A TECHNICAL MANUAL FOR ASSESSING, MAPPING AND MITIGATING SNOW AVALANCHE RISK

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ABSTRACT: In summer 2018, the Canadian Avalanche Association will publish a book entitled *Planning Methods for Assessing and Mitigating Snow Avalanche Risk*. This book describes the *methods* used to assess, map and mitigate snow avalanche hazard and risk. The book is intended for the consultants, engineers, geoscientists, and their teams who prepare the reports and maps. However, to encourage readers interested in, or starting land-use planning for snow avalanche risk, the book includes hypothetical examples and illustrations in which qualitative, semi-quantitative and quantitative assessment and mapping methods are applied to diverse situations where elements at risk are exposed to snow avalanches. The book does not prescribe which methods are to be used in specific situations or jurisdictions; rather it provides a toolbox of methods for practitioners to select from, adapt and apply. The assessment and mapping chapters may be most relevant to North America and other regions where there are few written records of avalanche runouts, dynamic models are poorly calibrated, yet vegetation damage from extreme runouts are often available. The book does not cover the operational (day-to-day) management of snow avalanche risk by avalanche forecasters, ski guides, etc. There are 14 chapters: an introduction that frames the methods in the ISO 31000 context, six chapters about characterizing the terrain and avalanches for the situation of interest, four chapters about assessment and mapping methods, and three chapters that overview mitigation methods. The 280-page book has 16 authors with diverse experience in assessing, mapping and mitigating snow avalanche hazard and risk.

KEYWORDS: snow avalanche, planning, assessment, mapping, mitigation, hazard, risk

1 INTRODUCTION

In summer 2018, the Canadian Avalanche Association (CAA) will publish a technical manual, entitled *Planning Methods for Assessing and Mitigating Snow Avalanche Risk*. This book is about the methods used to assess, map and mitigate snow avalanche hazard and risk for land-use planning.

This book does not propose any new thresholds (i.e. guidelines) for acceptable avalanche hazard or risk for specific activities. Such guidelines are included in documents like *Technical Aspects of Snow Avalanche Risk Management - Resources and guidelines for avalanche practitioners in Canada* (CAA, 2016). Although the guidelines for human activity, infrastructure and buildings in snow avalanche terrain vary by jurisdiction, the methods to assess and mitigate avalanche hazard and risk generally do not. Hence, the methods in this technical manual should apply in Canada and beyond.

The methods follow the framework from ISO 31000 (CSA, 2010) and CAA (2016) in which hazard or risk assessment consists of the stages: identification, analysis and evaluation, which are preceded by establishing the context, and followed by mitigation. Figure 1 shows these stages and how they relate to the chapters of the book. Chapters 2 and 3 summarize the current understanding of avalanche terrain and its interaction with avalanche characteristics. The steps in assessing avalanche hazard and risk for land-use planning usually include interpreting evidence such as vegetation damage (Chapter 4), statistical runout estimation for large avalanches (Chapter 5), analysis of snow climate data (Chapter 6), and modelling the velocity and runout of large avalanches (Chapter 7). Qualitative and quantitative methods for assessing avalanche hazard and risk are summarized in Chapters 8, 9 and 10. Information from Chapters 2 through 8 on the spatial extent of avalanches is summarized in maps as described in Chapter 11. The basic calculations for avalanche impact are introduced in Chapter 12. The advantages and limitations of various structural defenses, including protection forests, are summarized in Chapter 13, which also includes references to guides for designing structural defenses.

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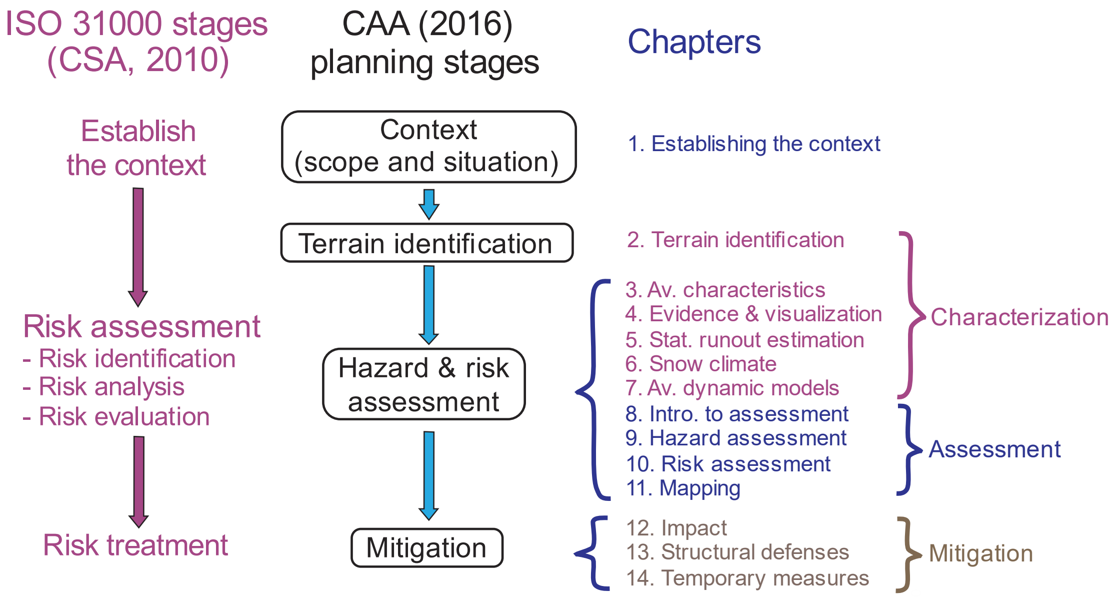

Figure 1: Stages of risk management based on CSA (2010) and CAA (2016) related to chapters of the book.

Since avalanche hazard and risk are often managed with a combination of structural defenses and day-to-day operational mitigation, Chapter 14 outlines operational measures such as forecasting, detection systems, and exploders known as remote avalanche control systems (RACS).

Rather than include the detailed methods from design guides such as Margreth (2007), Jóhannesson et al. (2009) and Rudolf-Miklau et al. (2015), the book describes the concepts and principles behind the design methods and provides references to the applicable design guides.

The extreme runout position (or simply “runout”) of avalanches is a key component for spatially assessing avalanche hazard or risk. Runout assessments are based on: written and oral records of long running avalanches; vegetation damage; statistical runout models; and dynamic models. The typical confidence in the runout estimates from these sources or methods varies between North America and western Europe. The records of extreme runout are often very good in the historically populated mountain valleys of western Europe and very limited in the areas proposed for development elsewhere. Also, the dynamic models are better calibrated in western Europe than elsewhere. In North America, statistical runout models have been calibrated for most major mountain ranges and are widely used. Also, vegetation damage near areas considered for development in North America is often a very useful indicator of the extent of previous extreme avalanches.

This book is intended for avalanche practitioners including engineers and geoscientists, consultants and those on their teams that assess, map or mitigate snow avalanche hazard or risk. It does not cover the operational (day-to-day) management of snow avalanche risk by avalanche workers such as forecasters and ski guides.

Each of the fourteen chapters is written by two or three of the following avalanche practitioners: Chris Argue, Ryan Buhler, Cam Campbell, Michael Conlan, Dave Gauthier, Brian Gould, Bruce Jamieson, Greg Johnson, Katherine Johnston, Alan Jones, Arni Jonsson, Alexandra Sinickas, Grant Statham, Chris Stethem, Scott Thumlert and Chris Wilbur.

The content of Chapters 2 to 14 of the book are summarized in Sections 2 to 14 of this paper, respectively.

2 CHAPTER 2 TERRAIN

This chapter covers the basics of avalanche terrain starting with definitions of avalanche path, start zone, track and runout zone. The characteristics of a start zone are summarized, including slope angle, area, orientation to wind and sun, downslope and cross-slope curvature, elevation and vegetation as well as ground roughness. The chapter explains the role of many of these factors in producing the large infrequent avalanches that can threaten infrastructure.

The key characteristics of avalanche tracks and runout zones are summarized, including discussion of the effects of terrain confinement (e.g.

gullies). For example, where a gully changes direction, momentum causes large fast avalanches to run up on the outer gully wall (super-elevation) and potentially spill over the gully wall.

3 CHAPTER 3 CHARACTERISTICS

Snow avalanches can start in wet or dry snow, as slabs or point releases. Most large and long-running avalanches start as dry slabs. In large paths, dry snow avalanches can reach speeds of 70 m s^{-1} and perhaps higher. Wet avalanches are typically slower than dry avalanches, but can also be very destructive because of their higher flow density.

The flow density of large avalanches decreases with increasing height in the flow column. Mixed-motion (dry) avalanches can be described as a lower dense flow and an upper powder (suspension) layer. Detailed descriptions of avalanche motion include a saltation layer above the dense flow and below the powder layer. For large avalanches moving in the track, the maximum slope-parallel speeds are similar in these layers. However, in any specific mixed-motion avalanche, the dense flow decelerates more in the runout zone and typically stops before the powder layer.

For infrastructure planning, it is important to characterize the avalanches in a path by their frequency (or return period) and magnitude. In a given path, avalanche mass, flow depth, maximum speed and runout increase with increasing return period.

4 CHAPTER 4 EVIDENCE OF AVALANCHES AND VISUALIZATION METHODS

Evidence of past avalanches is important for estimating the runout and lateral extent of future large avalanches. Evidence can be obtained from written and oral records, and observations of vegetation damage. Away from developed areas, written and oral records are usually limited outside of western Europe, and are often poor with regard to dates and runout distances. Vegetation records from air photographs, satellite images as well as field studies are often important where avalanches runout in forests. Boundaries between vegetation of different ages are called trim lines. The age of vegetation upstream of an avalanche trim line indicates the years since the last avalanche reached the line. The age of vegetation can be estimated in a variety of ways including tree species, tree height, and tree rings in core samples obtained from increment borers.

5 CHAPTER 5 STATISTICAL RUNOUT ESTIMATION

Estimating extreme runout is important for land use planning including transportation corridors, recreational developments, industrial use and residential land use. While statistical runout estimation cannot be used for every path, for many paths – especially in North America, it is one of several useful methods for estimating the extreme runout along the centerline of a path. The statistical models use runout data from paths in the range with known runout to provide an estimate of the extreme runout in a specific path to be mapped.

6 CHAPTER 6 APPLICATION OF CLIMATE DATA

The focus of this chapter is on extreme values of snow supply, which often relate to extreme avalanches.

Relevant snow climate variables include snowpack height HS or its water equivalent HSW, slab volume, release depth, avalanche volume or mass, 3-day increase in snow height, and monthly precipitation. For planning projects, extreme values of these variables are typically analyzed for return periods of 10 to 300 years.

7 CHAPTER 7 AVALANCHE DYNAMIC MODELS

Avalanche dynamic models have two distinct applications:

1. *Indirect calibration* where friction coefficients from other nearby paths with known extreme runouts and/or published values are adjusted using regional and sometimes local knowledge and then used to predict runout in the path to be mapped (Chapter 11).
2. *Direct calibration* (back calculation) where friction coefficients and release parameters are fitted to match a known extreme runout in the path. A directly calibrated dynamic model yields velocity to calculate impact pressure at selected points along the path.

Four dynamic models that are currently used in practice, PCM, PLK, AVAL-1D and RAMMS, are summarized. All four models use an empirical coefficient for “dry” sliding friction μ_k and another coefficient that is applied to velocity-squared in the underlying dynamic equation. All of these practical models use depth-averaged flow, i.e. they neglect shear within the dense flow.

AVAL-1D and RAMMS allow the practitioner to visualize the flow height along the path, which is important for impact on tall structures.

8 CHAPTER 8 INTRODUCTION TO HAZARD AND RISK ASSESSMENT

This chapter introduces the terminology, concepts and components of avalanche hazard and risk for Chapter 9 (hazard assessment), 10 (risk assessment) and 11 (mapping).

The assessment methods can be either qualitative, semi-quantitative or quantitative, each having their own advantages and limitations.

Some probability distributions commonly used in quantitative assessment methods are introduced.

Uncertainty can be found in most components of avalanche hazard and risk and in the ways the components are combined. Uncertainty – even if it cannot be quantified - should be identified and carried through the stages of assessing avalanche hazard or risk and communicated to the risk owner.

9 CHAPTER 9 HAZARD ASSESSMENT

Avalanche hazard is defined in terms of the spatial and temporal distribution of avalanche magnitude. For land-use planning – the focus of the book – the emphasis is on the spatial distribution of frequency and magnitude of avalanches. Hazard includes components of avalanche frequency (or likelihood or probability) and magnitude, e.g. destructive size, impact pressure and/or runout.

For the evaluation stage, the hazard is compared to criteria or thresholds, sometimes provided by the jurisdiction or risk owner.

10 CHAPTER 10 RISK ASSESSMENT

At its simplest, avalanche risk is defined as the combination of avalanche frequency (or likelihood or probability) and consequence for one or more scenarios. However, for many assessments, avalanche risk is analyzed with components for:

- frequency (or likelihood or probability),
- magnitude (or runout, impact pressure),
- exposure of elements at risk (including people), and
- the vulnerability of elements at risk

for one or more scenarios.

Most qualitative and semi-quantitative risk assessments are summarized in a risk matrix, usually with rows for likelihood or frequency, and columns for consequence. When the assessment includes an evaluation of the risk, cells of the matrix can be marked or colored to indicate the level of risk associated with the combinations of avalanche frequency and consequence.

For quantitative assessment, avalanche risk is analyzed in terms of the probability of an avalanche reaching one or more elements at risk that are exposed over space and/or time, and the consequences to those elements, for specified scenarios.

For quantitative methods, vulnerability is defined as the fraction of loss when property is exposed, and probability of death when people are exposed. Examples of quantitative vulnerability are given for various elements including buildings, people in buildings, people in vehicles, and people in the backcountry (i.e. terrain where avalanches are not controlled).

Assessment for specific scenarios is advantageous for mitigation planning since the mitigation is often different for frequent, less destructive, avalanches than for larger, infrequent avalanches even when these scenarios have the same level of risk. The risk due to all the identified scenarios yields the total risk, which can be compared to the risk due to other hazards or activities, or to the cost of mitigation.

The latter part of the chapter includes five illustrations that show different analytical methods (e.g. qualitative, quantitative with expected values, quantitative with Monte Carlo simulations of uncertainty) and different applications including transmission lines, fixed structures, and transportation corridors.

11 CHAPTER 11 AVALANCHE MAPPING

This chapter introduces five common types of avalanche maps: locator maps, path maps, terrain class maps, hazard zoning maps, and risk zoning maps. The typical applications, terrain survey level of effort (TSLE), and methods used to prepare the maps are summarized.

Since hazard mapping is well defined in western Europe and can be applied to zoning for occupied structures, the methods for hazard mapping are presented in more detail than for other methods. The method for hazard mapping for occupied structures is illustrated with a hypothetical example.

12 CHAPTER 12 AVALANCHE IMPACT

Impact pressures are proportional to flow density ρ and flow velocity v squared. A coefficient C can be applied to include the effect of flow regime, heterogeneity of the flow, impacted area, structure shape, structure stiffness, and structure orientation to the flow. Peak impact pressures can be substantially higher than average pressures because of heterogeneities and velocity variations in the flow. The peak pressures from medium to large avalanches are often in the hundreds of kPa.

Simple formulas are presented for avalanche impact on wide structures and drag on narrow structures. For design calculations of impact (normal pressure and tangential stress) on wide structures, drag forces on narrow structures as well as the heights over which these pressures and forces act, design guides such as Jóhannesson et al. (2009) or Rudolf-Miklau et al. (2015) are recommended.

13 CHAPTER 13 STRUCTURAL DEFENCES

Structural defenses are used to reduce the avalanche risk to a wide variety of elements of value, including communication structures, recreationists at ski resorts, towers for passenger ropeways, passengers and vehicles in transportation corridors, as well as occupied and industrial buildings.

14 CHAPTER 14 TEMPORARY MITIGATION MEASURES

Temporary mitigation measures including warnings, temporary closures and controlled release (intentional triggering) of avalanches depend on avalanche forecasting. The inputs to forecasting include weather, observed or modelled snowpack information, and observations or signals from recent avalanches. The spatial distribution of these factors over terrain is complex, but understanding the distribution is important to effective forecasting.

Systems to detect avalanches such as infrasound and radar are increasingly used by forecasting programs, notably for public transportation corridors.

During closures, many forecasting programs trigger avalanches intentionally (controlled release), which usually shortens the closure, reducing costs associated with the closure. The chapter includes an overview of many of the methods for intentionally triggering avalanches, including conventional explosive charges that may be placed by ground crews, or deployed from a helicopter. Alternatively, remote avalanche control system (RACS) in or near start zones can trigger avalanches by explosive charges or gas explosions. RACS tend to have higher capital cost but can trigger avalanches regardless of daylight or visibility, and often reduce the length of closures because they can be used at the optimal time during or following a storm.

Warning systems and evacuation planning for occupied areas are briefly summarized. These systems are currently more common in Europe than in North America.

Examples are provided in which temporary mitigation measures have been combined with defense structures to reduce the hazard or risk to people and/or infrastructure.

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