Chapter 12

Snow Avalanches

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ABSTRACT
Snow avalanches are a major natural hazard in most snow-covered mountain areas of the world. They are rapid, gravity-driven mass movements and are considered a meteorologically induced hazard. Snow avalanches are one of the few hazards that can be forecast, and in situ measurements of instability are feasible. Advanced hazard-mitigation measures exist, such as land-use planning based on modeling avalanche dynamics. The most dangerous snow avalanches start as a dry-snow, slab avalanche that is best described with a fracture mechanical approach. How fast and how far an avalanche flows is the fundamental question in avalanche engineering. Models of different levels of physical complexity enable the prediction of avalanche motion. Although the avalanche danger (probability of occurrence) for a given region can be forecast—in most countries with significant avalanche hazard, avalanche warnings are issued on a regular basis—the prediction of a single event in time and space is not (yet) possible.

12.1 INTRODUCTION

Snow avalanches occur in snow-covered mountain regions throughout the world and have caused natural disasters as long as mountainous areas have been inhabited or traveled. One of the oldest records dates back to 218 BC when Roman historian Livius described that Hannibal, while crossing the Alps, lost 12,000 soldiers and 2000 horses due to avalanches. Large disasters have often been associated with military operations such as the crossing of the Alps by Napoleon in 1800, the fighting in the Dolomites in 1916 during World War I, and most recently the conflict between India and Pakistan where, for example, an avalanche killed about 130 soldiers in April 2012.

The number of avalanche fatalities per year due to snow avalanches is estimated to be about 250 worldwide. In fact, in Europe and North America alone, avalanches claimed the lives of about 1,900 people during the 10-year period of 2000−2001 to 2009−2010. In addition to these well-established

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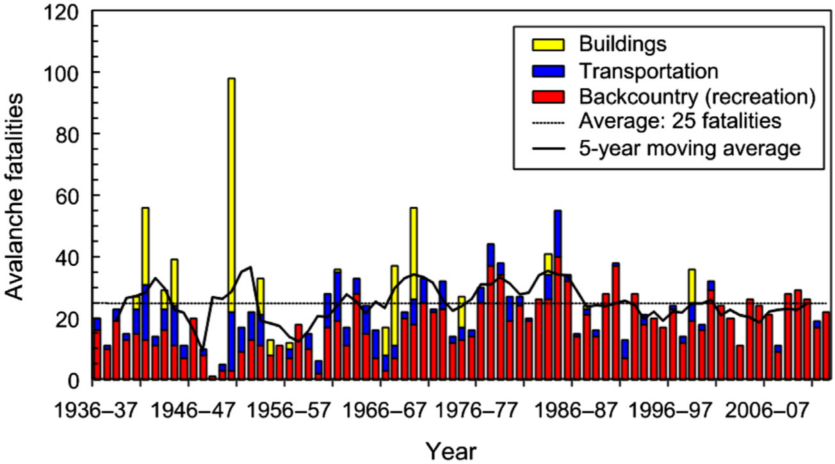

FIGURE 12.1 Avalanche fatalities in the Swiss Alps for the period of 1936–1937 to 2012–2013 (77 years). Most victims were caught during recreational activities such as skiing ("Backcountry"); victims on roads, etc. ("Transportation") and in villages ("Buildings") are less frequent.

statistics, occasional large disasters occur in mountainous countries in Asia. In Europe and North America, most of the fatalities involve personal recreation on public land. Avalanche fatalities on roads or in houses have become less frequent during the twentieth century due to extensive mitigation measures.

In Switzerland, for example, the number of avalanche fatalities on roads or in settlements was about 11 per year until the mid-1970s and has now decreased to less than three, with a long-term total average of 25 victims per year (Figure 12.1). Since the disastrous avalanche winter in 1950–1951 when 98 people in Switzerland (and 135 people in Austria) were killed (Figure 12.2), Switzerland has constructed avalanche defense works worth about $1.5 billion. The effect of these mitigation measures was clearly shown during the winter of 1998–1999 when a similar number of avalanches to that in the winter of 1950–1951 released, but only 17 fatalities occurred (on roads or in buildings), despite the obvious increase in land use and mobility in the Swiss Alps (Figure 12.3). The total damages amounted to $800 million (Wilhelm et al., 2001). In Canada, the yearly average direct and indirect costs are estimated to be more than $5 million (CAA, 2002b).

Even if avalanches are a major threat to people living and recreating in mountain communities, their contribution to the overall risk due to natural hazards in a country such as Switzerland is only about 3 percent—though they contribute more than one-third of all injuries and deaths. The risks due to an earthquake and flooding are estimated to be considerably higher in Switzerland primarily due to the larger area that is affected by these hazards so that damage to people, property and infrastructure is expected to be higher than in the case of snow avalanches (BABS, 2003).

FIGURE 12.2 In Airolo (Switzerland), the Vallascia avalanche destroyed 23 buildings and killed 10 residents on February 12, 1951. *(Photograph: SLF archive.)*

Avalanche risk analysis involves the determination of an avalanche return period or frequency and some measure of consequences that describe the destructive potential (CAA, 2002a). To reduce avalanche risk, protective measures are characteristically used in combination. Avalanche mitigation includes temporary measures (forecasting, road closure) and permanent measures (land-use planning, protective means such as snow sheds or tunnels, reforestation). By combining temporary and permanent measures in a cost-efficient way, otherwise known as integral risk management (Bründl and Margreth, 2014), the avalanche risk can be reduced to an acceptable level. Because snow avalanches are still relatively rare events, personal experience is limited and expertise is generally not readily available. Therefore, it is

FIGURE 12.3 In Evolène (Switzerland), a large avalanche destroyed or damaged several chalets and killed 12 people on February 21, 1999. *(Photograph: M. Phillips.)*

essential for hazard mitigation to increase the awareness of land managers, consultants, governmental agencies, and individual recreationists about snow avalanches.

12.2 THE AVALANCHE PHENOMENON

Snow avalanches are a type of fast-moving mass movement. They can additionally contain rocks, soil, vegetation, or ice. Avalanche size is classified according to its destructive power (Table 12.1). A medium-sized slab

TABLE 12.1 Avalanche Size Classification

Size	Description	Destructive Potential (Definition)	Typical Mass (Tons)	Typical Path Length (m)	Typical Impact Pressure (kPa)
1	Small	Relatively harmless to people	<10	10–30	1
2	Medium	Could bury, injure, or kill a person	100	50–250	10
3	Large	Could bury a car, destroy a small building (e.g., a wood frame house), or break a few trees	1,000	500–1,000	100
4	Very large	Could destroy a railway car, large truck, several buildings, or a forest with an area up to 4 ha	10,000	1,000–2,000	500
5	Extreme	Largest snow avalanches known; could destroy a village or forest of 40 ha	100,000	>2,000	1,000

Adapted from McClung and Schaerer (2006).

avalanche may already involve 10,000 m^3 of snow, equivalent to a mass of about 2000 tn (snow density 200 kg/m^3). Avalanche speeds vary between 50 and 200 km/h for large dry-snow slides, whereas wet-snow avalanches are denser and slower (20–100 km/h). If the avalanche path is steep, dry-snow avalanches generate a powder cloud.

Snow avalanches come in many different types (e.g., wet or dry) and sizes. The morphological classification published by the former International Commission on Snow and Ice (UNESCO, 1981) takes into account the three principal zones of an avalanche: origin (or starting zone), transition (or track), and runout (Table 12.2). It helps one to classify the type of avalanche based on observable features such as the manner of starting or the form of movement.

A snow avalanche path consists of a starting zone, a track, and a runout zone where the avalanche decelerates and the snow is deposited (Figure 12.4). The starting zone, or in analogy to hydrology, the catchment area, is where the initial snow mass releases and generally consists of terrain steeper than 30°. Only a low percentage of dry-snow avalanches start on terrain under 30°. Wet-snow slides, on the other hand, can occur on slopes under 25°. Slope angle is the most important terrain factor influencing avalanche release. A snow avalanche will then flow downstream from the starting zone along the track, which often consists of creek beds and gullies. If the track is steep and a powder cloud develops, the powder snow avalanche may run straight down, regardless of the topography, that is, not follow, for example, any bends in the creek bed. Although small avalanches may stop in the track (typically 15–30° steep), large ones move with an approximately constant speed to the runout zone where they slow down and stop. On large avalanche paths, the slope angle in the runout zone is generally $<15°$ (Jamieson, 2001). Runout zones for large avalanche paths are common on alluvial fans—a preferred area for infrastructure, including businesses and residences, in mountain areas.

12.3 AVALANCHE RELEASE

A snow avalanche may release in two distinctly different ways: as a loose snow avalanche or as a snow slab avalanche (Figure 12.5). Loose snow avalanches start from a point, in a relatively cohesionless surface layer of either dry or wet snow. The initial failure originates in one location when a small mass of snow fails and begins to move and entrain additional snow. The process is analogous to the rotational slip of cohesionless sands or soil, but occurs within a small volume (<1 m^3) in comparison to much larger initiation volumes in soil slides (Perla, 1980). As the snow mass descends, the avalanche spreads outward in an inverted V shape. Most loose snow avalanches are relatively small and harmless since only a cohesionless surface layer is involved. However, when the entire snow cover is saturated with water, loose snow avalanches can entrain large volumes of snow and cause damage.

TABLE 12.2 International Morphological Avalanche Classification (UNESCO, 1981)

Zone	Criterion	Characteristics	Denomination
Origin (starting zone)	Manner of starting	From a point	Loose snow avalanche
		From a line	Slab avalanche
	Position of failure layer	Within the snowpack	Surface-layer avalanche
		On the ground	Full-depth avalanche
	Liquid water in snow	Absent	Dry-snow avalanche
		Present	Wet-snow avalanche
Transition (track)	Form of path	Open slope	Unconfined avalanche
		Gully or channel	Channeled avalanche
	Form of movement	Snow dust cloud	Powder snow avalanche
		Flow along ground	Flowing snow avalanche
Deposition	Surface roughness of deposit	Coarse	Coarse deposit
		Fine	Fine deposit
	Liquid water in snow	Absent	Dry avalanche deposit
		Present	Wet avalanche deposit
	Contamination of deposit	No apparent contamination	Clean avalanche
		Rock debris, soil, branches, trees	Contaminated avalanche

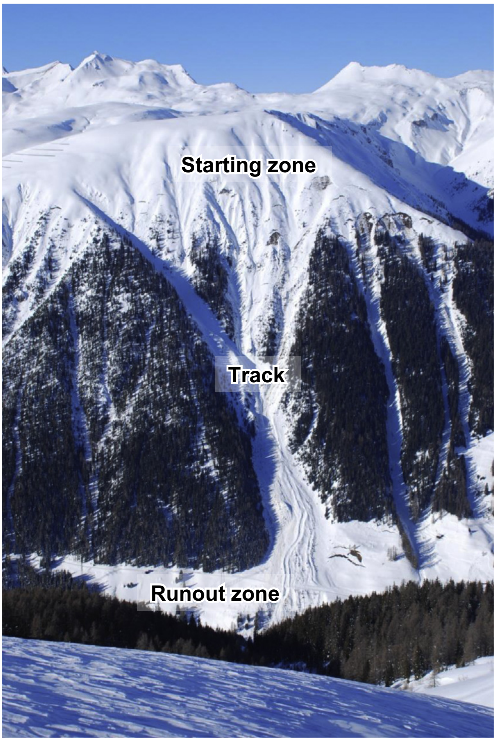

FIGURE 12.4 Large avalanche path showing the starting zone where the avalanche initiates, the track and the runout zone where the avalanche decelerates and the snow is deposited. *(Breitzug, Davos; photograph: J. Schweizer.)*

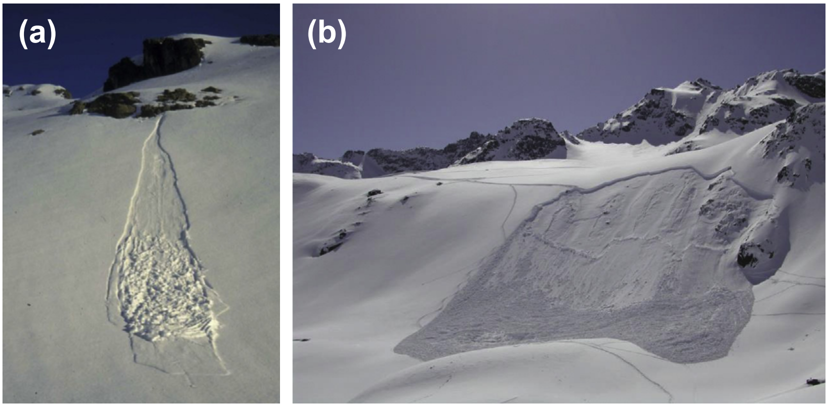

FIGURE 12.5 Snow avalanches may release in two distinctly different ways: (a) as loose snow avalanche or (b) as snow slab avalanche. *(Photograph: J. Schweizer.)*

Snow slab avalanches behave quite differently. They involve the release of a cohesive snow slab over an extended plane of weakness, analogous to the planar failure of rock slopes and landslides rather than to the rotational failure of soil slopes (Perla, 1980). The observed ratio between width and thickness of the slab varies between 10 and 10^3, and is typically about 10^2. Slab thickness is generally <1 m, typically about 0.5 m, but can reach several meters in the case of large disastrous avalanches (Schweizer et al., 2003). Slab avalanches are the more hazardous of the two types and represent the vast majority of fatal avalanches. Slab avalanches are more harmful as they typically involve more snow and are harder to predict than loose snow avalanches. Slab avalanches are the focus of most avalanche-related studies.

Predicting snow slab-avalanche release can be approached either by (1) exploring the complex interaction between three main contributing factors: terrain, weather and snowpack or by (2) studying the physical and mechanical processes of avalanche formation (Schweizer et al., 2003). We first discuss the former approach that is applied by most avalanche forecasting services. It involves empirically weighting the influence of the contributory factors in a specific situation.

Terrain is an essential factor and the only factor that is constant in time. A slope angle of about 30° is required for a slab avalanches to release. However, other topographic parameters such as curvature, aspect, distance to a ridge, and forest cover are also important. In general, the identification of potential avalanche release areas is a difficult task requiring considerable expertise, but it is a prerequisite for large-scale, hazard mapping, numerical avalanche simulations, and planning of hazard-mitigation measures. Today, starting zones can automatically be identified within a geographic information system (GIS), provided that a high-resolution digital terrain model (DTM) is available. However, for detailed planning, including various release scenarios, manual adjustment of the starting zone perimeter is generally required (Bühler et al., 2013). Forests inhibit avalanche formation; in particular, in dense forests, the snow cover is too irregular to produce avalanches. The main effects that alter the snow cover characteristics in forests compared to open unfrosted terrain are (1) the interception of falling snow by trees; (2) the reduction of near-surface wind speeds; (3) the modification of the radiation and temperature regimes; and (4) the direct support of the snowpack by stems, remnant stumps, and dead wood (Schneebeli and Bebi, 2004; Teich et al., 2012).

The main meteorological conditions contributing to avalanche formation are precipitation (new snow or rain), wind, air temperature, and solar radiation. For large, catastrophic avalanches, precipitation is the strongest forecasting parameter. Although the total amount of precipitation plays an important role, the precipitation rate can also strongly influence avalanche release. Wind contributes to loading and is often considered the most active contributing factor after precipitation. Loading by wind-transported snow can be fast and produce irregular deposits, increasing the probability of avalanching in certain areas. Snow deposition by wind is strongly influenced by terrain so that snow-drift accumulations commonly occur at the same location year after year. The persistence of accumulation patterns has been revealed by terrestrial layer scanning (Prokop, 2008) and offers the possibility for modeling these patterns, based simply on topography and mean wind direction (Schirmer et al., 2011). Temperature, and in general, the energy balance at the snow–atmosphere interface, can be decisive factors contributing to avalanche formation, especially in the absence of loading. Its effects on snow stability are complex and commonly subtle, but it is often assumed that a rapid increase in air temperature and/or solar radiation promotes instability. In any case, instability always stems from changes in slab properties (Reuter and Schweizer, 2012; Schweizer and Jamieson, 2010a). Increased deformation due to reduced stiffness of the surface layers increases the strain rate in the weak layer, increases the energy release rate, or increases the skier stress at depth. Although these effects occur rapidly and promote instability, delayed effects, such as snow metamorphism and settlement, tend to promote stability (McClung and Schweizer, 1999). Surface warming (of a dry snowpack) is most efficient with warming by solar radiation as radiation penetrates the surface layers where the energy is released. Surface warming due to warm (relative to the snow surface) air temperatures is a secondary effect—except in the case when a moderate or strong wind blows (Schweizer and Jamieson, 2010a).

Finally, snow cover stratigraphy is recognized as the key contributing factor for snow slab avalanche formation (Schweizer et al., 2003). The mountain snowpack can contain many different snow layers with distinctive properties. Each layer is the result of a snowfall, wind transport or energy exchange between the snow surface, and the atmosphere. Each interface between two layers was once the snow surface and was influenced by the atmosphere before it was buried. Snow layers are generally characterized according to grain type, grain size, hardness, and density following the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009). Some layers are softer so that the strain is concentrated within these layers (Reiweger and Schweizer, 2010); they have lower strength than the layers above and below, and are more often associated with slab avalanching and are hence termed weak layers. Some weak layers are very discernible within the snowpack and are several centimeters or even tens of centimeters thick. Other weak layers can be very thin (few millimeters) and hard to identify, but equally important. This weakness can either be within the old snow (typically a weak layer composed of facets, depth hoar, or surface hoar) or at the old snow surface underlying the new snow. Weak layers differ distinctly in grain size and hardness from the adjacent layers (Schweizer and Jamieson, 2003). They can be grouped into non-persistent and persistent weak layers (Jamieson, 1995).

Non-persistent weak layers, also called storm-snow instabilities, generally consist of precipitation particles that may remain weaker and lower in density than the adjacent layers during the initial stages of rounding. These layers tend to stabilize within a few days after burial, hence the name non-persistent. Persistent weak layers can remain weak for extended periods of time, sometimes months. They consist of surface hoar, faceted crystals, or depth hoar; these layers are more prone to failure in shear than in compression (Reiweger and Schweizer, 2013b). Although wet layers on the snow surface that freeze and become melt-freeze crusts form the bed surface for many slab avalanches, they are not considered weak layers. Failure often occurs in a layer of facets above the crust, so thin it is hard to identify. These so-called weakly bonded crusts form when snow falls on a wet snow surface so that a weak layer of faceted crystals develops while the underlying wet layer freezes into a crust, often within a day (Jamieson, 2006). With regard to avalanche accidents, persistent weak layers are the main concern for skiers as the majority of fatal avalanches occur on persistent weak layers (Schweizer and Jamieson, 2001).

Any loading by new or wind-blown snow or any temperature increase has no effect on snow stability if no weakness exists within the snowpack. The presence of a weak layer is a necessary, but not sufficient condition for slab-avalanche formation. Apart from the weak layer, the properties of the overlying slab are equally important for avalanche formation, in particular because the slab provides parts of the energy for crack propagation.

The slab-avalanche nomenclature (Perla, 1977) reflects the fact that a slab avalanche is the result of a fracture process involving at least four fracture surfaces. The first failure is within the weak layer, and the bed surface is defined as the surface over which the slab slides. The bed surface can be the ground or older snow. The weak layer is always just above the bed surface and just under the slab. The breakaway wall at the top periphery of the slab is called the crown (fracture), and is approximately perpendicular to the bed surface reflecting the fact that the initial failure is in the weak layer below the slab. The flanks are the left and right sides of the slab. The flanks are generally smooth surfaces, as is the crown. The lowest down-slope fracture surface is termed the stauchwall (Figure 12.6) (Schweizer et al., 2003).

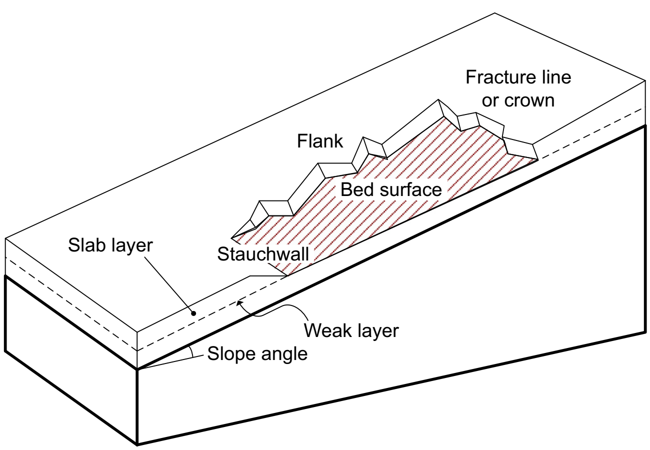

FIGURE 12.6 Slab-avalanche nomenclature. *(Adapted from Schweizer et al. (2003).)*

Depending on the processes leading to slab release, three types of slab avalanches occur: dry-snow, wet-snow, and glide-snow avalanches.

12.3.1 Dry-Snow Avalanches

The release of a dry-snow slab avalanche is due to the overloading of an existing weakness in the snowpack. Most dry-snow slab avalanches start naturally during or soon after snow storms. High precipitation rates favor snowpack instability. In general, about 50 cm of new snow within 24 h (equivalent to about 50 mm of precipitation) is critical for avalanche initiation. Large disastrous avalanches usually follow storms that deposit >1 m of snow. Therefore, for large new snow avalanches, the 3-day sum of precipitation is the strongest forecasting parameter (Schweizer et al., 2009) and closely related to avalanche danger (Schweizer et al., 2003). The triggering of a dry-snow slab avalanche can also occur artificially by localized, rapid, near-surface loading by, for example, people (usually unintentionally) or intentionally by explosives used as part of avalanche control programs. In general, naturally released avalanches mainly threaten residents and infrastructure, whereas human-triggered avalanches are the main threat to recreationists (Schweizer et al., 2003).

For a dry-snow slab avalanche to release, an initial crack in a weak layer has to propagate below the slab. For natural slab avalanches, it is believed that the initial failure is caused by a gradual damage process at the micro-scale leading to failure localization within the weak layer (Figure 12.7). For artificially triggered avalanches (e.g., skier-triggered avalanches), the external trigger induces localized deformations that are large enough to initiate a crack within the weak layer (van Herwijnen and Jamieson, 2005). In any case, if the initial crack in the weak layer reaches a critical size (length)—of the order of several tens of centimeters—it will propagate through the weak layer below the slab. Typically, weak layers are extremely porous and therefore the fracture

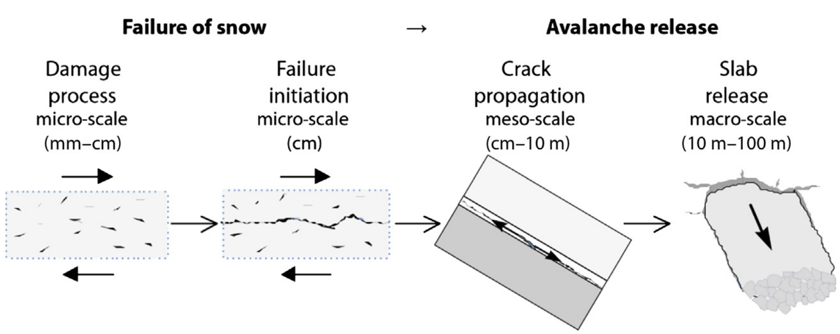

FIGURE 12.7 Conceptual model of dry-snow slab-avalanche release. *(After Schweizer et al. (2003).)*

process is associated with the collapse of the weak layer (van Herwijnen et al., 2010). Once the weak layer has fractured, slab and bed surface come into contact. If the gravitational pull on the detached snow slab is large enough to overcome friction, that is, the slope is steep enough (>30°), a snow slab avalanche releases (van Herwijnen and Heierli, 2009).

Considering avalanche release as a fracture process, and describing it accordingly, goes back to McClung (1979, 1981a) who adapted a failure model by Palmer and Rice (1973). Two decades later, Kirchner et al. (2000) performed the first fracture mechanical measurements needed to eventually apply models based on fracture mechanics. Based on laboratory measurements (Schweizer et al., 2004), a field test has been developed (Gauthier and Jamieson, 2006; Sigrist and Schweizer, 2007) that now enables the determination of two crucial properties: the specific fracture energy of the weak layer and the stiffness of the slab (Schweizer et al., 2011; van Herwijnen and Heierli, 2010).

12.3.2 Wet-Snow Avalanches

Wet-snow avalanches release due to the percolation of liquid water within the snow cover and primarily endanger communication lines and infrastructure. Wet-snow avalanches mostly release spontaneously and characteristically cannot be triggered artificially—in contrast to dry-snow avalanches. Although dry-snow avalanches cause most avalanche fatalities, mainly among winter recreationists, wet-snow avalanches may occasionally cause severe damage. Analysis of a 10-year record of avalanche victims in the Swiss Alps showed that about 50 percent of the fatalities caused by naturally released snow avalanches were due to wet-snow avalanches (either slab or loose snow avalanche) (Schweizer and Lütschg, 2001). When only considering human-triggered avalanches, however, fatalities due to wet-snow avalanches drop to 1 percent. Hence, spontaneous releases of wet-snow avalanches are as lethal as naturally released dry-slab avalanches but wet-snow avalanches are seldom triggered by recreationists themselves. Our understanding of the triggering conditions for wet-snow avalanches is still somewhat limited. This is partly due to a lack of observations, and the fact that wet-snow instability is a highly transient and spatially variable phenomenon related to the water transport in snow (Schneebeli, 2004).

Two prerequisites exist for wet-snow avalanche formation: (1) the presence of liquid water within the snowpack; and (2) a (large) part of the snowpack must be isothermal (0 °C). Water production at the snow surface is determined by the energy balance at the snow–air interface and/or the amount of water delivered through rain (Mitterer and Schweizer, 2013). Based on experience and observations, three possible triggering mechanisms (Baggi and Schweizer, 2009) occur: (1) loss of strength due to water infiltration and storage at a capillary barrier; (2) overloading of a partially wet and weak snowpack due to precipitation; and (3) gradual weakening of the snowpack due to warming to 0 °C and eventual failure of basal layers. Clearly, combinations of these three mechanisms may exist. Overall, it is still not entirely clear as to how water infiltration influences wet-snow instability. Snow stratigraphy is key as it controls the rate of infiltration, the pattern of infiltration and the concentration of water at a given location—which then ultimately will affect the mechanical strength (Peitzsch, 2008). Yamanoi and Endo (2002) observed a continuous decrease in shear strength with increasing liquid water content (up to 8 percent). Recent preliminary results of shear measurements on different substrates indicate that the decrease is highly nonlinear.

Wet-snow avalanches are particularly difficult to forecast. Once the snowpack becomes partly wet, the release probability rapidly increases, but determining the peak and end of a period of high wet-snow avalanche activity is particularly difficult (Techel and Pielmeier, 2009).

Air temperature is commonly related to days with wet-snow instability (Kattelmann, 1985), but is not suitable for forecasting wet-snow avalanches because many false alarms are produced (Mitterer and Schweizer, 2013; Trautman, 2008). By introducing a combination of air and snow surface temperature, predictive performance for days with high wet-snow avalanche activity improved (Mitterer and Schweizer, 2013). In addition, Mitterer and Schweizer (2013) showed that when modeling the entire energy balance for virtual slopes, avalanche and non-avalanche days could be classified with a good accuracy. However, modeling and interpreting the energy balance in terms of wet-snow avalanche release probability is complex and sometimes not feasible for operational avalanche forecasting. Therefore, Mitterer et al. (2013) introduced an index of liquid water content describing the amount of liquid water in the entire snowpack. The index related well with observed wet-snow avalanche activity and indicated spatial and temporal patterns of wet-snow avalanche activity. Onset and peak of wet-snow avalanche activity were mostly well detected, particularly when high temperatures and high values of shortwave radiation caused the percolating melt water. However, determining the end of a period with wet-snow avalanche activity was not possible, because the index showed no distinctive pattern at the end of such periods.

12.3.3 Glide-Snow Avalanches

Glide-snow avalanches can represent a serious challenge to avalanche programs protecting roads, towns, ski lifts, and other operations. These avalanches are notoriously difficult to forecast and can be very destructive, as large volumes of dense snow are mobilized at once. Mitterer and Schweizer (2012) have recently summarized what is currently understood about glide-snow avalanches. Glide-snow avalanches occur when the entire snowpack glides over the ground until an avalanche releases. Glide cracks, that is, full-depth

FIGURE 12.8 Glide-snow avalanches are often preceded by the appearance of a glide crack through the snow cover. Avalanche release can occur within minutes, hours, weeks, or not at all. *(Photograph: R. Meister.)*

tensile cracks exposing the ground, are often observed before glide-snow avalanches (Figure 12.8).

Glide-snow avalanches mostly release from specific and well-known starting zones, and their location is highly dependent on topography (Lackinger, 1987; Leitinger et al., 2008). Glide-snow avalanches occur mostly on steep terrain, that is, 30–40° steep slopes (Leitinger et al., 2008; Newesely et al., 2000), covered with smooth rock (e.g., Stimberis and Rubin, 2011), grass (in der Gand and Zupancic, 1966), or tipped-over bamboo bushes (Endo, 1985). Newesely et al. (2000) observed increased snow gliding on abandoned pastures compared to slopes with short grass. Leitinger et al. (2008) and Höller (2001) observed that the lack of dense forest stands contributed to glide-snow activity, in particular if the distance between surrounding anchor points is >20 m. Observations suggest that most glide-snow avalanches release on convex rolls (e.g., in der Gand and Zupancic, 1966).

Snow gliding processes and glide-snow avalanches are conceptually well understood, and it is widely accepted that a reduction in friction at the base of the snow cover due to the presence of liquid water is the main driver (e.g., Lackinger, 1987; McClung, 1981b). Once friction is reduced and a glide crack has opened, the peripheral strength, in particular of the stauchwall, seems to be crucial for stability (Bartelt et al., 2012a). Since various processes are involved in reducing friction at the base of the snow cover, the relationship between meteorological conditions and glide-snow avalanching is complex. Thus, relying on weather data to forecast glide-snow avalanches is still difficult and relatively inaccurate (Peitzsch et al., 2012; Simenhois and Birkeland, 2010; Stimberis and Rubin, 2005). As the presence of water seems to be decisive for the formation of glide-snow avalanches, it is paramount to know the processes that are responsible for the presence of water at the snow—soil interface. Three different processes may deliver liquid water to the snow—soil interface (McClung and Clarke, 1987): (1) Water percolating through the snow cover; (2) heat released from the warm ground melting the snow at the base of the snow cover after the first major snowfall; and (3) water, produced at terrain features with strong energy release (e.g., bare rocks), running downward along the snow—soil interface or originating from springs (ground-water outflow). In addition, it seems possible that the lowermost snowpack layer becomes wet due to capillary rise caused by different hydraulic pressures along the snow—soil interface (Mitterer and Schweizer, 2012).

The triggering case (1) is very similar to the triggering process related to wet-snow avalanches: the less permeable substrate below the snowpack often acts as a capillary barrier to infiltrating water. Thus, determining the arrival time of water at the base of the snow cover is crucial for predicting avalanche events (Mitterer et al., 2011). The main processes associated with producing the water are due to melting at the snow surface and rain-on-snow events. Many glide-snow avalanches are therefore observed during warm periods or rain events (Clarke and McClung, 1999; Lackinger, 1987). However, the so-called cold temperature events also release when the snow cover is still mostly below freezing. in der Gand and Zupančič (1966) stated that for these events the existence of a lowermost moist snow layer is especially important as a dry boundary layer would not cause glide motion on a grass surface. Moreover, they suggested that liquid water is produced due to warm ground temperatures. Snow layers with low temperatures ($<0\,^{\circ}\mathrm{C}$) may exist above the wet layer. These observations have been confirmed by several later studies (Höller, 2001; Newesely et al., 2000). In addition, the release of glide-snow avalanches, in particular cold-snow events, is often observed during snow loading as the additional load increases creep and glide (Dreier et al., 2013).

The reduction of friction at the base of the snow cover results in increased snow glide rates, and snow glide rates are closely related to glide-snow avalanche release (e.g., in der Gand and Zupančič, 1966). Clarke and McClung (1999) and Stimberis and Rubin (2011) suggested that glide-snow avalanche release may best correlate with periods of rapid increases in glide rates. Thus, measuring glide rates could improve glide-snow avalanche forecasting. Several methods have been used to measure glide rates in snow, including sprung probes (Wilson et al., 1997), seismic sensors (Lackinger, 1987; Stimberis and Rubin, 2005), accelerometers (Rice et al., 1997), and, most frequently, glide shoes (in der Gand and Zupančič, 1966; Lackinger, 1987; Clarke and McClung, 1999; Stimberis and Rubin, 2005). While all these methods can be used to measure glide rates, they are currently costly, somewhat unreliable, and difficult to conduct in multiple paths.

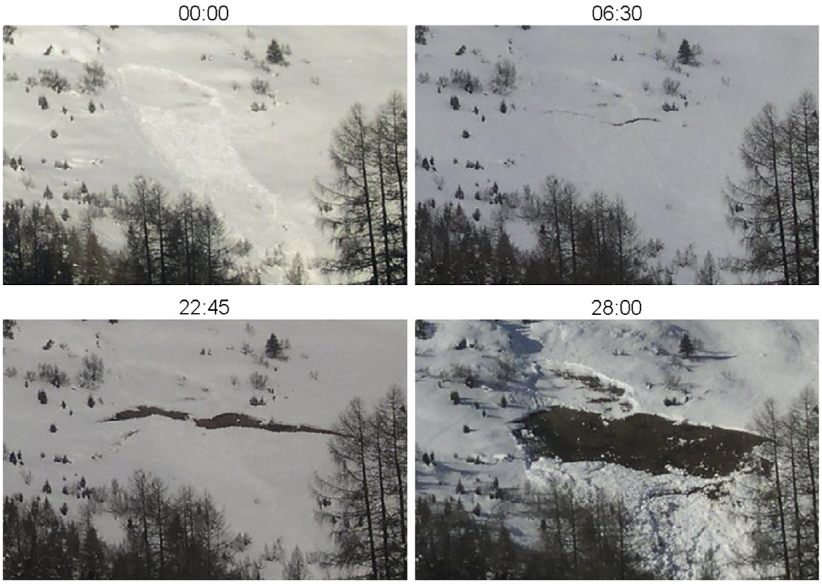

FIGURE 12.9 Sequence of images showing the gradual expansion of a glide crack, followed by the release of a glide-snow avalanche after 28 h. *(Photograph: A. van Herwijnen.)*

More recently, a different approach for measuring glide rates was proposed by tracking the expansion of glide cracks with time-lapse photography (van Herwijnen et al., 2013; van Herwijnen and Simenhois, 2012) (Figure 12.9). When a glide crack appears, the ground below the snow cover is exposed. Since the ground is much darker than snow, it can clearly be identified on the time-lapse images. Using a simple method based on dark pixel counting, glide rates can be derived. van Herwijnen and Simenhois (2012) showed that for glide cracks that resulted in avalanche release, the number of dark pixels rapidly increased a few hours before avalanche release, in line with previously published glide rate measurements. Although such new developments are encouraging with regard to glide-snow avalanche forecasting, it is still not clear how increases in glide rates relate to avalanche release.

12.4 AVALANCHE FLOW

Avalanche flow begins after snow is released and set in motion. How fast and how far an avalanche flows is one of the essential questions in avalanche engineering. Hazard maps and the planning of mitigation measures require an estimation of avalanche speed and the extent of the inundated area as a function of the release zone location and characteristics of the mountain terrain (steepness, roughness, gullies, vegetation, etc.). Hazard scenarios are typically based on the concept of avalanche return period, which is linked to snow cover fracture heights (e.g., Ancey et al., 2004; Bründl et al., 2010). Information regarding snowfall history and past avalanche events is necessary to predict reasonable starting masses, which greatly affect avalanche runout distances. Climatic conditions need to be considered to assess the possibility of extreme wet-snow avalanches or powder snow avalanches. To predict the motion of avalanches including these effects, models with different levels of physical complexity are employed in engineering practice. These include empirical (e.g., Lied and Bakkehoi, 1980), statistical (e.g., McClung and Mears, 1991), and physical and semiphysical analytical models (e.g., Salm et al., 1990). Increasingly physics-based numerical models (e.g., Christen et al., 2010) are being used because of the availability of high-resolution digital elevation models that allow an accurate representation of mountain terrain (Bühler et al., 2013). The newest generation numerical models also account for snow entrainment processes that allow the treatment of avalanche growth.

12.4.1 The Transition to Flow: Slab Break-up and Snow Granularization

When a dry-snow slab avalanche releases, it may first slide as a rigid block. For dry-snow avalanches, the sliding surface is typically a harder (older) snow layer; for wet-snow avalanches, the sliding surface can be the ground. Friction is low because the slab often slides on a hard layer lubricated by the poorly bonded remnants of the fractured weak layer; wet-snow avalanches often slide on wetted surfaces. Because of the low friction of the sliding surface, accelerations can be large and sliding snow can quickly reach velocities of >10 m/s. Terrain undulations or variations in surface roughness contribute to the quick break-up of the slab (Figure 12.10). First, large snow cover fragments form, but as the slab continues to displace, the fragments disintegrate into smaller granules of various shapes and sizes (Bozhinskiy and Losyev, 1998). By the

FIGURE 12.10 The break-up of the slab and the start of a large flowing avalanche. *(Photograph: T. Feistl.)*

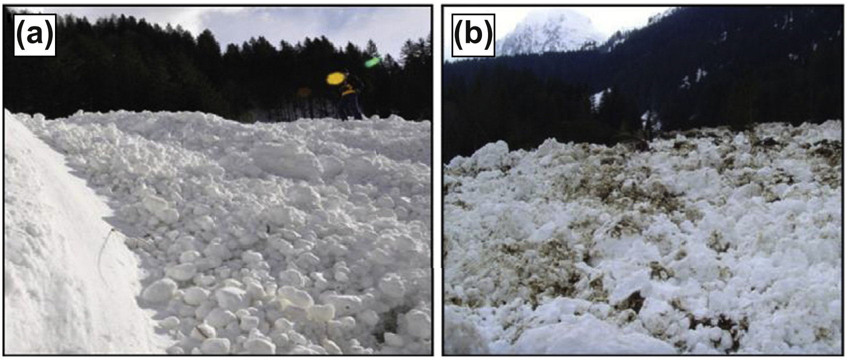

FIGURE 12.11 The granular deposits of (a) dry-snow flowing avalanche and (b) wet-snow avalanche. *(Photograph: P. Bartelt.)*

time the entire slab has exited the release zone and passed the stauchwall (which can also enhance the break-up process), the slab avalanche has transformed into a granular flow.

The bulk flow density of the avalanche is given by the distribution of granules within an avalanche flow volume. The break-up process, granule collisions, and other interparticle interactions lead to hardened granules and snow fragments. Typical granule densities range between 300 and 500 kg/m^3 (Bozhinskiy and Losyev, 1998). It is also possible to find hard ice granules in avalanche deposits as well as in rocks and woody debris (Figure 12.11).

The bulk flow densities of the avalanche can vary strongly (Gauer et al., 2007, 2008). For example, highly fluidized avalanches—a dry-snow flowing avalanche or powder snow avalanche—can have bulk flow densities at the front of $<100\ kg/m^3$. Such regions in the avalanche are commonly termed "saltation" layers because of their low solid mass content (Gauer et al., 2008). Wet-snow avalanches or the dense core of flowing avalanches have higher bulk flow densities, varying between 200 and 400 kg/m^3. That is, with bulk densities near the granule densities suggesting less interstitial air space. Avalanches, depending on the snow properties and the granule formation, can exhibit both "collisional" and "frictional" flow regimes. It is entirely possible that with one single avalanche a transition will occur between flow regimes (Bartelt et al., 2011). For example, at the head of a dry-snow flowing avalanche or powder avalanche, we are often confronted with a collisional regime or dispersed, dilute flow regime, whereas toward the tail of the avalanche, the flow densifies, producing the dense core of the avalanche. An understanding of the avalanche flow density is necessary as it determines both the mobility of the flow and the magnitude of the avalanche impact pressures.

The second salient feature of the granularization process is that it modifies the internal energy fluxes of the avalanche (Figure 12.12) (Bartelt et al., 2006). When a slab releases, potential energy P is transformed into kinetic energy K and heat E. This kinetic energy is associated with the mean slope-parallel

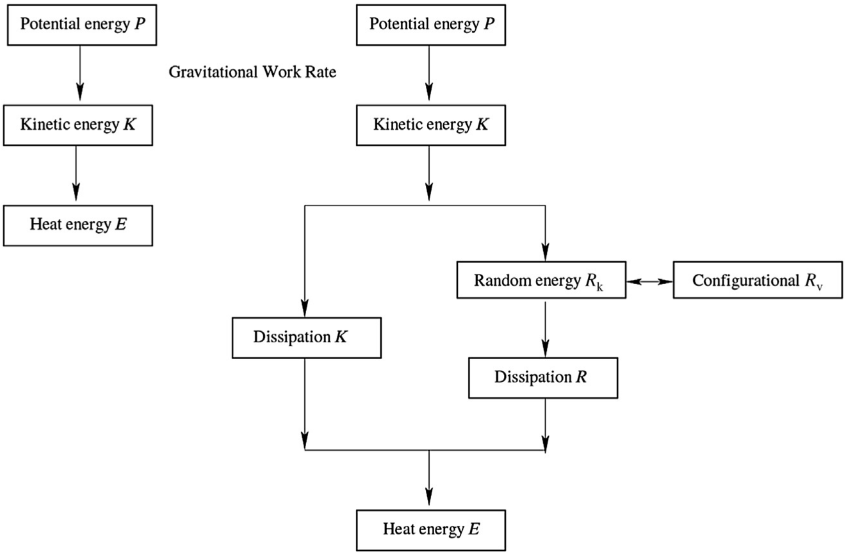

FIGURE 12.12 Two models of avalanche flow. (Left) Potential energy is transformed into kinetic energy and heat (block models, simple hydrodynamic models). (Right) Potential energy is transformed into kinetic energy, random kinetic energy R_k, configurational energy R_v and heat E (granular models).

movement of the avalanche, the velocity U. Frictional processes dissipate the kinetic energy, raising the internal heat energy E of the avalanche. In this model of avalanche flow (Figure 12.12), the motion of the avalanche can be described completely, once the frictional processes have been defined. This flow model is the basis of many (useful) block-type avalanche models (Perla et al., 1980; Salm et al., 1990). However, the granularization of the snow slab at release changes this simple energy model dramatically. As the slab displaces, space opens up between the granules. Movements in the slope-perpendicular direction are possible, implying an increase in the avalanche flow volume and a decrease in the avalanche flow density. This energy, denoted R_v, is termed "configurational" as it is associated with volume changes and therefore with flow densities and flow regimes. Importantly, the granules no longer all move with the same speed or direction of the mean flow. That is, the avalanche motion is no longer a rigid block, but a highly variable and deformable mass of particles. This energy has been termed R_k for "random kinetic" as it is associated with granule movements that vary from the mean translational velocity (Bartelt et al., 2006; Buser and Bartelt, 2009).

12.4.2 Avalanche Flow Regimes

After the transition phase of release and slab break-up in an avalanche, the flow phase begins. The avalanche at first accelerates and reaches a relatively

FIGURE 12.13 The muddy deposits of a large wet-snow avalanche near Klosters (Switzerland), April 2008. *(Photograph: P. Bartelt.)*

steady velocity (transition zone) before decelerating on a flatter slope (runout zone). The length of the transition and runout phases depends strongly on the geometry of the avalanche path and also on the avalanche type and the frictional properties of the flowing snow (Figure 12.13).

Mitigation of snow avalanche hazard requires determining the propagation speed of the leading edge, the avalanche flow density and the dimensions of the avalanche body (depth, width, and length). These parameters vary over the length of the avalanche track, from the point of release to the point of maximum runout. The total volume of avalanche deposits is often an additional parameter that is required to assess the height of avalanche dams and avalanche deflecting structures.

The problem of predicting avalanche flow in mountain terrain is difficult. Many different models have been developed to estimate the parameters of avalanche flow. The models are based on relatively simple observations of avalanche drop height versus runout, or on detailed flow measurements (Harbitz, 1998). The models can be simple, for example, empirical formulas that average terrain features, or more intricate numerical models that require digital elevation models to represent the complexities of real mountain terrain. To date, however, both simple and complex models divide avalanche flow into one of two flow distinct and general categories: "dense flowing" and "powder" (suspension). This division essentially splits avalanche flow into a regime (or model) with relatively dense snow mass ($\rho = 100-500\ \text{kg/m}^3$) and a regime (or model) of highly dispersed snow and air mass ($\rho = 3-50\ \text{kg/m}^3$). The dispersed phase can be further subdivided into a "saltation layer" ($\rho = 10-50\ \text{kg/m}^3$) and a "suspension layer" ($\rho = 3-10\ \text{kg/m}^3$). Dry-mixed avalanches consist of a combination of both dense and powder parts and

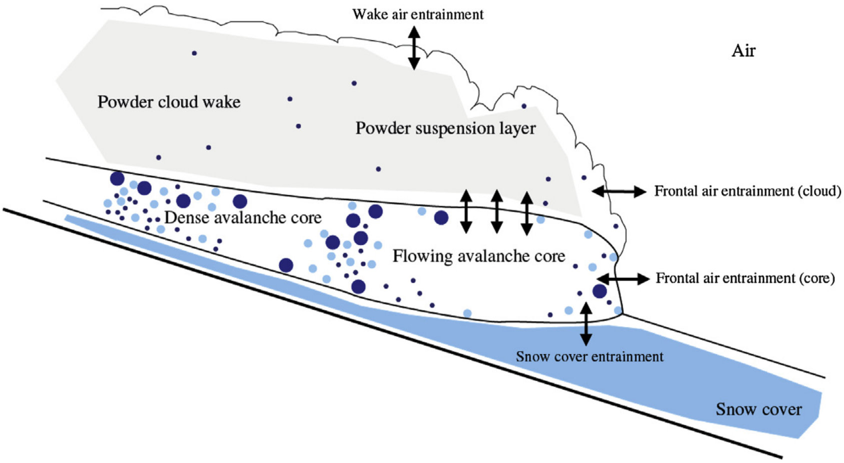

FIGURE 12.14 Avalanche cross-section. Avalanches consist of a dense avalanche core and suspension layer. The density of the avalanche core varies from 50 to 100 kg/m^3 ("saltation" like flows) to 500 kg/m^3 (heavy, wet-snow avalanches). The snow cover and ambient air can be entrained by the avalanche.

therefore consist of a dense core with saltation and suspension layers (Figure 12.14). See Gauer et al. (2008) for an overview of inferred density measurements in snow avalanches.

Here, it is important to reiterate that avalanches are composed of flowing snow debris mixed with air and the very fact that avalanche density varies is a result of the granularization and break-up process that allows density variations. Therefore, flow regime and flow regime transitions are intricately related to the granular properties of flowing snow, which are strongly temperature and moisture dependent (Gauer et al., 2008).

12.4.3 The Avalanche Core

The dense and saltation layers can be grouped together to form the "avalanche core." This is the destructive center of the avalanche. The core contains mass in granular form, that is, both large and small aggregates of ice grains. Mean granule sizes for dry-snow avalanches are in the range of 5—10 cm; wet-snow granules are larger, a result of the cohesive properties of moist snow (Bartelt and McArdell, 2009). Of course, there are many smaller and larger particles within the flow. The particles exist in a continual state of flux; they can break or they can combine to form particle agglomerates, especially in the runout zone where the terrain flattens and the flow becomes slower. Air mixed with ice dust is blown out of the core to form the suspension layer. Both small granules and ice dust are blown out of the avalanche core as well. However, the smaller granular aggregates are not suspended, but once ejected from the core, they will return rapidly to flow. The granular aggregates can be found high above the ground (10–20 m) increasing the height of the zone where large, but local, impact pressures can be exerted on tall structures, including trees. Because heavier particles fall out of the dust cloud, this region of the avalanche core is sometimes termed the "segregation layer." These aspects of the flow core are a result of the fact that the upper surface of the avalanche is essentially a free surface.

The denser regions within the avalanche core also exhibit significant variations in bulk flow density (Gauer et al., 2008). Because of several factors (ground roughness, terrain undulations, large overburden pressures, as well as the braking effects of snow cover deconstruction and entrainment), granules at the running surface move slower than granules in the upper region of the flow. Measured velocity profiles have been reported in Kern et al. (2009). Velocity gradients indicate not only granular collisions and thus frictional dissipation but also strong dilatative movements within the avalanche core (Buser and Bartelt, 2011). This causes an expansion of the avalanche flow volume and therefore a decrease in bulk avalanche flow density. The degree of volume expansion depends on the avalanche flow height. It is harder to change the flow volume of larger flow heights where the overburden pressures are larger. At the front of the avalanche, where flow heights are small and frictional forces are large, strong expansion movements can occur within the avalanche core.

12.4.4 The Suspension Cloud

If the avalanche snow is dry, ice grains (ice dust) become suspended in the surrounding air to form a "powder" or "suspension" cloud. The dust can arise from a layer of weakly bonded fresh snow, or the abrasive granular interactions between dry-snow granules within the avalanche. Mean grain sizes are 0.1 mm (Rastello et al., 2011). The ice dust is mixed with air in the avalanche core and blown out of the avalanche, often in violent vertical movements to form irregular plume-like structures. The plumes are formed at different locations and rise at different speeds; the stronger plumes will often rise and spread more quickly, spreading over and consuming slower rising plumes. The powder cloud surface is therefore uneven and composed of billows and clefts. This gives powder avalanches their distinctive turbulent appearance.

Japanese measurements of powder cloud densities from pressure measurements reveal bulk densities between 3 and 5 kg/m^3 (Nishimura et al., 1993). Although these densities appear low, they are more than enough to give powder clouds their opaque grey-white color. A cubic meter of powder cloud dust will contain some 10,000,000 ice particles. This is enough to obstruct the view of the avalanche core flowing below. It hinders a clear understanding of the formation process of powder clouds.

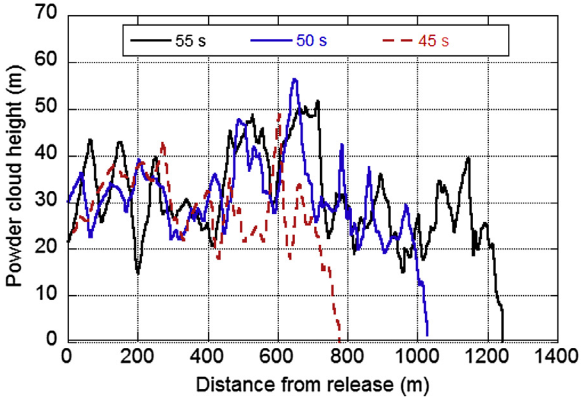

FIGURE 12.15 Cross-section of measured powder cloud heights of a Vallée de la Sionne avalanche for three times $t = 45$, 50 and 55 s. The heights reach over 50 m. The cloud is created at the front of the avalanche. The plumes initially move forward but are almost stationary 100 m behind the avalanche front.

Using stereogrammetric, georeferenced photographic images of the powder cloud at the Swiss Vallée de la Sionne test site, it has been possible to measure the total volume of powder clouds. These are immense. For avalanches consisting of 50,000–100,000 m^3 of flowing snow debris, the powder cloud volumes can exceed 10,000,000 m^3. The powder cloud volume can be well over 100 times the volume of the core. The suspension ratio (the ratio of powder mass to core mass) is estimated to be between 5 percent and 20 percent. This is an indication of the large amount of air entrained by the powder cloud.

Another use of stereogrammetric imaging is to trace the movement of plumes (Figure 12.15). This reveals that the plumes are primarily created at the front and edges of the flow. The plumes quickly decelerate and become stationary, sometimes only a 100 m behind the leading edge of the avalanche. This is an indication of large drag forces acting on the cloud. These drag forces arise from air entrainment and drag as the particles are expelled into the surrounding air. The front of the cloud is moving faster than the tail, or wake of the cloud. The movement of the powder cloud resembles the smoke blown out by a steam engine, that is, there is a continual creation of new powder at the avalanche front that becomes stationary as the avalanche moves forward. The motion of the cloud does not resemble a rigid body movement (in which the front and rear move at the same speed) as some powder snow avalanches models would suggest (Ancey, 2004; Beghin and Olagne, 1991).

12.4.5 Snow Entrainment

Observations reveal that avalanches can entrain snow layers, typically a layer of fresh snow. Wet-snow avalanches frequently remove the entire snowpack exposing the ground creating muddied depositions (Jomelli and Bertran, 2001). In fact, avalanches play an important role in transporting debris (soil, rocks, and dead wood) from the starting zone to the runout zone (Bozhinskiy and Losyev, 1998; Swift et al., 2014).

Entrainment processes are usually divided into three phenomenological categories (Cherepanov and Esparragoza, 2008; Gauer and Issler, 2004; Sovilla, 2004): (1) frontal ploughing; (2) basal erosion; and (3) snow layer fracture entrainment.

Snow entrainment affects avalanche motion in four ways: (1) It changes the overall mass balance of the avalanche; (2) It can change the temperature and moisture content of the flowing snow and therefore snow entrainment can change the avalanche flow regime from dry to wet, or from dilute to dense; (3) As the avalanche runs over the snow cover, it produces internal shear gradients in the avalanche core, and therefore, entrainment can enhance the production of chaotic and vertical motions (granular fluctuations and rotations), especially at the front of the avalanche; (4) Dry snow covers are a good source of ice dust that is subsequently mixed with the air blown out of the avalanche core to create the suspension cloud of powder snow avalanches.

Avalanche flow volume and avalanche mobility are related: in general, observations reveal that larger avalanches have longer runout distances (Bozhinskiy and Losyev, 1998). This fact is reflected in calculation guidelines where larger (extreme) avalanches are assigned lower friction values. Theoretically, this indicates that snow entrainment should positively affect avalanche mobility. At present, however, no physical explanation exists as to why this should occur. In fact, many experts maintain that entrainment will slow down the avalanche and reduce runout distances because accelerating the entrained snow to the avalanche velocity, breaking the snow cover, or snow cover ploughing consume avalanche flow energy. In practice, the effect of avalanche entrainment is handled simply by using extreme (and therefore low) friction values for large avalanches, without actual consideration of the entrained mass.

More advanced avalanche dynamics models not only consider the entrained mass but also consider the entrained heat energy (temperature) and moisture content (Vera and Bartelt, 2013). This modifies the internal energy fluxes in the avalanche core. That is, even after the energy losses of entrainment are accounted for, an increase in mobility occurs due to flow regime transitions induced by the production of random energy (more dilute flows), or melt water lubrication (temperature effects), or enhanced moisture content (reduced shear resistance) (Bartelt et al., 2012c). Clearly, entrainment has a much greater effect on avalanche flow than simply increasing the flow mass.

12.4.6 Stopping and Depositional Features

A better understanding of how avalanches stop is being driven by new methods to measure avalanche deposits, particularly by accurate terrestrial and airborne laser scanning techniques (Bartelt et al., 2012b; Bühler et al., 2009). Increasingly accurate and hand-held global positioning system devices are useful to trace the extent of avalanche deposits in field investigations. Because modern avalanche dynamics models predict the distribution of mass in the runout zone, an increased interest exists to compare measured and calculated runout distances, as well as calculated and measured deposition heights (Christen et al., 2010). Avalanche deposition patterns are strongly dependent on three-dimensional terrain characteristics (roughness, steepness of runout zone, counterslope, terrain undulations, gullies, etc.) and therefore are ideal to test the stopping mechanics of avalanche dynamics models. Commonly, information gathered from avalanche deposits is the only hard evidence available to reconstruct an avalanche event.

Stopping is driven by the imbalance between the driving gravitational forces G and shear friction S. The point where avalanche deceleration begins is generally estimated to be given at the point P where the tangent of the slope angle Φ_P is equal to the value of the Coulomb friction μ:

$$\tan\left(\phi_P\right) = \mu.$$

This is a useful formula as most avalanche dynamics models rely on some kind of Coulomb friction to describe when an avalanche stops, that is,

$$\frac{S}{N} = \mu,$$

where S is shear and N is the normal pressure exerted by the avalanche on the basal running surface. For far reaching (extreme) avalanches, different investigators have found minimum values between $\mu \approx 0.12$ and 0.15 (e.g., Bozhinskiy and Losyev, 1998; Salm et al., 1990). The formula is well tested and facilitates a simple, direct approximation of runout distance.

Actual shear and normal force measurements in snow chute experiments (Platzer et al., 2007) reveal that avalanche friction cannot be well described by a constant μ. It appears that avalanche friction varies over the length of the avalanche (it is lowest at the front of the avalanche and increases toward the tail). Other factors, including snow temperature and moisture content, can also influence μ. Interestingly, snow chute experiments show that the shear S can have different values for the same normal pressure N. The fact that μ can vary—it is a frictional process, rather than a frictional constant—explains the tremendous variation in "calibrated" friction parameters used to model snow avalanches. Because this frictional process is mass dependent, smaller avalanches can stop on steeper slopes, giving the impression that smaller avalanches have higher friction values.

How the friction μ evolves over time determines the distribution of depositions in the runout zone. If the terrain permits, avalanche deposits can be very regular. A tendency exists for higher deposition heights at lower slope

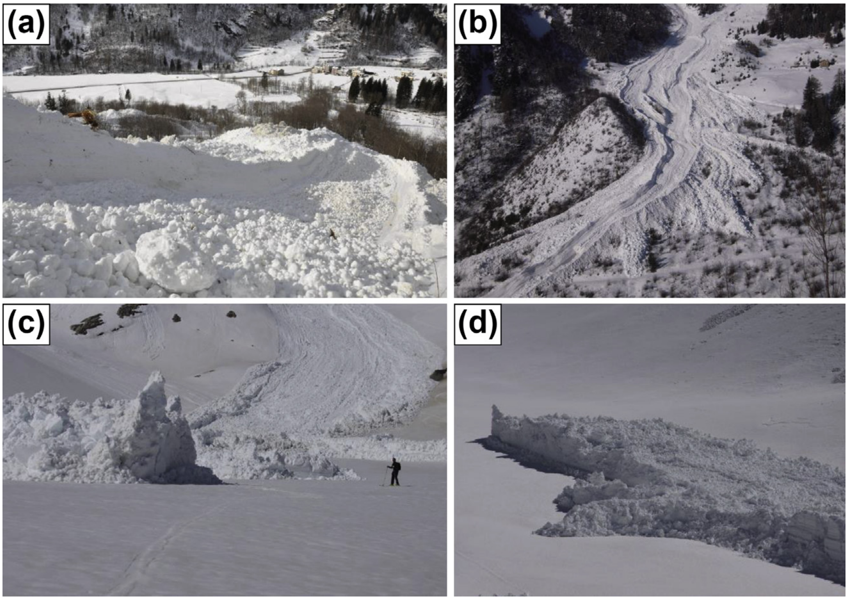

FIGURE 12.16 Different avalanche deposition types: (a) Levee with sidewalls. (b) Levee. (c) Avalanche flow finger with pile up. (d) Avalanche flow finger. *(From Bartelt et al. (2012b).)*

angles. However, avalanche deposits can be highly irregular and exhibit four unique features (Bartelt et al., 2012b):

1. *Levees and sidewall-type constructions* (Figure 12.16(a) and (b)). Levees commonly occur in wet-snow avalanche deposits. They arise when avalanche snow stops flowing at the outer boundaries of an avalanche. The interior flow continues to move forward, and internal shear planes are created several meters inward from the stopped outer boundary. As the interior flow drains, it leaves the sidewalls exposed, creating channel-like structures in the depositions. Levees are an indication of strong internal friction gradients within the flow. Although these friction gradients can be induced by terrain undulations, levees also occur on flat and relatively homogeneous runout zones, indicating that levee formation is triggered by internal variations of avalanche velocity (the velocity is smaller at the outer edges of the flow). Levees can form at the front of slow moving (wet-snow) avalanches, or at the slow moving tail of dry-snow flowing avalanches. The importance of levee sidewalls is that they can be large (>5 m in height) and thus form structures that can deflect the flowing mass of the same avalanche, or subsequent avalanches on the same avalanche track (Figure 12.16(b)).
2. *Avalanche flow fingers* (Figure 12.16(c) and (d)). Avalanche flow fingers commonly extend beyond the reach of the bulk of the deposited avalanche

mass. Typically, they are narrow structures (5−10 m in width, see Figure 12.16(d)), and they can also be rather wide depositional lobes (up to say 50 m). Flow fingers typically arise in moist or wet-type avalanches and are an indication of strong preferential flow behavior. Flow fingers can follow roads or other terrain features (gullies). The sides of flow fingers are steep, signifying strong cohesive properties of the flowing snow. In a sense, they are similar to the interior flow of a self-formed levee channel, except that the mass at the outer boundaries does not stop and builds no sidewalls. Flow fingers are a problem for avalanche runout calculations as they are difficult to predict. The flow fingers can bend $\geq 90°$.

3. *Shear planes and en-echelon shear faults*. Both vertical and horizontal shear planes occur in avalanche deposits. Vertical planes, parallel to the flow direction, occur on levee sidewalls. Horizontal (or basal) shear planes are formed as the avalanche moves in a plug-like motion over terrain undulations. Snow fills in the undulations and acts to smoothen the terrain. Commonly, the basal shear planes are formed in the avalanche interior between levee sidewalls. Frictional rubbing can produce heat which, depending on the initial temperature of the snow, can melt the frictional surfaces of avalanching snow. The melt water characteristically refreezes. This hardens the sheared surface, giving it a shiny appearance that is visible from a considerable distance. Because of the evolution of flow friction, avalanches do not stop at once: the avalanche tail can stop first, behind the front. This leads to the formation of en-echelon type fault structures in which the front is "pulled" away from the tail.
4. *Pile-ups* (Figure 12.16(c)). Avalanche pile-ups can occur at the end of levee-type channels, or they can occur at steep slope transitions, as, for example, at the exit of a gully at the beginning of a flat runout zone. Avalanche snow can also pile up at the transition between a slope and steep counterslope. Avalanche pile-ups are dangerous depositional features because they can be very high (>20 m) and therefore change the topography of the avalanche track.

12.4.7 Avalanche Interaction with Obstacles

The problem of how to adequately design buildings and other structures that stand in the path of an avalanche is central to hazard mapping and the planning of mitigation measures. Real-scale experiments in Switzerland, Russia, and Canada show that avalanches can exert immense pressures on obstacles (e.g., Bozhinskiy and Losyev, 1998; McClung and Schaerer, 1985; Sovilla et al., 2008). The obstacles (measurement pylons) are regarded as stationary, rigid bodies in comparison to the fluid behavior of the avalanche body, which can flow around or completely immerse the obstacle. Obstacle interaction is therefore not only an impact phenomenon but it also lasts significantly longer as the avalanche flows past the obstacle. Engineers are

FIGURE 12.17 Pressure measurements of a large dry-mixed flowing avalanche at the Vallée de la Sionne test site (Switzerland). The measurement pylon pressure cells with various diameters measure avalanche impact pressures at different heights. *(Photograph: F. Dufour.)*

mostly interested in the maximum pressure and pressure distribution, as this determines both the dynamic forces and overturning moments exerted on the structure.

Maximum pressures of 100 tn/m^2 have been measured at the Swiss Vallée de la Sionne test site (Figure 12.17); Russian researchers have reported pressures of up to 200 tn/m^2 (Bozhinskiy and Losyev, 1998). Several dry-mixed flowing avalanches recorded at Vallée de la Sionne site have exerted peak pressures between 20 and 50 tn/m^2 when traveling at speeds between 30 and 40 m/s. Pressure signals can be both intermittent and continuous functions in time, depending on the avalanche flow regime (dispersed, dense) and type (wet, dry). A problem with the analysis of pressure signals is that different measurement techniques can measure different pressures at different periods during the passage of the avalanche.

Pressure models of avalanche–obstacle interaction assume that the avalanche body is a continuum. Pressures p can be evaluated using the hydrodynamic formula

$$p = c\frac{1}{2}\rho U^2,$$

where c is the dimensionless coefficient of resistance, dependent on the shape of the object ($c = 1$ for slender objects; $c = 2$ for wider, wall-like structures). A prerequisite for a pressure analysis is an estimate of the avalanche speed U and bulk flow density ρ. It is necessary to have an idea of the avalanche flow height to determine the height of the applied pressure.

As we have seen, snow avalanches consist of hard snow granules (as well as rocks and dead wood) and will undergo significant variations in the bulk flow density. The application of the continuum formula is therefore questionable since it does not take into account the granular nature of the flow. The formula

$$p_g = \frac{4}{3}\rho_g U^2$$

can be used to predict local, granule impact pressures. The formula assumes that the time of a granule collision is $t = d/2U$, where d is the diameter of the granule. It assumes a plastic collision in which the granule is completely destroyed at impact. Our experience with this formula is that it well approximates measured impact pressures, which are often performed with pressure cells of size d. The granule density ρ_g varies between 400 and 500 kg/m^3 indicating significant densification of the snow during flow.

12.5 AVALANCHE MITIGATION

To avoid avalanche disasters, first of all, potential avalanche terrain and accordingly a potential avalanche problem needs to be recognized. Indications include oral and written history of previous avalanche events, vegetation clues and snow depth records, and most importantly, terrain. A terrain analysis can be done by identifying all areas steeper than about 25° by using a GIS and a DTM. Obviously, any infrastructure in these potential starting zones is endangered. The next step, the risk analysis, involves assessing the frequency, magnitude, and runout of avalanches initiating from the identified potential starting zones (e.g., Schweizer, 2004).

Depending on the object endangered and the frequency and size of potential avalanches, the resulting risk is too high, and mitigation measures are planned. If residential areas or areas where development is planned, are endangered, land-use planning measures should be established based on the hazard map so that buildings in hazard zones are avoided, restricted, or designed to withstand potential avalanche pressures. In Switzerland, for example, hazard zones are defined based on avalanche frequency and impact pressure. For residential areas large avalanches with return periods as high as 300 years need to be taken into account. For roads, return periods are typically much shorter, up to several times a year. If a road is endangered by several potentially large avalanches with return periods of $<$10 years, an active avalanche control program (including the use of explosives) and/or the construction of snow sheds should be considered (Figure 12.18). If the avalanches potentially hitting the road are rather small and or infrequent, temporary closures based on an avalanche forecast may be the adequate protection measure (CAA, 2002b). For highly endangered infrastructure (highways, railways, mining operations, ski areas, etc.) local forecasting services need to be established that also run the avalanche control program (Schweizer et al., 1998).

FIGURE 12.18 Avalanche mitigation measures include snow sheds (protecting the railway line), deflecting dams (protecting the Trans-Canada Highway) and warning signs that reduce the risk by reducing the exposure. *(Field BC, Canada; photograph: J. Schweizer.)*

Various mitigation measures should be applied, usually in combination, in a coordinated manner to reduce the avalanche risk to an acceptable level. This approach is known as integral risk management (Wilhelm et al., 2001). In general, mitigation measures are grouped into temporary (or short-term) and permanent (or long-term) measures, both of which can be subdivided into either active (e.g., preventing avalanche release by snow supporting structures) or passive measures (e.g., establishing hazard maps). The various mitigation measures are described in more detail by, for example, Bründl and Margreth (2014), McClung and Schaerer (2006) and Rudolf-Miklau and Sauermoser (2009).

12.6 AVALANCHE FORECASTING

Predicting snow avalanches is generally called avalanche forecasting, which McClung (2000) defined as predicting snowpack instability in space and time relative to a given triggering level. In the framework of integral risk management avalanche forecasting is considered a short-term, passive mitigation measure. Snow avalanches are the only natural hazard—apart from some purely meteorological hazards such as storms and heavy precipitation—that can be forecast.

Snow avalanche prediction (forecasting snowpack instability) can be made for various scales (McClung and Schaerer, 2006). We focus here on the regional scale (1,000 km^2), the local scale (100 km^2), and the scale of an individual avalanche path (1 km^2). Typically, the prediction is about the danger level, the avalanche activity (or occurrence), and the probability of the single event for these three scales, respectively. In avalanche forecasting, a mismatch often occurs between the scale of the forecast and the scale of the underlying data (Hägeli and McClung, 2004).

Today, most countries with areas where people and infrastructure are significantly endangered by avalanches operate an avalanche forecasting service, similar to a weather service, which issues warnings, or so-called avalanche bulletins. These services primarily forecast the regional avalanche danger by describing the hazard situation with one of five degrees of danger: very high (or extreme), high, considerable, moderate, and low (Table 12.3).

Operational avalanche forecasting mainly relies on meteorological observations and forecasts in combination with observations of snow cover instability, ideally direct observations of avalanches (McClung and Schaerer, 2006). It involves the assimilation of multiple data sources to make predictions over complex interacting processes. For many decades now, avalanche professionals have developed successful decision-making strategies to deal with this complexity (LaChapelle, 1980). These rule-based empirical strategies, sometimes applied intuitively, are able to deal with many of the numerous processes and scales involved in avalanche formation. However, the employed methods are largely based on the experience of the forecaster and are therefore prone to subjectivity, unable to deal with unusual situations and difficult to

TABLE 12.3 Example of Avalanche Danger Scale as Used by Most Avalanche Forecasting Services. The Five Degree Danger Scale was Introduced by the European Warning Services in 1994

North American public avalanche danger scale
Avalanche danger is determined by the likelihood, size and distribution of avalanches.

Danger Level		Travel Advice	Likelihood of Avalanches	Avalanche Size and Distribution
5 Extreme	4 5	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 High	4 5	Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 Considerable	3	Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 Moderate	2	Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 Low	1	Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.

transfer to new personnel. Recently, rule-based decision support tools have been developed for recreationists that relate terrain to the danger level (McCammon and Hägeli, 2007).

Numerous attempts have been made to develop objective techniques for avalanche forecasting. Such efforts predominantly consist of statistically relating local weather observations to avalanche occurrence data or estimated avalanche danger. Statistical forecasting models are based on the idea that similar weather conditions lead to comparable avalanche situations. Various methods have been used, including linear regression analysis, multivariate discriminant analysis, time series analysis, nearest neighbors, or pattern recognition techniques (e.g., Buser, 1983; Pozdnoukhov et al., 2011; Schweizer and Föhn, 1996). Depending on the scale of the study area and the quality of the input data, the accuracy of the statistical models can vary greatly. A major drawback is the poor temporal resolution of avalanche observations or estimated avalanche danger. Therefore, coarse scale meteorological parameters, such as the amount of new snow in the last 24, 48, or 72 h, are typically used as input parameters (McClung and Tweedy, 1994). High-frequency meteorological data (e.g., recorded at 10-min intervals) or forecasts, which nowadays are widely available, can therefore not be exploited to their fullest extent.

Another shortcoming of most statistical forecasting models is the failure to include quantitative snowpack stratigraphy data (e.g., Schweizer and Föhn, 1996). Such snowpack data are important for avalanche forecasting, especially during periods of low avalanche activity and stable weather conditions. In fact, snow avalanches are the only hazard where in situ tests exist that can provide information on the state of instability. Of course these tests provide point information only, which needs to be extrapolated—a task hampered by the inherently variable nature of the mountain snowpack (Schweizer et al., 2008). A first step toward a more deterministic approach to avalanche forecasting (which would include simulating avalanche release) therefore consists of modeling snowpack characteristics and deriving stability information.

Essentially two types of numerical models exist: one-dimensional snow cover models and three-dimensional model systems. One-dimensional models, such as CROCUS (Brun et al., 1992) and SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b), compute the snow cover stratigraphy by solving the one-dimensional mass and energy balance equations using meteorological data as input. The modeled stratigraphy can then be interpreted with regard to stability (e.g., Monti et al., 2012; Schweizer et al., 2006). Alternatively, modeled snow stratigraphy variables can be used as input variables to improve the performance of statistical avalanche forecasting models (Schirmer et al., 2009). A limitation of one-dimensional models is the lack of spatial snow cover information.

Such information is provided by three-dimensional model systems, such as SAFRAN–CROCUS–MEPRA (SCM) (Durand et al., 1999) and Alpine3D, which includes SNOWPACK (Lehning et al., 2006). These model systems use spatial meteorological input data and account for three-dimensional processes such as radiation redistribution and snow transport by wind. A large part of the complexity was removed in the French SCM model chain by providing automated avalanche danger prediction for virtual slopes. It is the only real operational forecasting model on the basis of physical modeling. However, given the overall complexity of the interactions between the snowpack and meteorological parameters and the high spatial resolution required, surface process model systems are very computationally intensive and many uncertainties still remain. Furthermore, interpretation of spatial snow cover data with regard to snow-slope stability remains unclear.

Field observations on snow stratigraphy are widely used to investigate snow cover instability for avalanche forecasting (e.g., Schweizer and Jamieson, 2010b). Over the last decade, new in situ measurement techniques have been developed to objectively describe the stratigraphy of a natural snowpack, including near-infrared photography (Matzl and Schneebeli, 2006), the snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998), microcomputer tomography (Schneebeli and Sokratov, 2004), contact spectrometry (Painter et al., 2007), and upward-looking ground-penetrating radars (Schmid et al., 2014). While these methods primarily provide new insight into the microstructure of snow and its physical processes, interpretation of the data remains complicated, in particular with regards to snow stability (Bellaire et al., 2009; van Herwijnen et al., 2009). Recently, promising advances have been made by combining micro-tomography and SMP measurements (Reuter et al., 2013). Nevertheless, manual snow cover measurements, consisting of snow profiles and snow stability tests, presently remain the method of choice for avalanche forecasting. Snow cover observations are typically compared to observed avalanche activity or estimated avalanche danger to obtain empirical relationships (e.g., Schweizer and Jamieson, 2007; van Herwijnen and Jamieson, 2007). Although these in situ tests have a number of deficiencies, including an error rate of at least 5−10 percent, correlations between manual snow cover measurements and snow-slope stability have been identified (Schweizer and Jamieson, 2010b).

In general, prediction requires predictability, that is, some sort of a precursor, or observational variable that announces the event. In the case of snow avalanches, avalanche prediction during storms is mainly based on precipitation amounts; new snow is considered as precursor. Obviously, precursors more related to the state of the snowpack would be useful. Pioneering work in the 1970s tried to relate acoustic emissions from a natural snow cover to avalanche formation and slope stability (e.g., Sommerfeld, 1977; St. Lawrence and Bradley, 1977; Gubler, 1979). Given the differences in instrumental setup and the lack of a thorough description of the field experiments, in particular with regard to the signal processing and the treatment of environmental background noise, results from early microseismic studies remain ambiguous.

Whereas laboratory measurements on snow failure have indicated that monitoring acoustic emissions may reveal imminent failure, applying the technique in the field is difficult due to strong attenuation of high-frequency signals in snow (Reiweger and Schweizer, 2013a). Alternatively, seismic sensors can be used, but van Herwijnen and Schweizer (2011b) were unable to detect precursors to slab-avalanche release. However, the avalanche occurrence data (van Herwijnen and Schweizer, 2011a) suggest that avalanches could be used as precursors because often at the beginning of periods of significant avalanche activity the number of events increases (Schweizer and van Herwijnen, 2013). Obviously, direct observations of avalanches are the most reliable evidence of unstable snow conditions and of fundamental importance for avalanche forecasting.

12.7 CONCLUDING REMARKS

Disasters due to snow avalanches have caused the loss of life and property damage in most populated, snow-covered mountain areas. Although in the past people had primarily to rely on experience, which is known to be of limited value when dealing with rare and extreme events such as large snow avalanches, today advanced methods exist that enable recognition of the risk as well as its mitigation. Still, this does not mean that disasters due to snow avalanches will no longer occur. Even with modern monitoring and modeling methods it is not possible to predict the exact location and time of an avalanche release—primarily due to the lack of reliable precursors and the inherently variable nature of the mountain snowpack. Clearly, physics-based numerical models are helpful tools to predict avalanche motion and impact, but uncertainties remain despite major advances—also in view of the uncertain consequences of climate change. Even after applying mitigation measures, a residual risk remains because completely reducing the risk is definitely not cost-efficient. Therefore, combining permanent and temporary protection measures is most promising, but requires that the risk is actively managed. By doing so the risk to people—living, traveling, or recreating in the mountains—can effectively be reduced to an acceptable level.

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