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Evaluation of the snow penetrometer Avatech SP2

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A R T I C L E I N F O

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A B S T R A C T

Information on the structure of the snow cover is of great importance for operational avalanche forecasting. Manually observed snow profiles, including snow hardness, are therefore widely used to characterize snow stratigraphy. However, such manual measurements are subjective and observer dependent. While the ramsonde resistance profile provides a more objective alternative, it lacks the vertical resolution to identify thin layers and the hardness resolution to identify soft layers, which are essential components of a snow stability assessment. To overcome these limitations, digital cone penetrometers were developed to collect accurate and objective snow cover stratigraphy data. The SnowMicroPen provides highly resolved and accurate hardness profiles but its high price, size and weight, and fragility limit its usage to research purposes. Recently, a new lightweight penetrometer was released, the SP2, intended to fill the gap between the low-resolution ramsonde and the more expensive, accurate, high-resolution SnowMicroPen. We conducted an objective comparison of co-located vertical profiles measured by these three instruments in combination with manual stratigraphy and stability tests, in the French and Swiss Alps and in North America during winter 2015–2016. The SP2 profiles showed stratigraphic features similar to the SMP profiles. However, SP2 measurements were less repeatable with a profile variability generally larger than the spatial variability and influenced by the operator handling such as the penetration speed. The vertical accuracy was relatively low: the total depth was measured with a standard error of 7.5 cm and vertical shifts of the layer position were measured in the range $[-10, 22]$ cm with a standard error of 7.4 cm. Hardness measured by the SP2 showed no significant bias and a standard error of 34 kPa compared to the SMP. The SP2 resolution, as the ramsonde resolution, was too low to detect the weak layer of the considered new snow problem but sufficient to detect the weak layer associated to the considered old snow problems. Nevertheless, on these problems, the accuracy of the SP2 to characterize the slab and weak layer properties was too low to effectively derive stability indices directly from the SP2 profiles.

1. Introduction

Snow stratigraphy, i.e., the vertical arrangement of snow layers with different physical properties, is a key contributing factor to dry snow slab avalanche formation (Gaume et al., 2014; Schweizer et al., 2003). The formation of slab avalanches requires two prerequisites: a weak layer, whose low strength enables failure initiation, and an overlying slab whose relatively higher strength and stiffness enables crack propagation through the weak layer. Hardness, defined as the resistance against penetration of an object into snow (Fierz et al., 2009), has long been recognized as a good indicator of snow mechanical properties (Bader and Niggli, 1939). Vertical profiles of snow hardness thus contain information on the presence and mechanical properties of potential weak layers and overlying slabs, which is of particular importance to assess the avalanche danger.

However, objective measurements of snow stratigraphy are scarce. Manual observations still remain the main source of information about stratigraphy available to avalanche warning services. In these observations, the layer hardness is characterized by hand from manual penetration tests and other properties, such as grain type and size, from visual inspection. Even if the measurement procedure follows an international standard, these data inevitably contain some subjectivity (Fierz et al., 2009). More objective hardness measurements can be obtained from the ramsonde (Bader and Niggli, 1939). Ramsonde profiles can give an overall indication of the snowpack structure which can be used to classify it as either potentially stable or potentially unstable (Schweizer and Wiesinger, 2001). However, the vertical and hardness resolution of the ramsonde are too coarse to capture thin weak layers and small hardness variations in soft snow layers. Therefore, ramsonde profiles cannot be generally used on their own to assess

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precisely the snowpack stability nor help to determine stratigraphic features that could have been missed by the observer (Pielmeier and Schneebeli, 2003).

Over the years, various instruments have thus been developed to obtain objective hardness measurements with a higher resolution than the ramsonde resolution (Floyer, 2008; Pielmeier, 2003). The SnowMicroPen (SMP), initially developed by Dowd and Brown (1986), satisfies these requirements (Schneebeli and Johnson, 1998). Equipped with a small conical tip, the SMP accurately determines the penetration resistance of very fine layers. Studies using SMP profiles confirmed the relevance of measuring hardness to characterize snow layers at the microstructural scale (Proksch et al., 2015) and in terms of overall mechanical stability (Pielmeier and Marshall, 2009; Reuter et al., 2015). However, since the SMP remains a rather fragile instrument not particularly well suited for rapid field measurements over large areas, it is mainly used for research purposes and does not yet constitute an affordable alternative to the ramsonde for operational snowpack monitoring.

Recently, the company MoutainHub (previously called Avatech) introduced hand-driven digital cone penetrometers: the SP1 and the SP2 (Avatech, 2014). These penetrometers are intended for use by snow professionals, including ski patrollers, mountain guides and avalanche forecasters. They are easy to use and to transport and remain affordable. Beyond these appealing practical aspects, systematic and quantitative evaluations of their measurements are rather scarce. The SP1 was qualitatively evaluated by Lutz and Marshall (2014), Pilloix and Hagenmuller (2015) and quantitatively by Hagenmuller and Pilloix (2016). Lutz and Marshall (2014) showed that the SP1 measures snow hardness at the millimeter scale, yet the robustness as well as signal accuracy was limited. Pilloix and Hagenmuller (2015) found large variations in the depth accuracy especially in soft snow, in part due to problems with the detection of the snow surface. Hagenmuller and Pilloix (2016) showed that the SP1 hardness is in fair agreement with the SMP hardness, but the depth derived from the SP1 infrared sensor is inaccurate, with sizable errors having a standard deviation of 7.8 cm and maximum deviation of 20 cm at the considered site. Hence, the SP1 was recalled in the summer of 2015 and the improved SP2 probe, supposed to overcome the limitations of the first version, became available at the beginning of 2016. Many operational groups began to use the SP2, and an objective, quantitative evaluation was needed.

The goal of the present work is to evaluate SP2 data with a specific focus on relevant features for snowpack stability assessment. The main idea is to compare SP2 profiles to ramsonde and SMP profiles. The ramsonde and SMP represent, respectively, the low and high levels of measurement accuracy and resolution. This study combines and analyzes the data presented by three independent research groups (Hagenmuller et al., 2016; Marshall, 2016; Pielmeier and van Herwijnen, 2016). Firstly, the penetrometers, test sites and evaluation metrics are presented. The SP2 profiles are then compared to the reference profiles measured by the SMP according to different objective evaluation metrics. Finally, in view of a quantitative evaluation, the potential use of the SP2 in the framework of snow stability assessment is discussed.

2. Material and methods

2.1. Hardness measurements

Snow hardness is defined as the resistance against penetration of an object in snow. It is typically measured qualitatively by hand, and quantitatively by penetrometers. To compare the different measurements, hardness is here expressed in stress units (kPa) by scaling the penetration resisting force by the cross-section of the object penetrating the snowpack. The SP2 and SMP have a very similar sized cone penetrometer, while the ramsonde cone is much larger. It can thus be reasonably assumed that there is no scaling effect, i.e. a dependence of penetration strength to cone tip size, between the SMP and SP2 measurements. This assumption is no more valid to compare the ramsonde hardness to the SMP and SP2 hardnesses. Only the shape of the ram profile will therefore be compared to SMP and SP2 profiles in this paper. In this section, the different measurement methods are presented and their technical and operation characteristics are summarized in Table 1 and Fig. 1.

Table 1
Characteristics of different hardness measures (Avatech, 2014; Pielmeier and Schneebeli, 2003). (*) Manufacturer specifications, which will be evaluated in this work with field measurements.

	Hand	Ram	SMP	SP2
Probe weight (kg)	0	1 to 3	7	0.56
Probing depth (m)	Pit depth	1 to 3	1.2 to 1.7	1.47
Vertical accuracy (cm)	0.3 to 7	1 to 50	≤ 0.1	2 to 10*
Sensor range (kPa)	–	≥ 8	≤ 2000	≤ 1000
Sensor resolution (mm^{-1})	Variable	Variable	242	3 to 7*
Sensor accuracy (Pa)	Variable	Variable	63	344*
Probing time for 1 m snow (min)	2	5	1	0.1
Probe price (keuro)	0	1	35	1.5

2.1.1. Hand hardness

Hand hardness is measured by pushing the fist (F), four fingers (4F), one finger (1F), a pencil (P) or a knife (K) into the snowpack. The hand hardness corresponds to the biggest element that can be inserted while not exceeding a force of about 10 to 15 N (Fierz et al., 2009). If a knife cannot be inserted this way, the hand hardness is classified as "Ice" (I). Between the main classes, one (Swiss nomenclature) to two (Canadian nomenclature) intermediate classes can be considered to differentiate similar layers, such as F +, F–4F and 4F − between F and 4F. Since the size of the inserted object and the feeling of the maximum force is observer dependent, hand hardness is subjective. The vertical resolution of hand hardness depends on the size of the penetrating object required to capture the hardness. Previous comparisons between ram hardness and hand hardness have been used to develop a correspondence scale between these two measurements (Fierz et al., 2009).

2.1.2. Ramsonde

Because of its robustness and simplicity, the ramsonde is a standard instrument for measuring hardness. It was adapted from soil mechanics to snow studies by Haefeli in the 1930s (Bader and Niggli, 1939). It is used, e.g., by the observers of French and Swiss avalanche warning services to record snow hardness profiles. The ramsonde consists of a 1 m tube ending in a conical tip with a 60 degree apex angle and a maximum diameter of 40 mm (Fig. 1a). It is driven into the snow by mechanical hammer blows on top of the probe. Assuming that the work of the penetration resisting forces is equal to the change in gravity energy, the hardness can be calculated. The hardness resolution is limited by the weights of the probe (1 kg per tube) and the hammer (1 kg). The ramsonde is force-driven, so its vertical resolution depends on the snow hardness. It is also limited by the vertical extension of the tip (4 cm). It is at best 1 cm for hard snow (Pielmeier and Schneebeli, 2003). The penetration velocity is not constant, which can affect the hardness accuracy (Gubler, 1975). Moreover, significant energy losses that can occur, for instance at the connection between extension tubes or between the tube and the hammer, are not taken into account (Gubler, 1975).

2.1.3. SnowMicroPen (SMP)

The SnowMicroPen (SMP) measures accurately high-resolution hardness profiles which capture numerous layers in the snowpack stratigraphy (Pielmeier and Schneebeli, 2003). The SMP (version 4 used in this study) consists of a measuring conical tip with a 60 degree apex angle and a maximum diameter of 5 mm, which is driven into the