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Snowpack observations and fracture concepts for skier-triggering of dry-snow slab avalanches

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Abstract

Dry-snow slab avalanche release is generally believed to proceed in three stages: 1) initiation of a local failure (crack), 2) widespread fast propagation of that fracture beneath the slab, and 3) detachment of the slab from its margins. To date, most field stability tests primarily assess the strength of the weak layer and thus relate to the first stage of avalanche release — failure initiation. Field methods that comprehensively evaluate the second stage – fracture propagation – have remained elusive. In this paper, we explore evidence that field estimates of stability can be improved by integrating three elements: stability test score, fracture character or release type, and a simple index of structural stability (the stratigraphical threshold sum across the fracture interface). Using field data collected from skier-triggered avalanches and skier-tested slopes that did not release, we show that when these three elements fall into their respective critical ranges the accuracy of predicting the probability of a skier triggered avalanche is higher than when any one element is used alone. Further, we show through a qualitative analysis that these three elements fulfill, at least partially, the criteria for fracture initiation and propagation. As with any field stability method that relies on local snowpack data, the approach presented here is not intended to be used in isolation, but in conjunction with other measurements and observations that relate to the probability and consequences of avalanche release.

Keywords: Snow cover stratigraphy; Avalanche formation; Avalanche release; Skier triggering; Stability test; Snow stability evaluation; Avalanche forecasting; Fracture

1. Introduction

Dry snow slab avalanche release is ultimately a fracture process resulting in catastrophic failure of the sloping snow cover. Seen on the slope scale, a snow slab looses its shear support and slides downslope. Direct application of fracture mechanics to the snow avalanche problem is complicated by the fact that the snow cover is a layered material (Colbeck, 1991), the primary fracture is not in tension and that the fracture mechanical behavior of snow is best described as quasi-brittle which implies non-negligible size effects (Bažant et al., 2003). Only recently, fracture mechanical properties of snow have been measured and interpreted in view of the snow avalanche problem (McClung, 2007; Sigrist and Schweizer, 2007).

Shear (or mode II and III) fractures are not typical of homogeneous materials. Pure shear loading is rare, but usually mixed mode loading conditions prevail, so that cracks in brittle, isotropic, homogeneous materials grow

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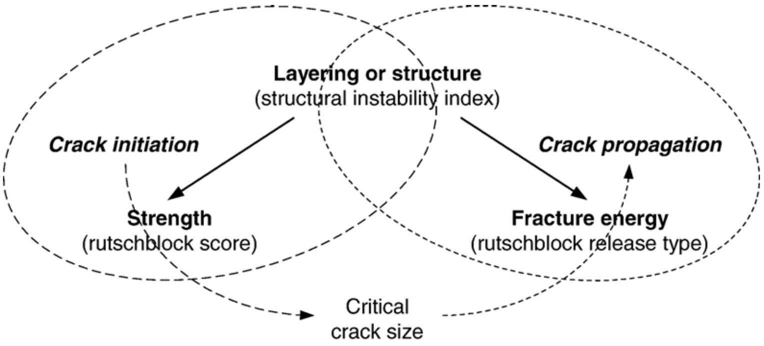

Fig. 1. Schematic display of the elements (structure or layering, strength and energy) believed to be essential for the fracture process and their corresponding proxies (structural instability index, rutschblock (RB) score, rutschblock release type).

in most cases by kinking in a direction such that the advancing tip is in mode I (Hutchinson and Suo, 1992). However, shear fractures under mixed mode loading conditions are common in heterogeneous, composite or layered materials where the interface presents a low-toughness fracture path through joined solids. The competition between crack advance within the interface and kinking out of the interface depends on the relative toughness of the interface to that of the adjoining material (Hutchinson and Suo, 1992).

The snow cover is a layered structure; one layer originating from a deposition process (e.g., precipitation or sublimation) is bonded to the layer below originating from the previous event. The stratified snowpack obviously offers opportunities for preferential interfacial crack growth, i.e. the crack is restricted to grow within a plane. Stiffness changes – as indicated by hardness changes – across layer boundaries act as stress concentrators so that cracks will preferentially grow on, or near, the interface between two layers of dissimilar stiffness.

If there is an avalanche prone structure (distinct differences in layer properties between layers), failure initiation and fracture propagation are required for a dry-snow slab avalanche to release. Failure initiation results from introducing a local failure, for example, when locally the strength of the weak layer or interface is overcome by the additional stress imparted by a skier or snowboarder while moving on the snow surface. Crack initiation, at least for localized dynamic loading due to skiers or explosives, is therefore related to critical stress or strength. If the local failure reaches a critical size, then fast fracture propagation will occur beneath the slab. Fracture mechanics tries to answer the question of how tolerant the snow is to that local flaw. The material property describing this flaw bearing capacity is called fracture toughness. In a material with a high fracture toughness, small cracks will generally not lead to catastrophic failure. We use fracture toughness in the general sense of resistance to propagation so that it also applies to the weak layer collapse model (Heierli, 2005; Heierli and Zaiser, 2006). Slope normal collapse is sometimes evident (van Herwijnen and Jamieson, 2005) but the failure mode at the scale of the snow microstructure is presently unclear. It is however clear that at the scale of the snow slope the slab slides down due to the loss of shear support, i.e. it appears to be a shear failure.

Snowpack observations for stability evaluation should ideally focus on the above mentioned essential

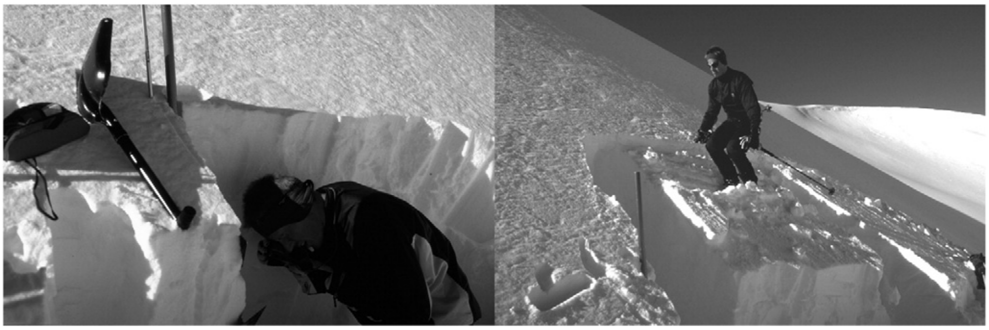

Fig. 2. Snowpack observations on skier-tested avalanche slope: snow profile (left) and adjacent snow stability test: rutschblock (right) that was performed subsequently.