow avalanches
30 – 50	Many local slab avalanches
50 – 80	General avalanche hazard; some major avalanches run down to the valley floor
80 – 120	Abundant major avalanches run down to the valley floor – also outside earlier known areas
> 120	High probability for catastrophic avalanches

At NGI, we have concentrated the work mainly to the connection between precipitation rates and avalanche occurrence. By plotting the precipitation in three and five days as a cumulative normal distribution, the possibility for an avalanche may be quantified. The method is tested for five different paths near the avalanche research station, with 25–37 avalanche events in each path. The straight line between the avalanche observations shows the strong connection between the amount of precipitation and the possibility for an avalanche (Fig. 9.6).

The precipitation intensity is of high importance for the avalanche hazard, as a certain intensity is needed to create a hazard. Generally speaking, an intensity of 2–2.5 cm of new snow per hour is regarded as dangerous.

The *wind* is of high importance for the formation of avalanches, as the wind is capable of transporting great amounts of snow into mountainous terrain. Major avalanches nearly always occur in connection with wind-deposited snow. As the wind velocity increases to more than 5–8 m s^{-1}, the snow starts to drift if the temperature is below zero degrees. Increasing wind forces transport higher amounts of snow, as the snow transport is proportional to the third power of the wind speed. Investigations show that lee-ward positions in the mountains may collect four times more snow than average wind exposed locations during periods with moderate wind speeds.

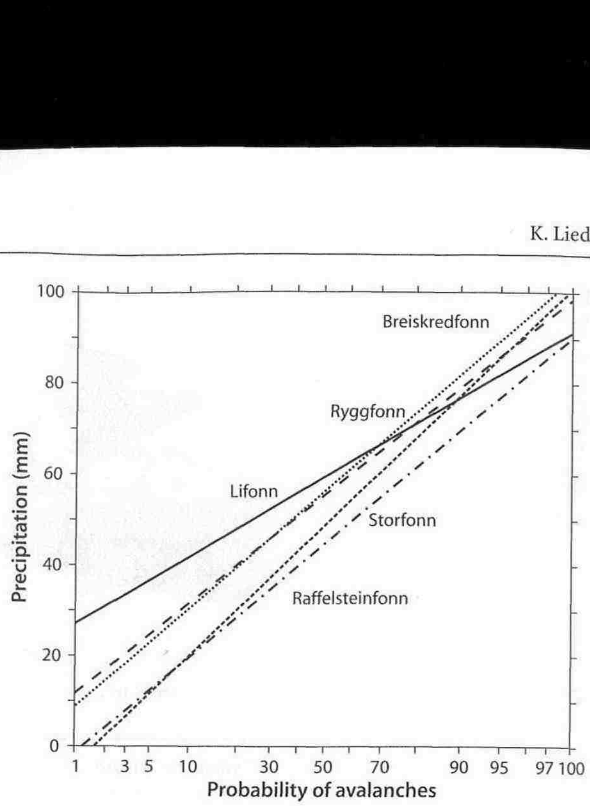


Fig. 9.6. Probability of avalanches in relation to precipitation.

Temperature is important for the strength and recrystalisation of the snow cover. Decreasing temperatures increase the strength of the ice in the snow crystals, and thereby make the snow pack stronger. On a long-term basis, low temperatures induce transformations of the snow crystals, such that internal bonds between the crystals disappear. The result is a loose aggregate of coarse grained snow (depth hoar) where the strength is heavily reduced.

Increasing temperatures decrease the strength, and at first increase the avalanche hazard. On the other hand, higher temperatures increase settlement in the snow cover, and the density and strength increases because of this. The effect of a temperature increase is therefore two-fold. First: the hazard increases, thereafter the hazard decreases as the snow settles.

9.3 Runout Models

One of the most difficult questions to answer concerning snow avalanche is the question of avalanche runout. How far will an avalanche travel into the runout zone, and how often will this happen? This is perhaps the most important problem concerning land use planning in avalanche-prone areas.

Many models have been tried out to solve this question, but we have to admit that we do not have models or methods that predict avalanche runout to the accuracy we need for hazard zoning and land use planning. Harbitz (1996b) has given an overview of different computational models for snow avalanches, on which the description in this chapter is based.

Snow avalanches usually start as a slab, about 0.5–3 m thick. The rupture consists of a tensile failure at the upper boundary and a shear failure at along a weak layer in the snow pack. The slab may have a width ranging from about 50 to 1 000 m or more, including snow volumes on the order of 10^2–10^6 m^3.

During the rupture and shortly afterwards, the slab breaks into blocks that glide on older layers of snow deeper in the snow pack. As the velocity increases, the blocks are broken into smaller pieces, turbulence increases and the movement takes the form of a particle flow. In bigger dry avalanches, maximum velocities are about 60–80 $m\,s^{-1}$.

Most avalanches consist of at least two parts. One is referred to as a dense snow avalanche (or flowing avalanche) which is a gravity flow. The other is a turbidity part referred to as an (airborne) powder snow avalanche, which is driven by the extra weight of small snow particles (<1 mm) suspended in the air. A fully developed avalanche can be divided in four flow layers. The major volume of the avalanche is represented by the basal and liquefied *dense flow layer*, where the particles are in close contact, and the volumetric density is high. The density is assumed to be almost constant. Above the dense flow layer is the transitional *saltation layer*, where the particles are transported in jumps similar to saltating particles in drifting snow. The volumetric density is reduced to a power of three with height in the saltating layer. Then the *suspension layer* follows, which constitutes the snow cloud of the avalanche. Here the density and the velocity are both reduced almost linearly with height. Above and around the avalanche is a backflow of air named the *recirculation layer*, with a height one to three times that of the suspension layer. The latter three layers constitute the turbidity part.

Since the material properties differ, the distinction between wet snow (generally cohesive with possible snowball formation) and dry snow (no free water content) avalanches is useful. Dense snow avalanches can occur under both wet and dry snow conditions. A turbidity part is normally generated in both circumstances, especially in steep slopes. Pure powder snow avalanches require dry snow conditions.

Both wet snow and dry snow avalanches involve high internal deformation and are more or less in a liquid state. For wet snow avalanches, solid concentrations are high, and energy dissipation is caused mainly by particle interactions. In dry snow avalanches, energy dissipation is caused mainly by particle interactions at high solid concentrations and by viscosity in the interstitial air at low concentrations.

The first attempt to formulate a general theory of avalanche motion was made by Voellmy (1955), and this theory is still widely used. Increased human activity in mountain regions, deforestation from pollution, forestry and ski resorts as well as anticipated warming of the Earth's atmosphere have caused a growing interest in the study of catastrophic avalanches.

Both statistical and comparative models for runout distance computations as well as dynamic models for avalanche motion simulations are now developed (Harbitz 1996a). However, no universal model has so far been made. The dynamics of avalanches are complex, involving fluid, particle and soil mechanics. The limited amount of data available from real events makes it hard to evaluate or calibrate existing models. Often several models with different physical descriptions of the avalanche movement can all fulfil the deficient recorded observations.

Material properties, boundary conditions, release mechanisms, impact pressure, defence structures, physical experiments, case studies or other related avalanche topics are omitted in this brief report.

9.3.1 Statistical α/β-Model

The statistical α/β-model (Lied and Bakkehøi 1980; Lied and Toppe 1989) was developed at NGI and governs maximum runout distance solely as a function of topography. The runout distance equations are found by regression analysis, correlating the longest registered runout distance from 206 avalanche paths to a selection of topographic parameters. The parameters that have proved to be most significant are listed in Table 9.2.

The β-angle is empirically found to be the best characterisation of the track inclination (Fig. 9.7).

The inclination θ of the top 100 vertical metres of starting zone indirectly governs the rupture height, and thereby the slide thickness, which is greater in gentle slopes than in steep slopes. Hence, smaller values of θ give longer runout distances or a smaller average inclination of the total avalanche path, α.

Table 9.2. Topographic parameters governing maximum runout distance

Symbol of parameter	Parameter description
β (deg)	Average inclination of avalanche path between starting point and point of 10° inclination along terrain profile
θ (deg)	Inclination of top 100 vertical meters of starting zone
H (m)	Total height difference between starting point and lowest point of best fit parabola $y = ax^2 + bx + c$
y'' (m^{-1})	Curvature of avalanche path

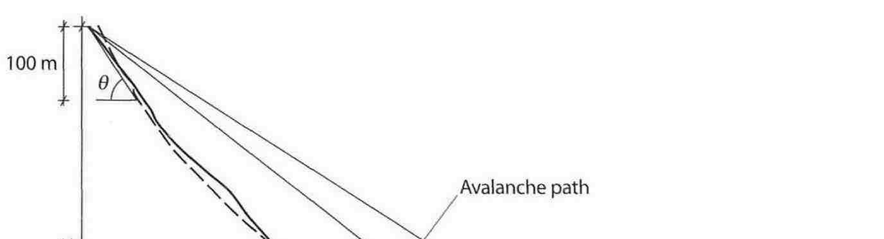


Fig. 9.7. Topographic parameters describing terrain profile (after Lied and Toppe 1989)

In Norway, most avalanche paths might be approximately described by the parabola $y = ax^2 + bx + c$, of which curvature is described by the second derivative $y'' = 2a$.

In slide paths with little difference in height, H, a smaller part of the potential energy is transformed into heat by friction. Hence, the avalanches have an apparently lower coefficient of friction, and obtain theoretically a smaller runout angle.

For a parabolic slope, the β-angle is determined by:

$$\beta = \tan^{-1}\left(\sqrt{\frac{Hy''}{2}} + \frac{\tan 10°}{2}\right)$$

Smaller values of the product Hy'' mean smaller values of β. This results in smaller values of α, because the avalanches run with smaller velocity, and the velocity-dependent frictional transformation of potential energy into heat is reduced.

The topography, the width and the degree of lateral confinement in the starting zone, as well as the drifting snow transport into the starting zone have little influence on the runout distance (Lied and Bakkehøi 1980). As opposed to what was presumed, no tendency was found that an avalanche with a wide rupture zone, which is channelled into a narrow track, has a longer reach than an avalanche following an unconfined path.

The regression analysis revealed that the β-angle is the most important topographic parameter. The result of the regression analyses is included in Table 9.3.

The model is most appropriate for travel distance analysis along longitudinally concave profiles. The calculated runout distances are those that might be expected under snow conditions favouring the longest runout distances. The authors have no explanation as to why there is such a small correlation in the data for $30° < \beta \leq 35°$.

Lied and Toppe (1989) redefine the starting zone as the part of the path lying between the starting point and the point of 30° inclination along the terrain profile. The average inclination of this zone is termed γ. They further describe the automatic computation of the avalanche parameters. Applying the relation $\alpha = f(\beta, \gamma)$ for 113 avalanches, the equation $\alpha = 0.91\beta + 0.08\gamma - 3.5°$ gives $R^2 = 0.94$ and SD = 1.4°, which is a small improvement to the relation between α and β in Table 9.2. Lied and Toppe (1989) also present combinations of the lengths of the starting zone, the avalanche track and the runout zone, L_1, L_2 and L_3 respectively, as well as the area A of the starting zone (evaluated subjectively from local topography as a substitute for the avalanche volume). The best relation is:

$$L \equiv L_1 + L_2 + L_3 = 0.93L_1 + 0.97L_2 + 0.61m \cdot [A] + 182m$$

with $R^2 = 0.96$ and SD = $137m$ ([A] represents the numerical value of A in m^2). Using L_3 alone as the dependent variable does not give R- and SD-values that enable sufficiently accurate calculations of runout distance. The prediction of path lengths will give runout distances independent of steepness of path, as opposed to the more realistic α/β-relations. McClung and Lied (1987) show that the avalanches with the 50 highest values of the ratio $L_3/(L_1 + L_2)$ give a very good fit to an extreme-value distribution.

Table 9.3. Results of regression analysis (with standard deviations (SD) and correlation coefficients (R). $[H]$ represents the numerical value of H

Assumption	No. of avalanches	Regression equation, $\alpha =$	Accuracy		Standard deviation (m) $H = 1\,000$ m, horizontal run-out		
			SD (deg)	R [-]	α (deg)	-ΔL (m)	ΔL (m)
$\beta \leq 30^\circ$	68	$0.89\beta + 0.035\theta - 2.2 \times 10^{-4}[H] - 0.9^\circ$	1.49	0.84	25	138	154
$30^\circ < \beta \leq 35^\circ$	59	$1.15\beta - 2.5 \times 10^{-3}[H] - 5.9^\circ$	2.50	0.53	30	162	189
$\beta > 35^\circ$	79	$0.81\beta + 0.036 Hy''\theta + 3.2^\circ$	2.67	0.62	36	127	144
$\beta \leq 30^\circ, H \geq 900$ m		$0.94\beta + 0.035\theta - 2.6^\circ$	1.02	0.90	25	96	103
All avalanches	206	$0.96\beta - 1.4^\circ$	2.30	0.92			
All avalanches	206	$0.92\beta - 7.9 \times 10^{-4}[H] + 0.024 Hy''\theta + 0.04^\circ$	2.28	0.92			

The assumption of small variations in the physical snow parameters giving the longest runout distance is only valid within one climatic region. Martinelli (1986) and McClung et al. (1989) have applied the basics of the statistical α/β-model in mountainous regions outside Norway.

The avalanche database of NGI is constantly extended, and contains at present 230 events. Both the statistical and the dynamic models are occasionally recalibrated.

9.3.2 Voellmy Block Model

Voellmy's (1955) model is a one-dimensional block model for the calculation of avalanche runout distance.

The sliding mass is considered as an endless fluid of height H reaching a terminal velocity by equilibrium of gravitational forces and shear forces on an infinitely long slope of constant inclination θ_1. Based on hydraulic theory, the shear forces are represented by a dynamic drag proportional to the terminal velocity squared on the free, upper surface and a combination of a similar dynamic drag and a Coulomb friction proportional to the normal forces along the bed. Hence, the terminal velocity is expressed by the two-parameter equation:

$$V_t = [\xi H(\sin\theta_1 - \mu\cos\theta_1)]^{1/2}$$

where density and drag coefficients are lumped together into the 'coefficient of turbulent friction,' ξ (m s^{-2}), and μ is the Coulomb friction coefficient. To account for lateral confinement, H is replaced by the hydraulic radius (flow cross-sectional area divided by wetted perimeter).

The deceleration starts at a certain reference point, normally located where the actual slope inclination equals $\tan^{-1}\mu$. From this point, the runout distance on a slope of constant inclination θ_2 is computed by energy considerations:

$$S = V_t^2\left[2g(\mu\cos\theta_2 - \sin\theta_2) + V_t^2 g/(\xi H_D)\right]^{-1}$$

H_D is the mean deposition depth accounting for the energy loss due to pile-up of debris, and g is the acceleration of gravity.

The computed runout distance is based on the assumption that terminal velocity is reached, and it depends strongly on the selected location of the reference point as well as on the values of the input parameters.

9.3.3 PCM Block Model

The 2-parameter PCM model (Perla et al. 1980) is a further development of Voellmy's model above. The avalanche is described as a one-dimensional block of finite mass moving on a path of varying curvature. The reference point is the initial rest position of the block's centre of mass. The equation of momentum includes Coulomb friction, centrifugal force due to curvature of the path, dynamic drag and inertia resistive ploughing. The Coulomb friction term consists of an adjustable friction coefficient μ multiplied by the normal force along the bed. The latter three terms are all proportional to v^2, the tangential velocity squared, and hence lumped together into one term consisting of v^2 divided by the second adjustable parameter interpreted as a mass-to-drag ratio, M/D (m^{-1}). The result is a linear differential equation in v^2:

$$\frac{1}{2}\frac{dv^2}{ds} = g(\sin\theta - \mu\cos\theta) - \frac{D}{M}v^2$$

where θ is the local inclination, s is the slope position and g is the acceleration of gravity. However, the inclination and perhaps the adjustable parameters are not constant along the path. An iterative solution procedure is described, dividing the slope into small segments of constant inclination and parameter values. To compensate for the absence of curvature along the linear segments, the velocity is corrected for conservation of linear momentum at each segment transition.

The usefulness of the model depends on a knowledge of the two adjustable parameters that can vary considerably. For avalanches, these values have been limited to some extent by testing the model statistically on 136 extreme paths in the north-western USA and Norway and on 206 extreme paths in Norway.

Alean (1984, 1985) analysed nineteen ice avalanches to establish parameter values and test whether the PCM model might be applicable for such events. He concludes that deviations between model predictions and observations are 'disappointingly high,' and that a one-parameter model leads to only slightly worse predictions of runout distances for ice avalanches.

For constant inclination and parameter values along an infinitely long slope, the result is analogous to that of Voellmy.

9.3.4
NIS Visco-Elastic Plastic Deformable Body Model

The dynamic model developed by NGI, the NIS-model (Norem et al. 1987), was originally developed for avalanches and has also been applied to submarine flowslides. Thus, it is constructed to treat both kinds of energy dissipation regimes. The mathematical deformable body model describes a two-dimensional, non-steady shear flow of varying height with slip velocity conditions when erosion is omitted or with no-slip velocity conditions when erosion is included. The shear flow moves along an arbitrary path originating centrifugal forces. The constitutive relations, which contain the visco-elasticity of a CEF-fluid (Criminale-Ericksen-Filbey 1958) combined with plasticity for a cohesive material, yield (as depicted in Fig. 9.8) for the normal stresses σ_x and σ_y parallel and normal to the slope respectively, and for the shear stress τ_{xy}:

$$\sigma_x = p_e + p_u - \rho(v_1 - v_2)\left(\frac{dv_x(y)}{dy}\right)^r$$

$$\sigma_y = p_e + p_u - \varrho v_2 \left(\frac{dv_x(y)}{dy} \right)^r$$

$$\tau_{xy} = a + p_e \tan\varphi + \varrho m \left(\frac{dv_x(y)}{dy} \right)^r$$

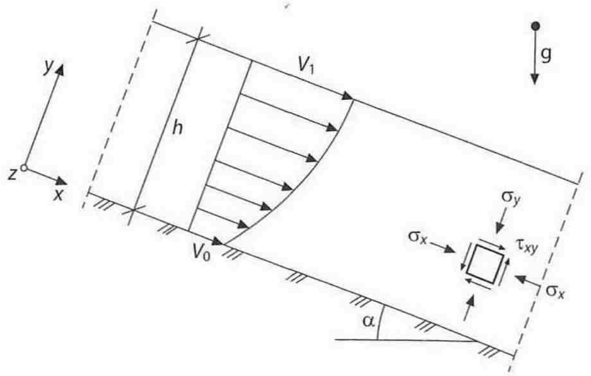
where p_e is the effective pressure (all normal compressive stresses have a positive sign according to soil mechanic practice), p_u is the pore pressure, ϱ is the average density of the flowing material, v_1 and v_2 are the normal stress viscosities, $dv_x(y)/dy$ is the shear velocity parallel to the slope at a height y above the bed, a is the cohesion, φ is the internal friction angle, m is the shear stress viscosity, and r is an exponent preliminary suggested equal to 2 for rock slides and avalanches (inertial regime) and 1 for debris flows of low concentration and submarine flowslides (macro-viscous regime).

As the viscometric functions are represented by power laws, they express flow induced dispersive pressure and dynamic shear. The model is quasi two-dimensional, as the vertical velocity profile is assumed to be identical in form to the steady shear flow profile. Cohesion and/or upper surface shear stress induce a plug flow velocity profile, as opposed to the parabolic flow profile of a non-cohesive material with zero shear stress along the upper surface.

Cohesion, upper surface shear stress and erosion are omitted in the numerical model. The resulting partial differential equations are solved by a Eulerian finite-difference midpoint scheme in space and a fourth-order Runge-Kutta procedure in time.

The rear and frontal grid cells in the finite-difference representation of the avalanche are considered equal to the other cells in between. Each time the accumulated volume (i.e. volume flux integrated in time) passing through the contemporary avalanche front (i.e. the foremost "wall" of the frontal grid cell) matches the volume of the grid cell ahead of the avalanche (i.e. product of contemporary avalanche front height and grid distance), the avalanche is said to advance one grid distance. Similarly, the rear grid cell is empty and neglected when the accumulated volume flowing out of the cell equals

Fig. 9.8. Definition of steady flow geometry (after Norem et al. 1989)



the volume contained in the cell when it was first defined to be the rear one, as the one behind was emptied.

To simplify comparison with other models, four programme options are implemented:

- Varying flow height and slip velocity conditions;
- Varying flow height and no-slip velocity conditions;
- Varying flow height and uniform profile;
- Constant flow height and velocity profile.

The latter is approximately equal to the Voellmy or PCM models.

Several input parameters are needed: the most important ones are the material friction coefficient (equals $\tan\varphi$) and the initial flow height h of the avalanche. For avalanches, a default value, h_{crit}, is presented for the latter, based upon the fact that an unstable situation occurs when the actual shear stress, $\tau = \varrho g h \sin\theta$ equals the yield strength, $\tau_y = a + \tan\varphi \varrho g h \cos\theta$, of the snow:

$$h_{crit} = \frac{a}{\varrho g(\sin\theta - \tan\varphi\cos\theta)}$$

where g is the acceleration of gravity and θ is the slope angle. The cohesion is eliminated by introducing a known reference height, $h_{40} = 1.3$ m, for a slope angle of 40°:

$$h_{crit} = h_{40}\frac{\sin 40 - \tan\varphi\cos 40}{(\sin\theta - \tan\varphi\cos\theta)}$$

A value of $\tan\varphi = 0.3$ ($\varphi = 17°$) is applied in the computations.

Bakkehøi and Norem (1994) also suggest that the length of the initial avalanche slab should equal one sixth of the total height difference of the slide path, with a maximum of 100 m.

The numerical results are verified by comparing them with and full-scale experimental data of avalanches, submarine slides and rock slides. For avalanches and submarine slides, the front velocity and the runout distance are simulated well by the model. With varying flow height, the programme is less sensitive to the shape of the path, and the computed deposits in the runout zone also agree fairly well with experimental data.

It is an admitted weakness by the authors that the model does not include effects of temperature and volume changes due to altering arrangements of the grains. Neither is the effect of active and passive earth pressure included. However, this effect is probably not significant, as the internal friction is low due to the dispersive stress (Norem 1995, personal communication).

For hazard zoning purposes, it seems that the following models are in use:

1. Lied-Bakkehøi statistical α/β-model
2. Voellmy block model (VSG-version)
3. PCM block model

Most of the other models described in this report need to be verified before they are applicable to snow avalanche hazard zoning. Figure 9.9 illustrates an overview of the different models for snow avalanche runout (travel distance).

9.4 Legislation and Avalanche Hazard

As a basis for the discussion on legislation concerning natural hazards and snow avalanches, the Norwegian system is presented below.

The *Building and Planning Act* in Norway has been under development since 1924, and the act was put into force for the whole country in 1966. The last revision was done in 1987. The building act is used when a detailed hazard plan is made with corresponding detailed maps. The ongoing hazard mapping on survey maps M 1 : 50 000 has been operative since 1979, and up until now approximately 110 maps have been finished. Still, a hundred maps are necessary to prepare, and we still need fifteen more years to accomplish this work. So far, these maps have no legal liability, but they will be used as an aid in land use planning in the communities.

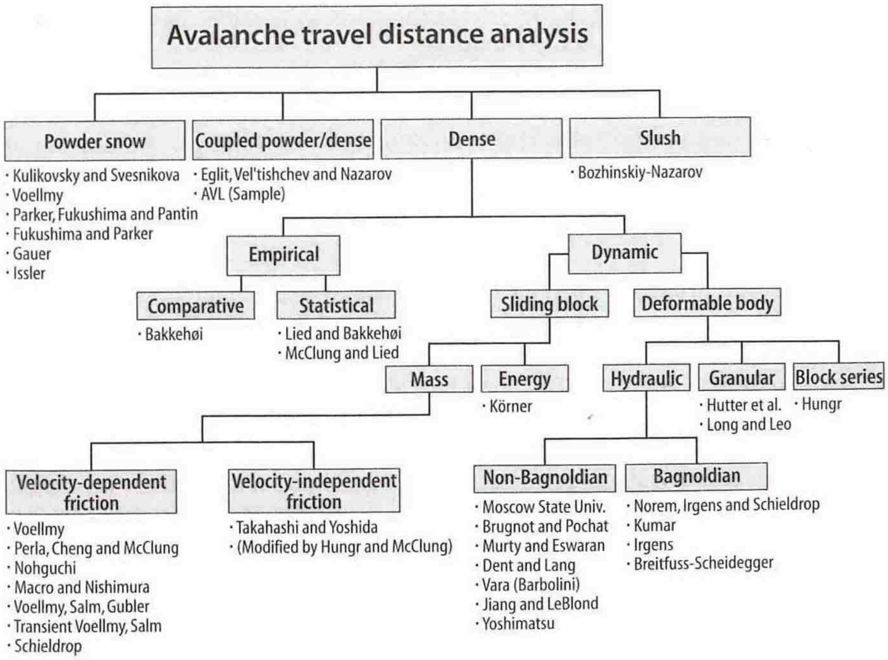


Fig. 9.9. Avalanche travel distance analysis

The building council of the communities will have to follow the rules stated in the act, and advice concerning hazard zones and protective measures is done by NGI as a private consultant in each case. In cases where houses built before 1966 are endangered by avalanches, the National Fund for Natural Disaster Assistance can give financial support to rebuild these houses with protective measures or to move them elsewhere.

In 1980, a new act became operative in Norway, which states that all objects with fire insurance are also obliged to take out natural hazard insurance. Damages caused by avalanches will normally be compensated in full unless the client has shown gross negligence. However, insurance companies will neither initiate any hazard evaluation nor safety measures. They may, on the other hand, increase the insurance premium or refuse to rebuild.

The estimation of natural hazards is connected to the Norwegian Planning and Building Law. According to the technical regulations in the law, three classes of avalanche and slide frequencies are usually taken into account, see Table 9.4.

In addition, the building regulation states that rebuilding after fires or other kinds of reparation may be done for class two, when the nominal yearly frequency is less than 3×10^{-3}, i.e. a return period of 333 years.

By using the word 'nominal,' as opposed to 'real,' one admits that the exact calculation of avalanche runout distance for the given frequencies is not possible, and the use of subjective judgement is therefore necessary.

The principles of return periods or frequencies of avalanches as the basis of hazard zonation and legislation is adopted in most of the European countries where avalanches represent a problem. Different countries use different return periods as a basis for the hazard zones, but the principleis the same: a quantified description of the maximum tolerated risk for a natural hazard.

9.5 Avalanche Hazard Zoning; Hazard Zoning Principles

9.5.1 Mapping Standard

Many types and principles for snow avalanche zoning exist; different countries have developed their own methods which differ from each other. To illustrate the snow avalanche hazard zoning, a method used in Norway is described here.

Table 9.4. Avalance classes and slide frequencies

Security class	Maximum nominal avalanche frequency per year	Avalanche return period (yr)	Type of construction
1	10^{-2}	100	Garages, smaller storage rooms of one floor, boat houses
2	10^{-3}	1000	Dwelling houses up to two floors, operational buildings in agriculture
3	$<10^{-3}$	<1000	Hospital, schools, public halls etc.

The principles of natural hazard zoning maps in Norway are described by Hestnes and Lied (1980). The Norwegian Geotechnical Institute has conducted hazard zoning of areas exposed to rock falls and snow avalanches since 1980.

The maps are divided into two categories according to mapping standard:

- Detailed maps
- Survey maps

9.5.1.1
Survey Maps

The maps used are standard topographic maps on a scale 1 : 50 000, with a contour line distance of 20 m. Since 1982, the 1 : 50 000 maps have been available in digital form in Norway, and since then the hazard zoning process has been computerised.

Survey maps are meant to give general information of hazard risks. The production covers a fairly large area in a short time at low costs. It is estimated that each map sheet that covers an area of approximately 600 km^2 should be evaluated in four weeks.

For the purpose of hazard zoning, a digital terrain model TERMOS was developed by NGI in 1984 (Toppe 1987), and this model had been in use until 1996. In this system, the topographical/statistical model mentioned in Sect. 9.5.1.1 is combined with TERMOS into a semi-automatic computerised hazard zoning method.

The main advantage with this system is that extensive areas may be surveyed for avalanche danger in a short time. The avalanche runout model used is based on topographical parameters identified by the computer from the information given on the map.

At present, this method of hazard zoning is performed by a commercial GIS programme (PUMASTATION) and the commercial digital terrain modelling system SURFER for the computation of avalanche runout, storage of avalanche data in a relation database, and for the graphical presentation of hazard zones.

9.5.1.2
Detailed Maps

Detailed maps should have a high degree of accuracy. These maps demand comprehensive field- and computational work, and they are time-consuming to produce. In Norway, such maps are based on the Norwegian economic map series on a scale of 1 : 5 000, a contour line distance of 5 m, or for certain areas on a scale of 1 : 1 000, a contour line distance of 1 m. In this zoning process, each avalanche path is examined in detail; both rupture area, track and runout zone are evaluated carefully, primarily to identify the magnitude, frequency, and runout distance of slides and avalanches.

9.5.2
Types of Maps

Depending on map content and methods used in data collection and data processing, NGI found it appropriate to distinguish between three types of hazard maps:

- *Hazard registration maps.* Maps containing historically known avalanches compiled from literature and documents, interviews and field work.
- *Geomorphic hazard maps.* Maps containing information of hazard prone areas identified by geomorphologic investigations in the field and by the use of topographic maps and air photos.
- *Hazard zoning maps.* Maps that define risk areas compiled on the basis of known historic events, geomorphologic investigations and the use of frequency/runout calculation models. The hazard zones should correspond to the safety requirements in the national building regulations, or specify other frequency/magnitude conditions of the hazard zone.

9.5.3 Zoning Procedure

9.5.3.1 *Survey Maps*

As a first step, all potential hazard zones are identified regardless of the frequency of avalanches. The hazard zones are divided into two areas:

- Starting zones
- Runout zones

The starting zones include all areas on the map that are steeper than 30° and are not covered with dense forest concerning snow avalanches.

The identification of the starting zones are done automatically by the computer, using vector information. On a map sheet with a surface area of 600 km^2, this process is completed in 30 minutes.

The runout zones are identified by using the terrain profile in each avalanche path. Each profile is drawn as a line on the computer screen, from the top of the starting zone, along the path, to the valley floor. Based on the information from this terrain profile, the runout distance is calculated by the computer in a few seconds by the topographical/statistical model for snow avalanches according to the empirical models described in Sects. 9.5.1 and 9.5.2, respectively.

After completion of the hazard map on the computer, the map is checked and corrected by inspection in the field.

9.5.3.2 *Detailed Maps*

Three different sources of information are used to complete a detailed hazard map:

- Records of historic avalanches;
- Geomorphic analysis of the avalanche path;
- Computational models for runout calculation.

All information of known avalanches and slides, their runout distance, damage, weather conditions connected to the release, etc. are collected. Both oral information and written records are used.

Geomorphologic evidence of avalanche frequency and runout is studied in the field. Primarily, this study entails how vegetation is influenced by avalanche activity and how loose deposits are eroded, transported and accumulated in the avalanche track.

Bedrock type and quality is investigated, together with the distribution and type of loose deposits.

Runout models for avalanches and slides are an important tool concerning the establishment of the hazard zones. Each avalanche and slide path is modelled in detail by using digital maps and terrain models. The runout models described in Sects. 5.1, 5.2 and 5.3 are used to calculate the hazard zones corresponding to the national safety requirements for natural hazards.

9.6 GIS as a Tool for Hazard Zoning

Digital maps and computer based runout calculations have been in operation in avalanche hazard zoning at NGI since 1982, when the digital terrain model TERMOS was developed at the institute (Toppe 1987). The basis for the computer-based hazard zoning was the digital maps on a scale of 1 : 50 000, which were developed by the Norwegian Geographical Survey from the beginning of the 1980s.

During the last years, NGI has applied a commercially available GIS programme for avalanche hazard evaluations. The GIS programme is used in combination with a commercial digital terrain model (DTM).

The GIS programme used by NGI is PUMASTATION GIS (PS-GIS), a geographical information system with Microsoft Windows user interface, which has been developed in close co-operation with Norwegian users. The system has a general SQL interface, which enables the connecting of data from external databases to digital map data. Both raster and vector data may be used. Standard picture files and scanned paper maps can be used as background for vector information. Vector data may be imported from SOSI, DXF or WMF format files. The GIS programme is integrated with other MS Windows based programmes. The system runs on Pentium PCs of standard capacities.

Each avalanche and slide path is drawn on the computer in its maximum known extent and given a name and identification number. The runout calculations are performed by using the SURFER DTM system, which is an accurate and easily accessible commercial DTM, with an accuracy well within the needs of runout calculations. In the Surfer programme, all areas steeper than 30° are calculated automatically. These 'steep' areas are regarded as the potential starting zones for snow avalanches, rock falls and debris slides.

The topographical runout models described in Sect. 9.5, are programmed into the GIS on the vectored digital maps. In this way, the potential runout distance may be calculated along defined avalanche paths.

The procedure for runout calculations is also described in Sect. 9.2.

Information on every avalanche and slide is collected in a relation database. (Access, Oracle). The database may be activated from the map by pointing at the actual avalanche or slide on the computer screen. The database contains topographical and climatic conditions connected to the avalanche or slide incidents, date and place of incident, damage done, and source of information. The database will be connected to a national database on properties (GAB-database; streets, addresses and buildings), where details on the actual property, such as the owner's identity, size and type of property, etc. are registered.

The hazard zones are compiled according to the national safety regulations described in Sect. 9.6.

9.7 Sustainable Development?

The interaction between snow avalanches and human activities probably does not represent a major problem for sustainable development on a global scale. On a local scale, in mountainous areas where the economic interests are high due to development of housing areas, tourist resorts, alpine ski areas, logging industry, etc., there exist local conflicts between outbuilding interests and avalanche hazard. This is the case in many locations in the Alps, North America and Scandinavia.

In North America, extensive logging and the use of clear-cutting have created avalanche paths in steep terrain, in such a way that regrowth and water runoff is affected.

Concerning ski tourism, the establishment of downhill runs have led to deforestation and erosion and have changed the water runoff in many locations. For instance in Tirol, Austria, one of the most heavily developed tourist areas in the Alps, 1% of the land area is occupied by alpine ski tracks and ski-lifts. The establishment of ski areas and tourist resorts was in many cases problematic concerning the environment in areas related to deforestation, altering of the natural drainage systems that led to erosion, etc. These problems were especially significant some decades ago. Presently, strict rules concerning the environment are implemented, and all outbuilding must pay careful attention to the environment (Hopf 1998, personal communication).

In countries where environmental issues and safety regulations are included in the building code, snow avalanche hazard does not seem to be a major problem for sustainable development. In other countries where such regulations do not exist, fairly big conflicts between human activities and the natural environment exist, and may develop into an increasing problem.

In what way future climatic changes will affect snow avalanche distribution, frequency and magnitude is not easy to foresee. A warmer climate may create more humid conditions, with increased precipitation and increased snow depths in the mountains. Bigger avalanches could be a result of such a trend. A warmer climate will, on the other hand, reduce the length of the winter season, reduce the extent of snow cover and thereby reduce avalanche activity. Many possible results of climatic changes concerning snow avalanches are conceivable, but prophetic skills are unfortunately not mastered by this author.

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