1 Introduction

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1.1 Avalanche hazards

1.1.1 Overview and terminology

Avalanches are defined as large masses of snow or ice that move rapidly down a mountainside or over a precipice. The term *snow avalanche* is more accurate to make the conceptual demarcation from other types of avalanches such as rock avalanches or mud flows. According to ONR 24 805, 3.34 [202], snow avalanches are characterized by rapid movement of snow masses that were triggered from the snow cover. Snow avalanches that cause human losses as well as severe property and environmental damage are classified as *natural catastrophes*.

Throughout history, avalanches have had a major impact on the development of settlements in mountain regions (Figure 1.1). This influence is obvious from the location and structure of historical villages and traffic routes. Typical toponyms like *Lähn* or *Lavin* indicate old avalanche paths and are probably derived from the Latin terms *labi* (gliding down) and *labes* (falling) [7]. For many centuries, humans were not able to protect themselves effectively from avalanche hazards and resorted to simplistic solutions such as avoiding areas at risk. Despite the sparse population in Alpine regions, major avalanche disasters with numerous victims occurred repeatedly in history, as people were not able to assess the risk of these infrequent but catastrophic events.

In the last century, increasing populations in the Alps (1870: 7.8 million; 2010: 13.6 million) in combination with growing demands for mobility and leisure activities in Alpine terrain have increased avalanche risk significantly. Traditionally, Alpine valleys were scarcely populated apart from mountain farms, whereas today there are a wide range of competing interests in land use such as settlement developments, traffic, trade and industry, tourism and recreation facilities. This has created progressive consumption of land and use of higher risk areas for building. Some Alpine valleys in well-developed regions are subject to urban sprawl and in areas where tourism is the only profitable economic branch, intensive development of higher elevation areas has occurred, especially for skiing. Though depopulation has been reported in infrastructure-poor mountain regions (*mountain escape*), the Alps will be subject to intensive land use in the future as well since mountains are a sustainable source of natural resources (timber, water, renewable energy and mining).

Increasing traffic density and volume of transportation have resulted in a growing demand for efficient and safe transit corridors across the Alps (e.g. Tenda, Fréjus, Mont Blanc tunnel, Simplon pass, Lötschberg tunnel, St. Gotthard, San Bernadino, Arlberg, Reschen pass, Brenner, Felbertauern, Tauern and Katschberg tunnel, Tauern railway Böckstein/Mallnitz, Gesäuse railway). Outdoor leisure activities and sports (mountaineering, mountain biking, skiing, hunting) have increased human activity in higher elevation areas. In the last decades, the majority of avalanche victims have been skiers off marked slopes as well as ski tourers and free riders.

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Fig. 1.1 Alpine living space, shaped by avalanches (© *Sauermoser*)

Increased human impact is noticeable in the European Alps and can be expected in the future in other mountain regions around the world. Avalanche risk and safety expectations have increased significantly while the risk acceptance of a modern society is constantly decreasing. Consequently, the demand for technical avalanche protection in the Alps increased within a short time and prompted rapid development in defense technology. The diverse technological innovations included both new types of avalanche defense structures with permanent protection effects and high-tech systems with temporary protection effects, especially for monitoring and detection of descent or artificial release of avalanches. The establishment of the field of technical avalanche defense as a stand-alone engineering discipline shows the central role avalanches play in mountain regions.

1.1.2 Avalanche hazards: historical and geographical relevance

An avalanche hazard refers simply to a source of potential harm, and is a function of the likelihood of triggering and the destructive size of an avalanche. The different dimensions of avalanche hazards are expressed in the five-point *European Avalanche Hazard Scale* [79] (Table 4.1). Avalanche risk must relate to a specific element at risk, for example people, buildings, vehicles, or infrastructure. Avalanche risk is determined by the exposure of that element and its vulnerability to the avalanche hazard. Avalanche hazards are not necessarily related to catastrophic events. Most of the avalanche accidents causing loss of human life occur in unsecured areas where the people involved actually triggered the avalanche. These so-called *tourist avalanches* happen frequently but generally do not affect settlement areas, traffic routes or infrastructure and thus are not considered target areas for permanent technical defense structures (also for economic reasons). As avalanche size increases, the probability of occurrence decreases but settlements and traffic routes may also be affected. For example, a so-called *hundred-year avalanche* represents an event that occurs – from a statistical point of view – on average once every 100 years.

Fig. 1.2 The Icelandic village Seydisfjördur is a high-risk area for avalanches (© Sauermoser)

Snow avalanches can occur anywhere where sufficient snowfall occurs within a short time on slopes with an inclination of more than 30 degrees. Avalanches occur throughout the Alps and many other mountain ranges in the world including the Pyrenees, Apennines, Norwegian Fjordland, Iceland (Figure 1.2), Rocky Mountains, Andes, Japanese and New Zealand Alps, Elbrus mountains, Hindu Kusch, Pamir mountain range, Russian Altai and Baikal mountains, Chinese Tianshan or Himalayas (Figure 1.3). In ancient times, the Greek geographer Strabon (63 BC to 23 AC) documented avalanche events in the Caucasus Mountains in his scriptures 'Geographica'. In Austria, more than 6000 avalanche paths have a potential impact on settlement areas [35] and countless other avalanches occur in undeveloped mountain areas or remote, seasonally used regions. In Switzerland, more than 20 000 dangerous avalanches are known. The capital of Alaska, Juneau, is an example of an urban area at high-risk from avalanches [60] (Figure 4.5).

1.2 Technical avalanche defense: classification

1.2.1 Classification scheme of defense measures and their effects

An avalanche hazard is not absolute, but is relative to an element at risk. *Avalanche defense measures* are also designed relative to a specific scenario, and several such measures are presented in this book. In countries where avalanche risk is considered substantial, avalanche defense should use a holistic approach that considers various relevant protection goals and possible measures.

Avalanche defense refers to any measure in the catchment area of an avalanche used to achieve the targeted protection goal [202], and is classified as follows [161]:

- *Active* defense measures prevent avalanches from starting or act directly on the flow process, and
- *Passive* defense measures mitigate the consequences of a potential avalanche hazard.

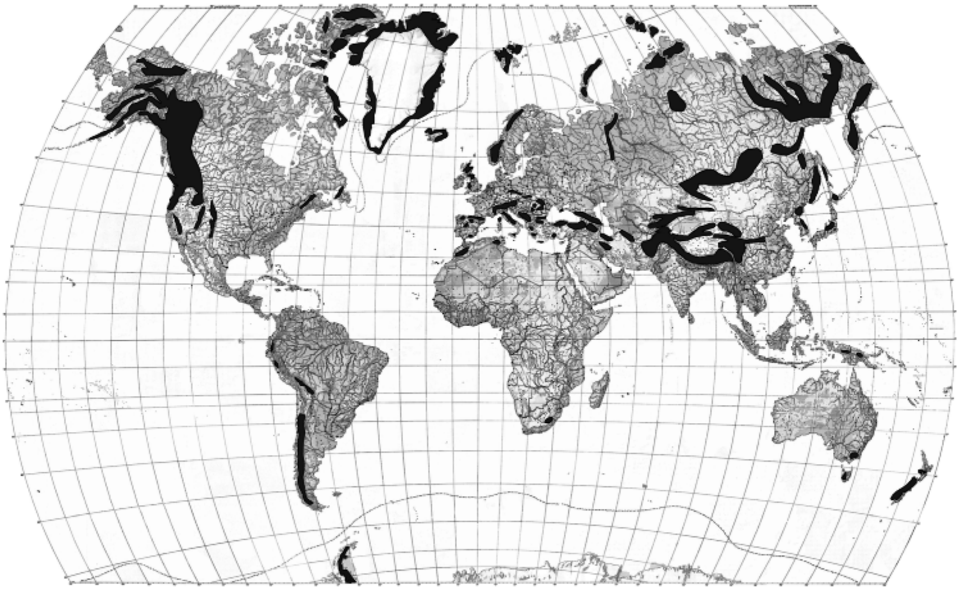

Fig. 1.3 Global overview of mountain regions with potential avalanche hazards (originally elaborated by Glazovszkaya [78]) (The map is only a rough presentation, as no exact survey was carried out)

Active measures are appropriate to reduce the frequency of hazardous avalanches or directly decrease the intensity of the avalanche process. In contrast, passive measures reduce either the damage potential or the vulnerability of objects at risk.

Avalanche defense measures provide either *permanent* (constantly effective) or *temporary* (time-limited effect, adjusted to a specific situation) protection [222]. Table 1.1 gives an overview of the classification scheme of avalanche defense measures.

Another classification of avalanche defense measures uses the *risk cycle of the natural hazard management* [209] (Figure 1.4). According to [222], the hemisphere of precaution comprises prevention, preparation and preparedness; the hemisphere of response (to catastrophes) integrates intervention, assistance and restoration. Most of the measures presented in this book are among the sectors of prevention and preparation.

Holistic systems for avalanche defense have been established in most Alpine countries (Austria, Switzerland, France, Italy, Germany, Slovenia), as well as in other European countries (Norway, Iceland), furthermore in Canada, USA, Japan and New Zealand. Avalanche defense is generally a public service (task of the state), though the degree of responsibility and actual duties varies substantially. This holds true especially for the organization, financing and execution of technical avalanche defense. Furthermore, in other mountainous countries in Europe and around the globe, such as in Poland, Slovakia, Romania, Bulgaria, Spain, Great Britain, Russia, Turkey, China, Andean states, Himalaya and the Caucasus region, avalanche defense has gained in importance due to major events.

Table 1.1 Classification scheme of avalanche defense measures

Defense measure			Permanent effect	Temporary effect
Active	Precautionary effect	Reducing the disposition for an event	Forest and bioengineering measures (protection forest, high-altitude afforestation) Avalanche defense structures: snow supporting structures, snowdrift control structures	Artificial release of avalanches
		Acting directly on the avalanche process	Avalanche defense structures: dams, breakers, tunnels, galleries	Closure for roads Evacuation (of buildings at acute risk)
	Reaction to an event			Emergency measures (after an event) Catastrophe management
Passive	Precautionary effect		Legal measures (regulations, prohibitions) Hazard mapping Planning measures (land use planning) Administrative measures (building permission, relocation of buildings at risk) Structural building (object) protection Catastrophe management plans	Information (risk communication) Avalanche monitoring and prediction Avalanche commissions Avalanche warning service
	Reaction to an event			Preparedness Catastrophe management

Fig. 1.4 Risk cycle for natural hazard management (© AdaptAlp)

1.2.2 Permanent technical avalanche protection (defense structures)

In the relevant technical standard literature (e.g. *Margreth* [165], *ONR 24805* [202]) the term *technical avalanche defense* is equated with structural (constructional) defense measures with permanent effects – in contrast to the technical avalanche defense measures with temporary effects (Section 1.2.3 and chapter 9). The protection effect of these measures is constant, that is independent of the actual avalanche risk or season.

Technical defense measures typically refer to avalanche defense structures, meaning constructed works (sometimes including mechanical and electronic components) and are termed *avalanche defense structures* in the engineering field (Figure 1.5 a and b).

According to [165], structural avalanche defense is based on one of two strategies:

- hinder initiation or propagation of an avalanche by stabilizing (support) the snow pack in the starting zone or by reducing snow drift (snow displacement by wind), or
- break, decelerate, retard, deflect or retain avalanches in motion (deflection or retarding structures).

Measures based on the first strategy are used in the starting zone of avalanches (Figure 1.5a), whereas measures based on the second are constructed in the avalanche path or runout zone (Figure 1.5b). Table 1.2 gives an overview of the classification and function of structural avalanche defense structures. A third group of measures includes structural building (object) protection, whereby the protection effect is defined for a single

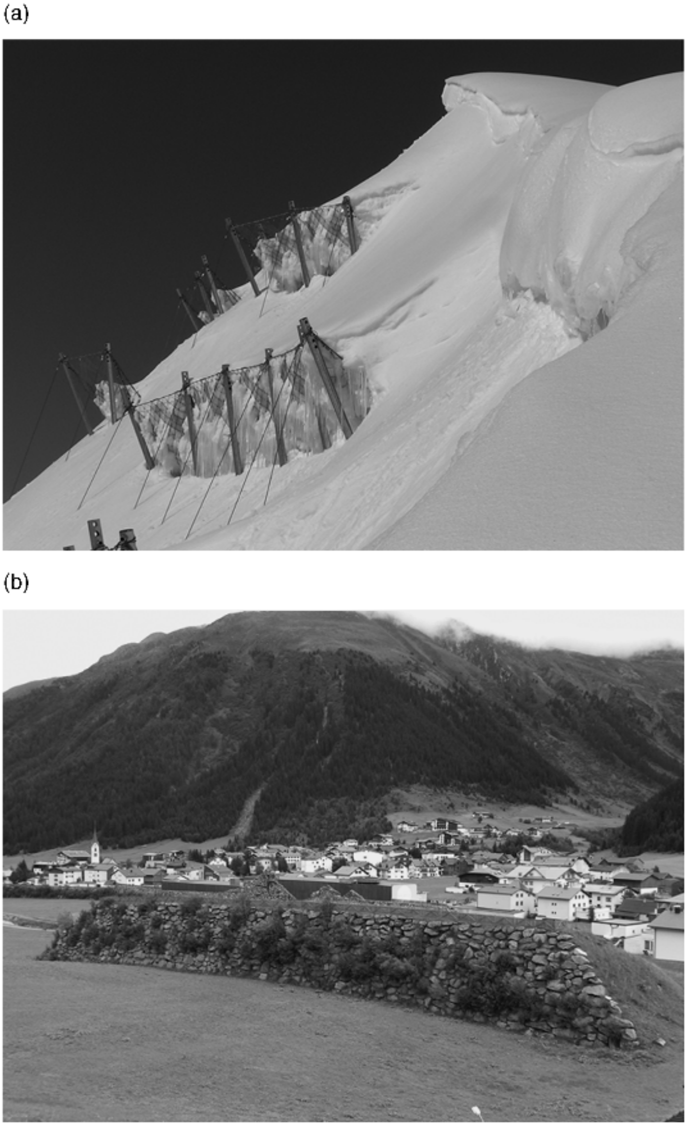

Fig. 1.5 Examples of structural avalanche defense structures: (a) snow nets in a starting zone (© Sauermoser); (b) avalanche retarding dam in the municipality of Galtür (Tyrol) (© Rudolf-Miklau)

object (e.g. residential house, towers of a cable car, electricity pole) (Chapter 8). Object protection measures are amongst the avalanche defense structures.

1.2.3 Technical avalanche defense with temporary effects

In this book the term *technical avalanche defense* is used in a broader sense and also comprises active and passive measures with temporary protection effects. These are

Table 1.2 Overview of avalanche defense structures classified by the function and location in the catchment area, according to [161]

Structural avalanche defense	Avalanche defense structures				Object protection
Category of defense measure	Snow drift control structures	Snow supporting structures	Avalanche catching and retarding structures	Avalanche deflection structures, snow sheds and tunnels	Structural building protection
Function (protection effect)	Structures that control the snow drift and snow accumulation in the starting zone.	Structures that stabilize and sustain the snowpack in the starting zone and prevent the release of avalanches.	Structures that stop or decelerate the motion of avalanches or dissipate the energy in order to reduce the run out distance.	Structures that deflect avalanches in motion from objects at risk or to by-pass them from traffic routes (roads, railway lines).	The building at risk is enforced in a way that it is able to withstand the impact (stress) of avalanches with little damage.
Type of defense structure	Snow drift fence Wind baffle Wind roof (Jet roof)	Snow bridge/rake/net Combined snow bridge (steel/wood) Terrace	Avalanche catching or retarding wall (dam) Avalanche mound Avalanche breaker	Avalanche deflecting dam (wall) Gallery (shed) Tunnel	Avalanche splitting wedge Roof terrace Impact wall
Location in catchment area	Starting zone	Starting zone	Avalanche path Runout zone	Avalanche path Runout zone	Avalanche path Runout zone

measures with effects that are limited in time and that require additional assessment of the actual avalanche danger (e.g. by an avalanche commission).

Technology for the artificial release of avalanches is amongst these temporary defense measures (Section 9.2) and includes structures or facilities adapted to specific avalanche hazard situations. These usually supplement other protection structures but may in a few special cases substitute them. To initiate avalanche release, additional loads are applied to the snowpack and fracturing occurs at natural weak zones/layers. According to [263],

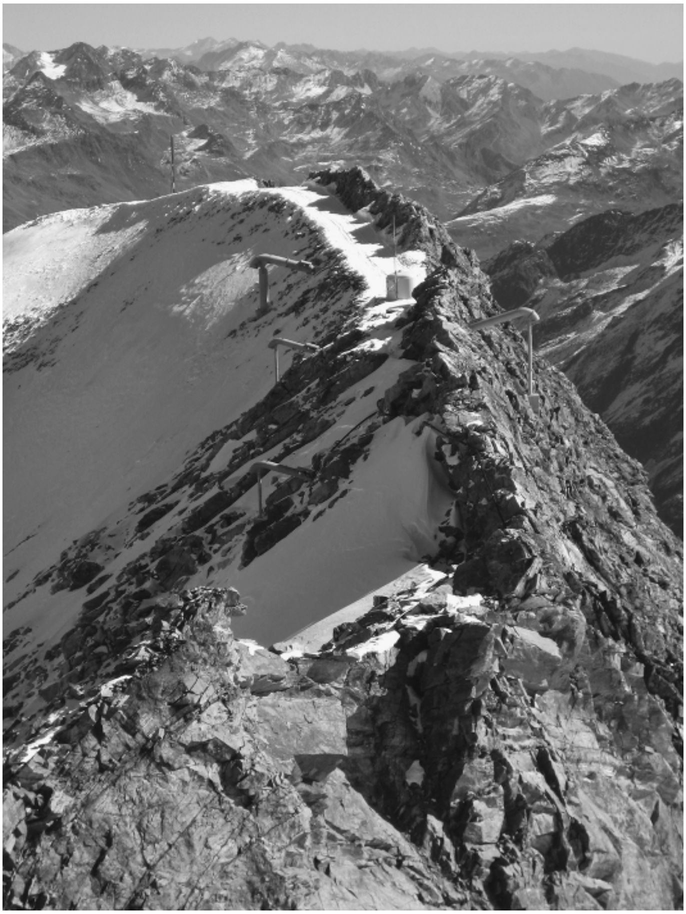

Fig. 1.6 Artificial avalanche release facilities with the system Gaz.Ex (© Interfab Snowbusiness GmbH)

a wide range of new technologies for artificial release of avalanches is available on the market (example system Gaz.Ex; Figure 1.6). Artificial release minimizes the duration of traffic routes closures (roads, railway lines, cableways, ski slopes) or evacuation of buildings (public places). In Europe, this measure is applied predominantly for protection in ski areas and traffic routes, albeit with some limitations, but is rarely used for the protection of settlements and buildings due to legal and safety concerns.

Technical systems (facilities) for avalanche defense are also used for avalanche monitoring, prognosis and warning (alert) (passive defense measures with temporary effect). Avalanche monitoring and prognosis (warning) requires digital measuring technology, remote sensing and computer-based models. According to [111], these technical systems facilitate assessment of avalanche hazards, recording of snow layering and compilation of relevant meteorological data with the aim to create daily updated avalanche reports (warning) with regional relatedness. Computer-based models for prognosis are appropriate to assess the actual avalanche hazards on a local level, if sufficient documents and data on historical avalanches are available (Section 1.3.1). All these technologies represent an indispensable support for the work of regional authorities and avalanche commissions for a specific emergency situation (blockage, evacuation, closure). In comparison, direct remote sensing and detection of moving avalanches (e.g. by high-speed cameras, geophones or radar) is primarily of scientific interest but will gain importance in the future with improvements in technology (Section 9.3).

1.3 Avalanche disasters, development of avalanche defense: historical overview

1.3.1 Chronicle of avalanche catastrophes

1.3.1.1 Avalanche disasters in the Alps

Avalanche events have been recorded throughout the history of settlements in the Alps. Livius [7] reported heavy losses caused by avalanches during Hannibal's crossing of the Alps (loss of 18,000 men and 2,000 horses). Famous Alpine villages such as Heiligenblut or St. Christoph/Arlberg owe their origin to avalanche disasters. One of the most disastrous avalanche winters was in February 1689 with a toll of 265 people including 80 people in the Swiss villages Saas and St. Antönien [117]. In 1667 in Switzerland, the village Anzonico was totally destroyed and 88 people died. Avalanches played a major role during World War I along the Dolomite front. Extraordinary snowfall and low temperatures led to catastrophic avalanches that buried several thousand soldiers on both sides of the front. On the Austrian side of the front alone, some 6000 soldiers were killed on December 16, 1916 on *black Thursday*.

Extreme avalanche events in the twentieth century include (see Figure 1.7):

1909	The most severe avalanche catastrophe of the European Railway history happened during the construction of the Tauern railway when 26 workers were killed [117].
1916	During World War II, Italy and Austria had military bases in the Alps and these troops were soon to find that bombs and enemy fire were not the only threats – heavy snow instigated a series of avalanches in the Tyrol region causing the death of 10 000 soldiers on what became known as *White Friday* 1916.
1924	Avalanches caused 9 deaths in Styria [117].
1935	Heavy snowfall (12.5 m snow depth in Langen am Arlberg, Austria) led to numerous avalanches in Austria, Switzerland and South Tyrol. More than 100 people were killed by avalanches, 50% of them were skiers [117].
1950/51	In Austria in more than 1000 avalanches, 135 people were killed. In Switzerland 98 people were killed.
1954	An avalanche catastrophe in Vorarlberg, Austria, caused 143 deaths [117].
1968/70	There were 24 avalanche victims in the region of Davos, Switzerland [5]. In 1970, several enormous avalanches occurred in Austria (Figure 1.8) and France with 39

deaths in Val d'Isère. An avalanche killed 74 people on the Plateau d'Assy in Savoyen.

1998/99 The most recent avalanche catastrophe occurred in February 1999 and caused 70 deaths in France, Switzerland and Austria; 31 persons died in a large avalanche in Galtür, Austria.

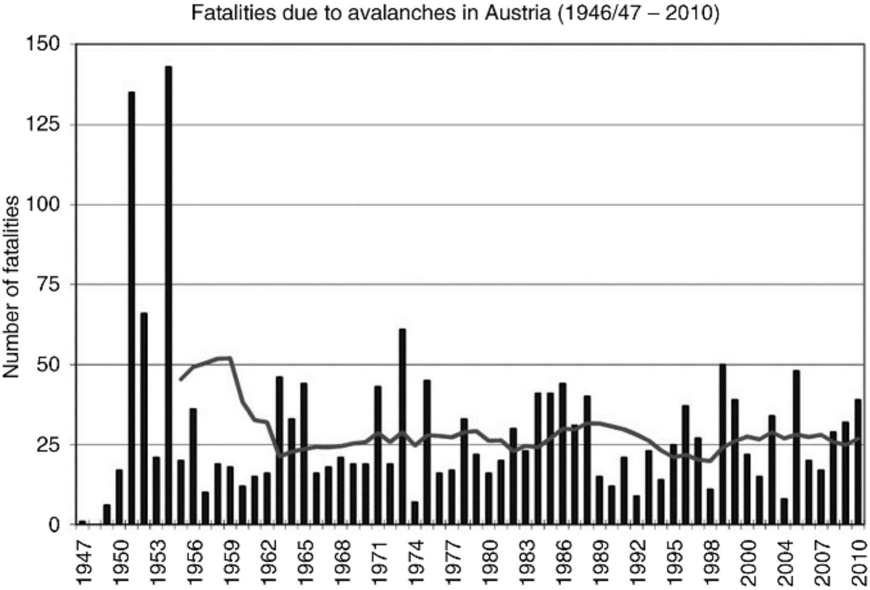

Fig. 1.7 Annual number of avalanche victims in Austria from 1945 to 2010 (© Austrian Board for Alpine Security Surveillance)

Fig. 1.8 Wiestal Avalanche (municipality Bichlbach, Tyrol) after the avalanche event in 1970 (© WLV Tyrol)

Statistical classification of the recurrence probabilities of historic avalanche cycles is limited because of a lack of long observation periods. For the avalanche event in Galtür in February 1999, the return period has been retrospectively estimated as 100–200 years [169] and the recurrence probability of the snow precipitation as 300 years [68].

1.3.1.2 Avalanche disasters in other regions

Avalanches are observed worldwide. The highest number of fatalities ever recorded in one event was the catastrophic mudflow in Huascaran, Peru, in 1970 where 25 000 people died [88].

Other notable avalanche events include:

Norway	From 1836 to 1998: 1510 people were killed in avalanches (in 1679, there were 130 fatalities in Western Norway; in 1868, there were 161 fatalities) [143]. March 5, 1986: In Vassdalen in Nordland county, a snow avalanche was released from Storebalak. 31 men from the North Norway Brigade were involved, 16 men were killed, 15 survived. March 1909 and March 1956: 51 fatalities on Lofoten islands. February 1928: 45 persons were killed mainly by slush flows in Hordaland, Sogn.
Iceland	1995: 34 avalanche fatalities in two avalanche events in Sudavik and Flateyri [125]. 1974: An avalanche killed 12 inhabitants in Neskaupstadur. 1910: An avalanche killed 20 inhabitants in Hnifsdalur. 1919: An avalanche killed 18 inhabitants in Siglufjördur.
USA/Canada	1910: Two passenger trains were buried by avalanches at Stevens Pass, Wellington, 97 passengers died [8, 142] 1910: 62 persons died at Rogers pass, Canada. 1965: 40 persons died in the Granduc mine disaster.
Turkey [87]	1975/76: 9 avalanche events with 170 fatalities. 1991/92: 112 avalanche events with 328 fatalities. 1992/93: 31 avalanche events with 135 fatalities.
Chile	The most disastrous avalanche event within the last 100 years happened in August 1944 in the working class district of the copper mine El Teniente with 102 casualties [150].
Pakistan	February 2010: 102 fatalities in Kohistan. April 2012: An avalanche hit a military camp near the Siachen glacier in the Karakoram branch of the Himalaya mountains, 135 soldiers died.
India	1979: A series of avalanches buried the valley leaving at least 200 victims in Lahaul Valley.
Afghanistan	2010: 166 fatalities at Salang Pass. 2012: Several avalanches in the Daspai area killed 201 people.

Corsica	1934: An avalanche from Castagniccia caused 37 fatalities in Ortiporia.
Romania	April 1977: 23 fatalities in Balea lac in the Southern Carpatians.
Slovakia	1924: Vel'ká Fatra avalanche in the Low Tatra mountains destroyed half of the village and killed 18 people. 1956: Vajskorska dolina avalanche caused 16 fatalities.
Japan	1993–1998: 143 avalanche disasters reported, these caused 50 fatalities.

1.4 History of avalanche defense

1.4.1 Historical development in Europe

The first structural avalanche defense structures were built in the form of earth or rock walls and were positioned directly above the endangered object (by hand, since machinery was not available). In Austria, the first known direct defense structure was a rock fill wedge erected in 1613 in the village of Galtür to protect the houses in the area called Birche. In Switzerland, technical defense structures have existed since the sixteenth century. One example is the defense wedge on the church Frauenkirche in Davos (Figure 1.9).

Avalanche defense walls in Austria were known as *Schneearchen*, *Spaltecken* or *Sauköpfe* [122]. Many houses had shed-like roofs to guide avalanches over the house. Although these first technical defense structures were primarily direct defense structures, organizational measures were also common. Houses located in safe areas were designated as meeting spots during evacuations and high-risk periods. It is still possible to find these cellars, called *Lahngrube*, *Lahnkeller* or *Lawinengruften* in old farmhouses today.

Fig. 1.9 Historical avalanche defense structures: Endangered by the avalanche Frauentobellawine, the church Frauenkirche was protected by an avalanche splitting wedge, constructed most probably in the 16th century (© Margreth)

Fig. 1.10 Historical avalanche defense structures: rock fill terraces at the Schafberg mountain in Pontresina (Switzerland), constructed around 1900 (© Margreth)

The need for a more systematic approach to defense structures arose in the 19th century, for example on a larger scale in the starting zones of avalanches. Emphasis was placed on the maintenance and restoration of protection forests and, through this, the frequency of avalanches was effectively reduced. Coaz [42] (the first Swiss forest inspector and pioneer in avalanche defense) reported the first avalanche defense structure in the 18th century; these were earth terraces with a length of 100–200 m, depth of 0.8 m and distance between the rows of approx. 20 m.

The erection of stone or earth terraces was the beginning of systematic protection in starting zones (Figure 1.10). However, Coaz noted already in 1910 that the height of the terraces was too low to support the accumulated snow cover and prevent avalanche release. Newer rock walls were built with a height of up to nine meters, and between 1876 and 1938, approx. 100 km of stone walls had been erected in Switzerland [64].

In Austria, the first systematic avalanche defense structures in a starting zone was built by the Austrian Service in Torrent Control at the Rax Mountain in Lower Austria. In the starting zone of the avalanche Lahngrubenlawine 770 m of rock fill walls and terraces and 23 wooden snow rakes were built [33].

A vast network of technical avalanche defense structures was necessary at the end of the 19th century during the construction of trans-Alp roads and railways. During the construction of the Arlberg railway from 1880 to 1884, serious avalanche accidents occurred on the western part of the pass. The first defense structures were built by Pollack (an employee of the railway company) (Figure 1.11a). In Switzerland, the first avalanche gallery was built on the Splügen and Simplon passes (Figure 1.11b). In

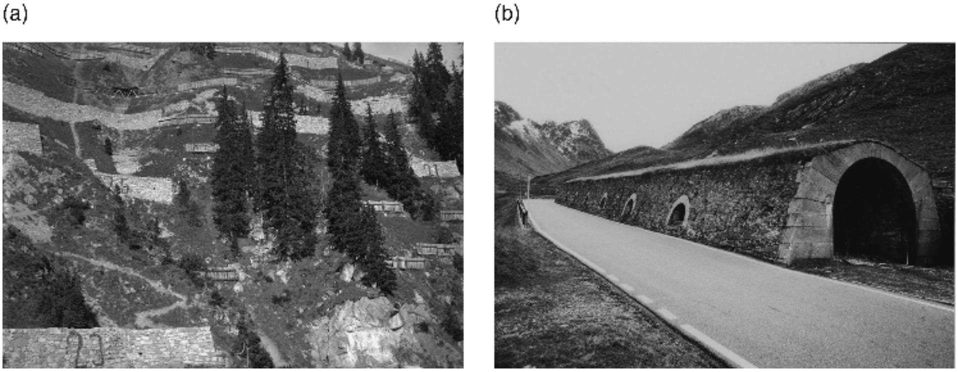

Fig. 1.11 Pioneer technical avalanche defense structures: (a) avalanche defense structures in the starting zone included rock fill terraces and snow rakes (*Arlbergrechen*) for the Arlberg railroad (© ÖBB); (b) avalanche tunnel with barrel vault, constructed in 1824 at the Splügen pass in Grisons (© Cantonal department of monument preservation Gisons, Switzerland)

Austria, the first avalanche gallery to protect a road was built by Karl Ritter von Geha in 1854. By 1888, 21 avalanche galleries had been constructed with a total length of 1.6 km.

The avalanche disasters of 1951 and 1954 intensified efforts to establish widespread technical avalanche protection in Alpine countries. In comparison to the vertical earth or stone terraces that had been used until this point but were ineffective because of rapid filling with falling or drifting snow, supporting structures made of steel, rope wires or wood erected perpendicular to the slope were thought to be more efficient. Steel snow bridges were developed by the Austrian Alpine Montan Union in 1955 and were used for the first time at the protection site on the mountain Heuberg in Häselgehr, Austria (Figure 1.12).

The first types of steel snow bridges were constructed with concrete foundations. This method carried high transportation costs since the concrete and steel parts had to be transported with a cable crane to the starting zone and from there with a narrow gauge railroad along the hillside to the construction site. To reduce costs, tests were made with anchors and blasting anchors. Nowadays foundations consist of ground plates for the supports and micropiles or anchors for the girders (Section 5.2.3).

Already in 1955, the first edition of the ‘Swiss guideline for defense structures in avalanche starting zones’ was published [50, 51]. After some revisions, the *Swiss guidelines* [163] have become the technical reference for supporting structures in many countries. Technical measures that influence the distribution of snow in or around the starting zone were also investigated. In Switzerland, the first snowdrift measures were erected in 1908 at the avalanche site Faldumalp in Valais, where rock fill walls were used to influence the snow distribution within the starting zone. In Austria, wind

Fig. 1.12 First avalanche defense structures in the starting zone with prefabricated snow bridges in steel, Heuberg, Häselgehr (© WLV Tyrol).

roofs and wind baffles were erected at the avalanche site Heuberg in Häselgehr (Sections 5.2.4.3 and 5.2.4.4).

If construction of protection measures in the starting zone was not feasible because of costs or unfavourable conditions for foundations, technical defense was implemented along the path or runout zone, usually in the form of deflecting or retarding dams or walls. Historical retarding mounds are visible along the Penzenlehner and Arzleralm avalanches above Innsbruck (Tyrol, Austria). After two severe avalanche cycles in Austria in 1935 and 1951, different kinds of retarding measures (concrete splitting wedges, earth or stone masonry retarding mounds) were erected on the mountain Nordkette near Innsbruck (Tyrol) to reduce the runout distance of the avalanches that endangered the town.

Many of these historical protection measures are still used today, which in part indicates that the basic principles of technical avalanche defense have not deviated far from the original principles introduced in the middle of the 20th century.