Snow avalanches can have highly destructive consequences in developed areas. Each year, avalanche catastrophes occur in mountain regions around the globe and cause unnecessary fatalities and severe damage to buildings and infrastructure. In some mountainous regions, especially in the European Alps, technical avalanche defence structures are built to increase the level of safety for inhabited areas; however, new infrastructure such as roads, railway lines and tourist facilities cause new risk potential in hazardous areas. As a result, the demand is increasing for technical avalanche protection solutions.

Avalanche defence structures and protection systems are used in most inhabited mountain regions worldwide. During the last decades, technical avalanche protection has evolved from a specialist field to an independent engineering branch that has gained importance in alpine countries such as Austria, Italy, France and Switzerland, as well as in other countries such as Canada, Iceland, Norway and USA.

This work is the first comprehensive, English-language overview of technical avalanche protection and establishes state-of-the-art best practices in the field. It covers the fundamentals of avalanche protection technology and includes plans, dimensions, construction and maintenance of defence structures. The editors have collaborated with an international team of experts from Austria, Canada, France, Iceland, Italy, Japan, Norway, Switzerland and USA to produce this landmark handbook.

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The Technical
Avalanche Protection
Handbook
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The Technical Avalanche Protection Handbook

Ernst & Sohn
A Wiley Brand
Preface

Large, high-energy snow avalanches can have high destructive consequences in developed areas. Each year, avalanche catastrophes occur in many mountain regions around the globe. This causes a large number of fatalities and severe damage to buildings and infrastructure. In some mountain areas, especially in the European Alps, a high level of safety for settlement areas is attained by application of technical avalanche defense construction. Simultaneously, new risk potentials continue to emerge in mountain regions from building in endangered areas, the establishment of new roads and railway lines across the mountains and development of tourism (skiing, alpine resorts). These are sometimes located partially or entirely outside protected areas. Consequently the demand for technical avalanche protection in these regions is constantly increasing.

During the last decades technical avalanche protection has evolved – especially in the Alpine countries Austria, Switzerland, Italy and France as well as Norway, Iceland, USA and Canada – from a specialist field to a stand-alone engineering branch. Currently avalanche defense structures and protection systems are established in practically all inhabited mountain regions worldwide. With this engineering handbook the editors are able to provide the first comprehensive overview of the field of technical avalanche protection in the English language and establish a common state-of-the-art. The book is based on the German edition, which was published in 2011, and comprises all relevant facts on fundamentals of avalanche protection technology as well as of planning, dimensioning, construction and maintenance of defense structures.

Technical avalanche protection denotes structural measures (defense structures), which are predominantly applied to protect inhabited areas. In such areas frequent and/or large avalanches may occur and cause significant risks to humans and material assets. The structures may consist of steel, concrete, earth, rock or wood material. Planning of defense structures is based on an intensive analysis and assessment of avalanche hazards and risks. Structure design usually considers a design event, which takes into account avalanches with a certain probability of occurrence and the applicable mass and energy associated with this design event. An unusual aspect of design, construction and maintenance is the enormous force of impact by avalanches and the extreme environmental and climatic conditions (alpine high altitude areas, subarctic climate) to which the structures are exposed. The extreme terrain and climatic conditions at the construction sites also bring about extraordinary challenges to workers and engineers.

However, several decades of experience in avalanche protection engineering have demonstrated the limits and usefulness of structural avalanche defense systems. Alternatively new technologies were developed in the field of artificial avalanche release, supported by sophisticated methods of avalanche monitoring. One of the starting points for emerging new technologies was the large avalanche cycle in the Alps in 1999. The new methods can be combined with classical defense structures and applied together with other kinds of protection measures (e.g. avalanche warning, closure, evacuation) for the purpose of an integrated avalanche risk management
procedure. Temporary avalanche protection systems – in the wider sense of the term technical avalanche protection – are also comprehensively presented in this book.

Until recently the state-of-the-art of technical avalanche engineering was available in several normative documents; however most advances in this field result from empirical developments in engineering practice. The highest stage of development and standardization was reached in the field of snow supporting structures in the starting zone. The oldest and best established standard in this field is the Swiss guideline on ‘Defense structures in avalanche starting zones’ (in its current version 2007) [194], which represents one of the most important sources of this handbook. Recently in several European countries standardization processes took place which lead to the publication of normative documents, partially in order to adapt the Swiss Guideline to national framework conditions: for example France: Norme Française (1992) [219]; Iceland: Jóhannesson und Margreth [148]; Austria: ÖNORM-Regeln 24805 ff. [244–246]. In other countries such as Norway, USA, Canada or Japan still no specific national standards are available. One of the most important steps was the adaptation of norms to the regulation of the Eurocode (unified European standardization). This handbook includes a comprehensive overview of the relevant standards and guidelines of technical avalanche protection at the current status. The Eurocode refers to Swiss (SIA), Austrian (ON), German (DIN) and US standards.

In Chapter 1 the reader is introduced to the system of technical avalanche protection and its historical development based on a fundamental classification of protection measures. Chapter 2 deals with the fundamentals of avalanche formation and the criteria for frequency, magnitude and risk assessment. Subsequently Chapter 3 presents the physical principles of avalanche dynamics impact on objects and the numerical avalanche process models best established in engineering practice. Chapter 4 is dedicated to the system of hazard and risk mapping, based on hazard and risk assessment, and shows the planning processes for structural avalanche defense. The most important protection concepts and goals are also provided in Chapter 4 as well as criteria of a sustainable planning according to technical, economic and environmental principles. Chapter 5 provides a comprehensive and systematic overview of defense structures in the avalanche starting zone as well as the avalanche path and runout zone. All relevant, applicable and historic construction types are presented by technical description system sketches and photographs. The construction and dimensioning of avalanche defense structures, with special respect to supporting components, building material and geotechnical fundaments of foundation are dealt with in Chapter 6. This chapter also comprises all relevant information for dimensioning and technical calculation of required in engineering practice. Chapter 7 presents the fundamentals of construction works and maintenance for avalanche defense structures and with special respect to the Alpine environment. Details on construction methods, construction site infrastructure, transportation systems and construction equipment is included as well as the system of monitoring (inspection) and maintenance for avalanche defense structures over their useful life. Chapter 8 gives a comprehensive overview of the methods of building protection (object protection) in areas endangered by avalanches. Finally Chapter 9 comprises the fundamentals and technology of temporary avalanche protection by artificial release, avalanche warning and monitoring. In this chapter current
developments and best practice examples of artificial avalanche release technology from Switzerland and Austria were added (referring to the chapter in the German edition). Chapter 10 finally presents an international overview (table) of avalanche protection in the most endangered countries (based on the German edition).

During the writing of this handbook the editors were able to bring together an international team of leading experts in technical avalanche protection. Authors from Austria, Switzerland, USA, Norway, Canada, Iceland, Japan, France and Italy have directly contributed to this book or supported it with essential information. The book represents a sequel of publication in the field of natural hazard engineering in the framework of Wiley/Ernst & Sohn Berlin publishing house. The main purpose of this publication is to share specialized engineering knowledge and experience in avalanche protection among experts worldwide and contribute to more safety in mountain regions exposed to avalanche risks.

Special thanks go to the Federal Ministry of Agriculture, Forestry, Environment and Water Management in Vienna, the Austrian Service for Torrent and Avalanche Control, the Austrian Standards Institute, the WSL Institute for Snow and Avalanche Research SLF in Davos, the Tyrolean Avalanche Warning Service in Innsbruck, the Austrian Research Centre for Forests, the Austrian Meteorological Service, the Icelandic Meteorological Office (Reykjavík), the American Avalanche Association (AAA), the South East Alaska Avalanche Center (AAC) and the Canadian Avalanche Association CAA (Revelstoke), who have actively supported the creation and elaboration of this handbook. The publication of this handbook would not have been possible without the intensive translation work by DeAnn Cougler (Munich; MB eurocom international languages Vienna) and the critical review by Emily Procter (Bolzano) as well as the design work of Andreas Herbert (Innsbruck). We also thank the legion of colleagues, who have given technical advice and the companies in the field of avalanche protection, who have supported us by latest information on new technologies. Finally special appreciation goes to the team of Ernst & Sohn in Berlin, especially Claudia Ozimek and Ute-Marlen Günther, for the support, patience and engagement to bring avalanche protection technology to the global engineering community.

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1 Introduction

Siegfried Sauermoser, Florian Rudolf-Miklau and Stefan Margreth

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 Bernardino, 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.
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. 1.1 Alpine living space, shaped by 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.
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.

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)
### Table 1.1 Classification scheme of avalanche defense measures

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