Available online at www.sciencedirect.com
ScienceDirect
Cold Regions Science and Technology 51 (2008) 253 – 272
cold regions science and technology
www.elsevier.com/locate/coldregions

Review of spatial variability of snowpack properties and its importance for avalanche formation

Jürg Schweizer [a,*], Kalle Kronholm [b], J. Bruce Jamieson [c], Karl W. Birkeland [d]

[a] WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, CH-7260 Davos Dorf, Switzerland
[b] International Centre for Geohazards ICG, Norwegian Geotechnical Institute NGI Oslo, Norway
[c] Department of Civil Engineering, Department of Geology and Geophysics, University of Calgary, Calgary AB, Canada
[d] US Forest Service National Avalanche Center, Bozeman MT, United States

Received 8 November 2006; accepted 12 April 2007

Abstract

The seasonal snow cover is spatially variable. Spatial variability of layer properties is due to various external and internal process drivers interacting with terrain and ground cover during and after the deposition process. Many processes that act as process drivers such as radiation and wind cause spatial variations of the snowpack at several scales. The most challenging process is probably wind that might hinder prediction of variability at the slope scale. The complexities and uncertainties involved in snow slope stability evaluation and avalanche prediction are largely due to the variable nature of the snow cover. Many studies have tried to quantify spatial variability. Different methods have been used and the studies covered a variety of scales. Accordingly, some results appear contradictory, suggesting that the degree of spatial variation varies widely. This is not surprising, and is partly due to the methods used and of course, due to varying natural conditions. For example, the variation will strongly depend on the measurement scale — the so-called support — of the method which varies from 10^{-4} m^2 for the SnowMicroPen to 3 m^2 for the rutschblock test. The layering was found to be less variable than, for example, the stability of small column tests. Whereas it is often perceived that the results of the studies were not conclusive, they completely changed our view of spatial variability. The importance of scale issues, in particular for avalanche formation became evident. Geostatistical analysis has been introduced and used to determine the length of spatial autocorrelation and to derive appropriate input data for numerical models. Model results suggest that spatial variation of strength properties has a substantial “knock-down” effect on slope stability and that the effect increases with increasing spatial correlation. The focus on scale has also revealed that spatial variations can promote instability or inhibit it. With the awareness of scale the causes of spatial variability can now be addressed. We will review the present state of knowledge, discuss consequences for avalanche forecasting and snow stability evaluation, and recommend future research directions.

Keywords: Snow cover; Snow stratigraphy; Snow mechanical properties; Snow slope stability evaluation; Avalanche formation; Avalanche forecasting; Spatial variability; Numerical modeling; Scale

1. Introduction

The way spatial variability has been analyzed and treated since the early snow studies differs. Early snow researchers understood that the snow cover varied in

* Corresponding author. Tel.: +41 81 4170164; fax: +41 81 4170110.
E-mail address: schweizer@slf.ch (J. Schweizer).

0165-232X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2007.04.009

space, and even suggested that wind was the most significant cause of the variability (Seligman, 1936). The stratigraphy of the snow cover was seen as the result of a sedimentation process causing layers with rather homogeneous as well as layers with rather heterogeneous properties (Paulcke, 1938). However, much research focused on describing the basic properties of the snow cover at a single location and its evolution over time, rather than analyzing spatial variability. This meant that observed variations in snow cover properties such as strength were primarily seen as the result of measurement errors (e.g., Keeler and Weeks, 1968). Only a few spatial investigations were done. For example, Neher (Bader et al., 1939) did a series of ram profiles and temperature measurements in different aspects and elevations, and Bradley (1970) studied the dependence and timing of deep slab instabilities by slope aspect using a specially constructed resistograph to rapidly measure penetration resistance.

When McClung (1979, 1981) presented a model of snow slab avalanche release based on fracture mechanical principles, he indirectly introduced a spatial component. Fracture mechanics assumes that there is no perfect material and describes whether and how a fracture grows from an initial imperfection in the material. In spatial variability terms, applied to avalanche release, the weak layer consisted of areas of lower than average strength (imperfections) and areas of about average or higher than average strength (everywhere else). This was used more as a conceptual model incorporating fracture mechanical principles rather than an actual model of the snow cover. However, Colbeck (1991) already pointed out in his review on the layered character of the snow cover that spatial variation of the weak layer thickness and strength would be critical to determining the likelihood of a failure and whether or not a failure would propagate or arrest.

Conway and Abrahamson (1984) first analyzed field measurements of stability in a spatial context. They measured shear strength along the fracture lines of slab avalanches shortly after triggering, and on slopes that had not failed. Along fracture lines, they found large variations between adjacent measurements, and some of their snow cover samples failed during test preparation. They assigned these measurements to so-called deficit zones where the shear strength of a weak snowpack layer or interface was less than the gravitational stress due to the overlying slab. They concluded that the weak layer or interface below the slab of an avalanche may contain deficit areas and pinning areas. If a deficit area was found by a test, the slope was considered to likely be unstable. Subsequently, Conway and Abrahamson (1988) used spatial statistics to derive the failure probability based on the size of deficit zones.

Conway and Abrahamson's papers triggered two things: (1) an increase in the number of field studies focusing on analyzing the spatial variability of various snowpack properties at the slope scale and concurrently the search for deficit zones, and (2) the representativity or validity (and hence the usefulness — in particular for recreationists) of single point stability tests became questioned (e.g., Munter, 2003). However, the importance of the spatial structure and its scale in the context of avalanche formation got lost in most of the research that followed. During the 1990s field results were rarely analyzed using spatial statistics. One exception is a study by Chernouss (1995) who presented autocorrelation functions for snow depth, snow density and strength from spatial measurements in the Khibini mountains to derive a probabilistic model of avalanche release (Chernouss and Fedorenko, 1998).

Currently, the focus is less on the validity of point observations. Rather, it is recognized that the spatial variability is important for slope stability evaluation and avalanche formation (Schweizer et al., 2003a), and should be investigated and described in detail for that purpose.

Furthermore, spatial variability of the snow cover, including terrain effects, was recognized as a major source of uncertainty in avalanche forecasting (Hägeli and McClung, 2004). They proposed a hierarchical framework that highlights scale issues that are relevant to avalanche forecasting.

Snow cover variability with regard to snow slope stability has been investigated in many studies (see below), and the interpretation of the results varies widely. Sturm and Benson (2004) saw similar differences in the interpretation of snow stratigraphy studies, and attributed this to two contradicting views: regular vs. irregular. In their review on the heterogeneity of snow stratigraphy they proposed that some studies suggest that the snow cover consists of well behaved and laterally homogeneous layers with properties that can be perfectly extrapolated. Other studies describe the layers as being so variable that cross-correlation of layers (finding the same layers) and extrapolation of layer properties is impossible for distances of kilometers or as little as tens of meters. Sturm and Benson (2004) suggested that the truth is probably somewhere in between. This view on snow stratigraphy might also apply for snow stability.

Considering the snow cover as a sediment promotes the understanding of the causes of the spatial variability of the snow cover. These causes (or agents) can be subdivided into external and internal causes acting