Inter-comparison of snow penetrometers (ramsonde, Avatech SP2 and SnowMicroPen) in the framework of avalanche forecasting

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INTER-COMPARISON OF SNOW PENETROMETERS (RAMSONDE, AVATECH SP2 AND SNOWMICROPEN) IN THE FRAMEWORK OF AVALANCHE FORECASTING

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ABSTRACT: Snow hardness, defined as the resistance against penetration of an object into snow, is a good mechanical indicator of the snowpack stratigraphy and is therefore a fair predictor of stability. Moreover, its measurement by a penetrometer does not require the time-consuming digging of a snow pit. For these reasons, hardness is a measure of choice in snowpack observations. The ramsonde can reliably quantify hardness but its resolution in depth and hardness is too poor to resolve thin features such as weak layers or soft features such as non-permanent slab structures. However, this instrument remains the worldwide standard to measure hardness. There is thus a need for highly resolved penetrometers. The SnowMicroPen fits these requirements but its high price and fragility limit its usage to research purposes. Recently, the company Avatech has released a new penetrometer, the SP2, intended to fill the gap between the robust and lowly resolved ramsonde and the costly and highly resolved 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 Alps during winter 2015-2016. The dataset comprises more than one hundred co-located SP2 and SnowMicroPen profiles measured for ten different snowpack configurations. The profiles are evaluated in terms of hardness and depth but we also focus on the features relevant to assess the snowpack stability. The SP2 is shown to successfully recover the main stratigraphic sequences but its depth measurement suffers from variable accuracy and its force sensor cannot resolve the vertical hardness variations in soft layers, which are measured by the SnowMicroPen or indirectly revealed by stability tests.

KEYWORDS: penetrometer, hardness, Avatech SP2, ramsonde, SnowMicroPen.

1. INTRODUCTION

Snow hardness, defined as the resistance against penetration of an object in snow (Fierz et al., 2009), has long been recognized as a good indicator of snow mechanical properties (Bader and Niggli, 1939) and thus as an indicator of avalanche-prone stratigraphies. Since penetration tests are relatively easy to conduct in field conditions, they remain a measure of choice for snowpack stratigraphic observations within the framework of operational avalanche forecasting.

Snow hardness can be measured by penetrometers or qualified by hand (hand hardness HH). In 1930's, Haefeli adapted the cone penetration test used in soil mechanics to snow and developed the first snow penetrometer, the ramsonde. Since then, many attempts to improve this device have been made (Floyer, 2008). Among these developments are the SnowMicroPen (SMP), a highly sensitive digital penetrometer composed of a small tip, the penetration of which is controlled by a motor (Schneebeli and Johnson, 1998), and the SABRE, a portable manually-driven penetrometer using an accelerometer to measure penetration depth (Mackenzie et al., 2002). More recently, the company Avatech (www.avatech.com) released a commercial version of the latter kind of penetrometer, the SP2, intended to be use by snow professionals. In practice, however, the reference instrument for operational avalanche forecasting remains the ramsonde.

The goal of this paper is to evaluate the SP2 profiles against the ramsonde profiles, using the SMP profiles as reference. To our knowledge, Lutz and Marshall (2014) and Hagenmuller and Pilloix (2016) presented the first evaluations on previous versions of this instrument, but no quantitative evaluation of the SP2 was presented so far. Note that evaluating the unit's functionality is beyond the scope of this work.

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2. MATERIAL AND METHODS

2.1 Penetrometers

The ramsonde consists of a 1 m tube (1 kg) ending in a conic tip with a 60° apex angle and a maximum diameter of 40 mm (Fig. 1a). Extension tubes can be added to probe deeper snow. The ramsonde is driven into the snowpack by dropping a hammer (1 kg) 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 ramsonde is force-driven, so its vertical depth resolution depends on the snow hardness and it is at best 1 cm for hard snow (Pielmeier and Schneebeli, 2003). The hardness resolution depends on the drop height and is limited by the weight of the tubes and the hammer. We refer to the ram hardness as the measured resisting force divided by the maximal horizontal cross-section area of the ramsonde tip.

The SP2 consists of a measuring conic tip with a 60° apex angle and a maximum diameter of 5.44 mm. The probe is pushed manually and vertically into the snowpack in a few seconds up to a depth of 147 cm (Fig. 1b). A force measurement is recorded every millimeter. Depth is calculated by combining the signals of different infrared sensors, the tip force sensor and an accelerometer. The force sensor measures forces between 0 and 23 N with an accuracy of 0.7 N. We refer to the SP2 hardness as the measured resisting force divided by the maximal horizontal cross-section of the SP2 measuring tip.

The SMP (version 4) consists of a measuring conic tip with a 60° apex angle and a maximum diameter of 5 mm, which is driven into the snowpack by a motor with a constant speed of 20 mm/s up to a depth of 120 cm (Fig. 1c). Two hundred and fifty force measurements are recorded per millimeter at this speed. The SMP motor is held fixed above the snow surface on a table composed of ski poles. Due to slight movements of the table when the tip hit hard layers, the depth accuracy is estimated to be roughly 1 cm. The force sensor measures forces in the range [0,40] N, with a resolution of 0.01 N. We refer to the SMP hardness as the measured resisting force divided by the maximal horizontal cross-section area of the SMP measuring tip.

2.2 Field data

The data used in this study was collected during winter 2015-2016 in the French Alps and spans different snowpack conditions. The data was collected during ten days on three sites (col de Porte: 2016/03/11, 2016/03/16; col du Lautaret: 2016/02/18, 2016/02/25, 2016/03/17; la Botte: 2016/01/06, 2016/01/20, 2016/02/04, 2016/02/10, 2016/03/10). The measurement were taken inside a 3 m x 3 m zone of an apparently homogeneous snowpack and is composed of the following data (with some discrepancy between measurement sites):

- 10 SP2 profiles,
- 5 SMP hardness profiles,
- 1 ramsonde profile,
- 5 stability tests (mainly compression tests),
- Snowpack manual stratigraphy.

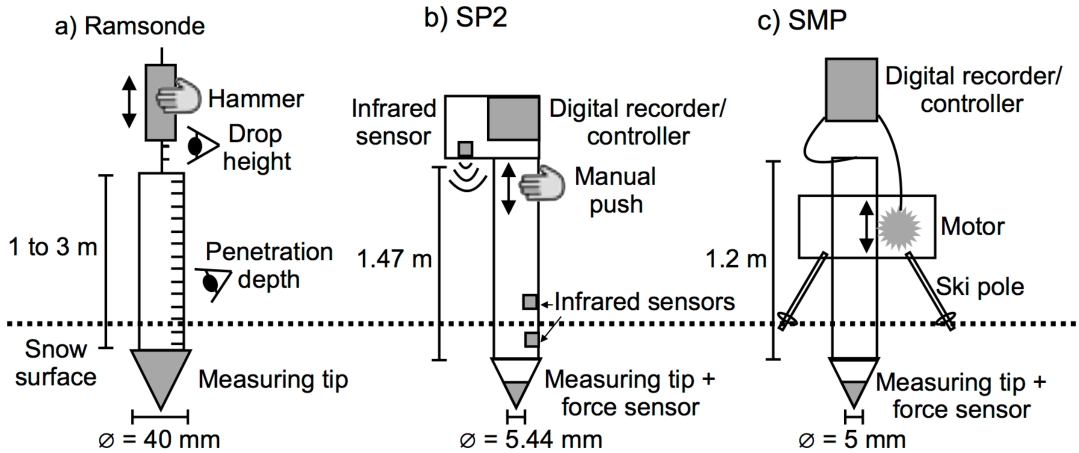

Fig. 1: Main characteristics of the penetrometers used in this study: a) Ramsonde, b) SP2 and c) SMP.

2.3 *Methods*

The SP2 profiles are evaluated on three main points:

- Total snow depth
- Layer hardness and depth,
- Detection of avalanche-prone structures.

Firstly, the total depth measured numerically by the SP2 is compared to the depth visible on the probe stick.

Secondly, the hardness and vertical positioning of the identified layers are compared between the different penetrometers. To this purpose, the algorithm developed by Hagenmuller and Pilloix (2016) is used. The idea of this algorithm is to consider layer thicknesses as adjustable parameters to maximize the correlation between hardness profiles (see Hagenmuller and Pilloix (2016) for details). The algorithm enables to partition the difference between profiles into separate depth and hardness differences (Fig. 2). Moreover, in order to assess whether the observed difference between instruments is due to snow spatial variability or measurement errors, the hardness profile variability measured with a given penetrometer is also quantified on the measurement sites with this algorithm.

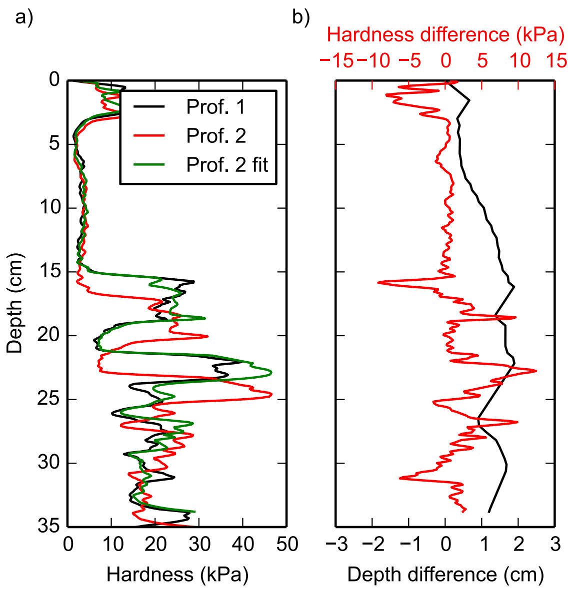

Fig. 2: The difference between profile 1 (Prof. 1) and profile 2 (Prof. 2) is decomposed into hardness and depth differences (b) by adjusting the layer thicknesses to maximize the hardness correlation (Prof. 2 fit).

The last evaluation criterion is the capability of the penetrometers to detect unstable snowpack configurations. To this end, the presence in the hardness profiles of potential weak layers detected by stability tests and manual stratigraphy is qualitatively evaluated. The stability of the whole weak layer – slab system cannot be directly quantified from the evaluation of the SP2 in terms of hardness and depth, since it results from the complex interplay between slab stiffness and weight, and weak layer strength (Reuter et al., 2015).

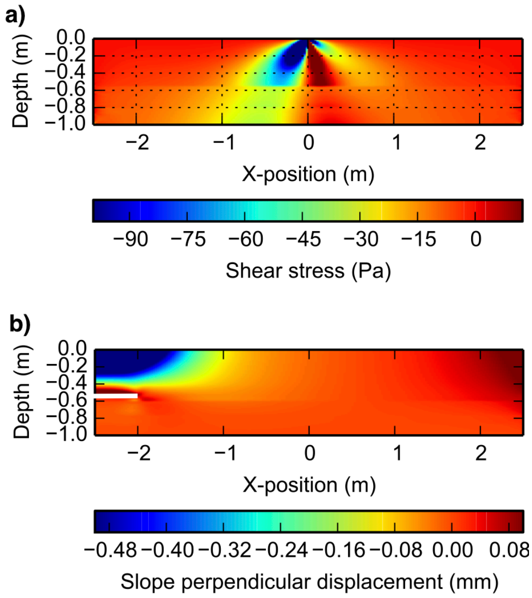

Fig. 3: Finite element model of the mechanical behavior of a slab – weak layer system on a 40° slope. a) Shear stress distribution under a punctual vertical skier load located on the snow surface. b) Displacement of the slab due to an artificial crack in the weak layer.

In order to account for this complex interplay, we adapted the method of Reuter et al. (2015) to SP2 hardness profiles. This numerical method computes indices of the likelihood of failure initiation and failure propagation from a SMP hardness profile. The main idea of this method is to derive the mechanical properties (density, elastic modulus and strength) of each layer from the hardness profile and to feed a finite element model with these layer properties. The failure initiation index is defined as the ratio between the weak layer strength and additional shear stress at the weak layer due to a skier on top of the snowpack on a 40° slope (Fig. 3a). The failure propagation index is the critical crack length calculated with the changes in total mechanical energy with increasing crack length along the weak layer (Fig. 3b). Comparing these indices computed from the SMP profiles or the SP2 profiles is an objective method to evaluate the SP2 directly in terms of the weak layer - slab system characteristics.

3. RESULTS

3.1 Total depth

Figure 4 shows the total depth measured with the SP2 as a function of the “true” depth measured manually on the probe stick, for 229 tests. The overall root mean square error (RMSE) is equal to 7.5 cm for the considered data set. The error tends to decrease with increasing total depth. Indeed, the main SP2 infrared depth sensor (Fig. 1b) is closer to the snow surface at the end of a test when the snowpack is deeper and thus tends to be more accurate. Note the presence of few outlier points, with errors larger than 30 cm, which could have been sorted out manually in the field.

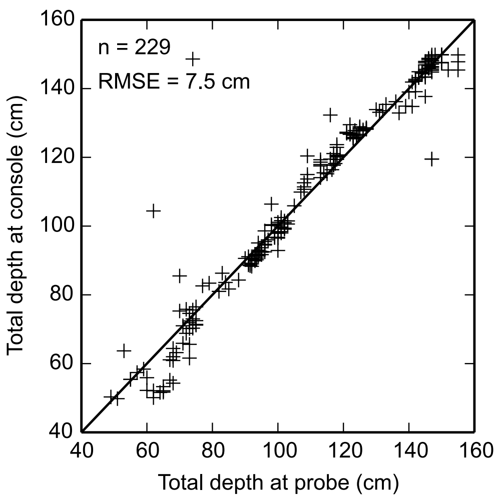

Fig. 4: Total depth measured with the SP2 as a function of the “true” depth computed on the whole data set.

3.2 Layer hardness and depth

Due to the spatial variability of snow and possible measurement errors, the 5 SMP profiles (respectively the 10 SP2 profiles) are never exactly the same but show differences in hardness and depth. Figs. 5a and 5b show these differences for the SMP and SP2 profiles measured on one particular site. The variability of the “layer” depth between the profiles is greater for the SP2 measurements (standard deviation of 4.5 cm) than for the SMP measurements (standard deviation of 2.1 cm). The variability of the hardness is also greater for the SP2 (standard deviation of 20 kPa) than for the SMP (standard deviation of 45 kPa). Given, the accuracy of the SMP sensor, the higher variability of the SP2 profiles can be attributed to measurement noise and not to snow spatial variability. Similar results are obtained for the whole data set, except for certain SP2 profiles whose variability is too high to perform the matching algorithm. The variability of the ramsonde profile due to the observer was not estimated here.

The mean SP2 and SMP profiles obtained with the matching algorithm, and the ramsonde profile are compared in Figure 6. The SP2 hardness is in very good agreement with the SMP hardness and shows relevant details not visible in the ramsonde profile. On this example, both accuracy and resolution of the SP2 are higher than those of the ramsonde. In particular, the hardness of the soft layer at depth 80 cm is over-estimated by the ramsonde but well re-covered by the SP2. The main difference between the SMP and SP2 profile is the difference in depth estimated in the range [-15,0] cm for this example. Similar results are obtained for the whole data set, except for shallow and soft snowpacks on which the SP2 profiles were too discrepant to perform a quantitative analysis with the matching algorithm.

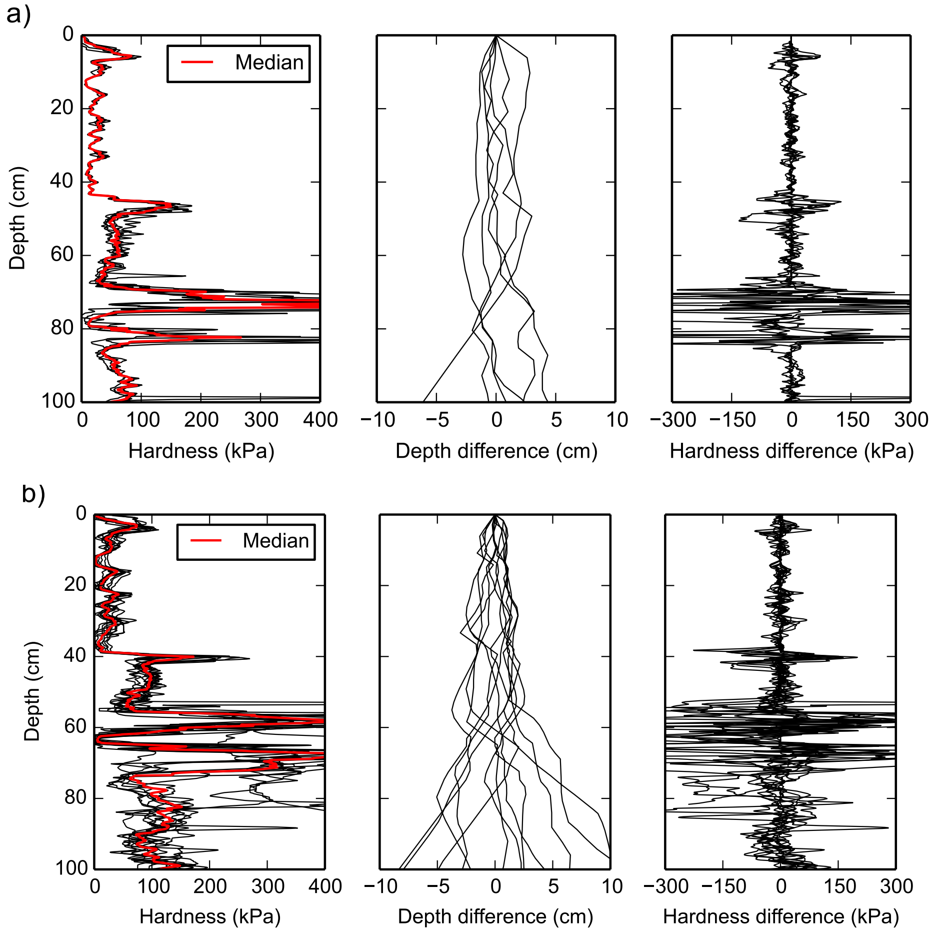

Fig. 5: Decomposition of the variability of hardness profiles measured on the same site by the SMP (a) and the SP2 (b). The matched profiles are shown in the left subplots, the depth differences in the center subplots and the hardness differences in the right subplots (see Figure 2 for details). The variability of the SP2 profiles is greater than the variability of the SMP profiles. Data collected at la Botte on 10th February 2016.

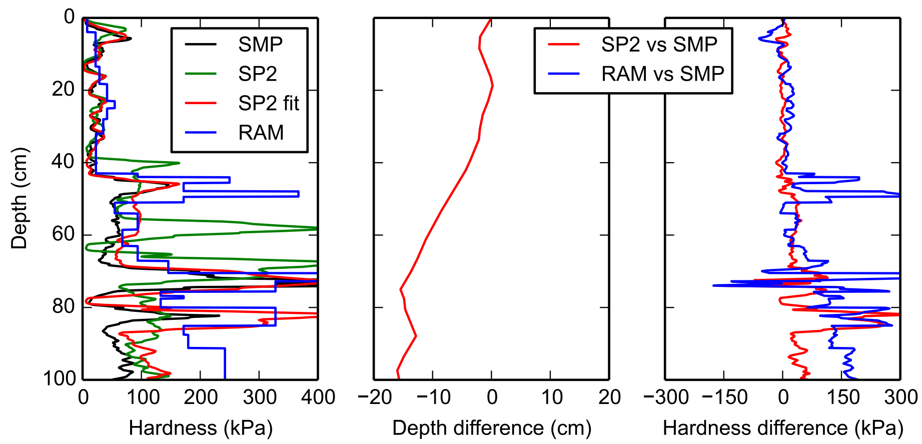

Fig. 6: Comparison of the SMP, SP2 and ramsonde profiles. The differences of the profiles shown on the left are decomposed into depth differences (center) and hardness differences (right). See Figure 2 for details. Data collected at la Botte on 10th February 2016.

3.3 Stability

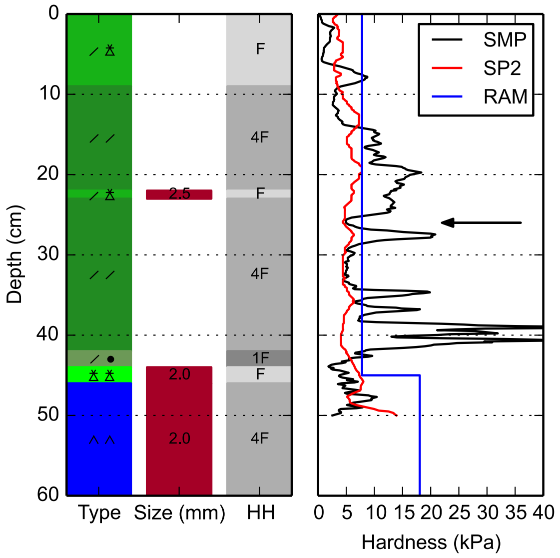

Fig. 7: New snow problem. Non-permanent weak layer composed of new snow located at 26 cm depth (arrow) below a slab of slightly blown snow. This avalanche problem is not detected by the SP2 or the ramsonde. Data collected at la Botte on 6th January 2016.

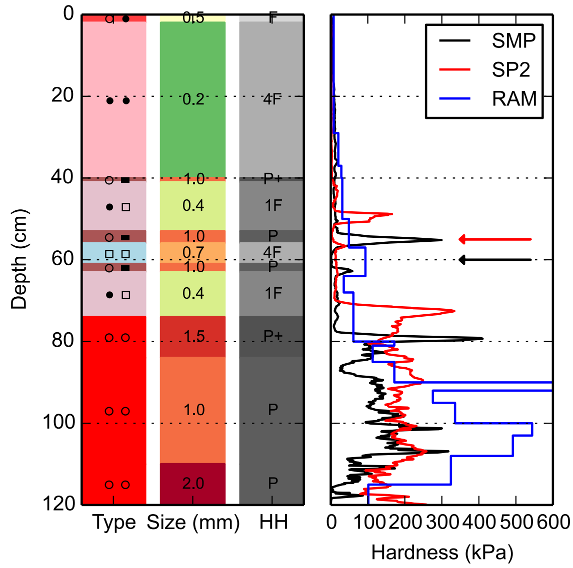

Fig. 8: Old snow problem with a weak layer composed of faceted crystals located at about 60 cm depth (arrow). This avalanche problem is detected by the SP2 but not clearly by the ramsonde. Data collected at la Botte on 10th March 2016.

Two different avalanche problems are considered in this section to evaluate the capability of the SP2 to detect unstable snowpack configurations.

Firstly, a so-called new snow problem is presented in Figure 7. It is composed of new snow with a very low mean hardness. The stability tests (compression test scores between 11 and 20 taps) reveal the presence of a weak layer at a depth of about 26 cm. From the manual stratigraphy, it can be inferred that this weak layer is probably composed of new snow deposited without wind and probably including graupel, below a slab composed of new snow partly decomposed by wind during precipitation. The SMP hardness profile clearly reveals low penetration strength at a depth of about 26 cm between layers of larger strength (Fig. 7). On the contrary, the SP2 and the ramsonde profiles are almost constant over depth and do not show any particular hardness feature (Fig. 7). On this example characterized by small variations of hardness with depth in a snowpack with very low mean resistance to penetration, the SP2 and the ramsonde do not reveal the potential instability visible in the SMP profile and the stability tests.

Secondly, a so-called old snow problem is considered (Fig. 8). It is composed of "evolved" snow types that have not been modified for several days. The stability tests (compression test scores between 11 and 20 taps) reveal the presence of a weak layer at a depth of about 60 cm. This weak layer is composed of faceted crystals. It is located below a slab mainly composed of rounded grains, and between two thin crusts. Note that the upper crust is too thin to avoid all potential instabilities. The SMP and SP2 hardness profiles clearly reveal low penetration strength at a depth of about 60 cm (the weak layer) between two marked hardness peaks (the two thin crusts) (Fig. 8). These hardness features do not appear clearly in the ramsonde profile. On this example characterized by a permanent weak layer composed of faceted crystals, the SP2 provides valuable information on the snowpack stability compared to the ramsonde.

The characterization of this old snow problem (Fig. 8) by the SP2 is quantitatively evaluated by comparing the failure initiation and propagation criteria computed with the SP2 and SMP profiles (Tbl. 1). On this example, the load due to snow weight (respectively due to a potential skier) is underestimated (respectively over-estimated) by the SP2 compared to the SMP. These differences are due to an underestimation of the hardness above the weak layer and of the weak layer depth. The weak layer fracture energy (and strength) simulated with SP2 data is over-estimated compared to the SMP. The over-estimation of the skier load compensates the overestimation of the weak layer strength and consequently the initiation criterion (strength divided by skier load at weak layer) computed with SP2 data is close to the one computed with SMP data. Similar results are obtained for the critical crack length: the SP2 critical crack length (71 cm) indicates slightly more stable conditions than the SMP critical crack length (55 cm).

Tbl. 1: Simulated mechanical characteristics of the weak layer - slab system modeled with the SMP and SP2 profiles presented in Figure 8.

Characteristics	*SMP*	*SP2*
Snow load at weak layer (kPa)	0.50	0.22
Skier load at weak layer (kPa)	0.03	0.05
Weak layer fracture energy (J/m)	0.76	1.43
Initiation criterion (-)	68	87
Critical crack length (m)	0.55	0.71

4. CONCLUSION

The SP2 is shown to successfully recover the main snow stratigraphic sequences. However, its depth measurement suffers from variable accuracy with errors up to 15 cm for some layers and on the order of 7 cm for the total snow depth. Moreover, its force sensor cannot resolve the vertical hardness variations in very soft layers.

The profile variability measured by the SP2 is due to the snowpack spatial variability and also measurement errors. To get a correct observation of the snowpack stratigraphy with the SP2, it is necessary to collect several profiles next to each other and to combine them with a numerical method.

The SP2 failed to detect the considered new snow problem revealed by the SMP and stability tests. The SP2 succeeded to detect the considered old snow problem invisible to the ramsonde. The millimetric vertical resolution of the SP2 catches thin layers with great hardness difference, which cannot be detected by the ramsonde. However, the absolute values of the SP2 hardness still appears to be too coarse to enable automatic processing of the collected data in terms of quantitative stability criteria.

CONFLICT OF INTEREST

The creation of this document was not supported financially or materially by the producer of the SP2 (Avatech). The authors did not benefit financially from the production or sale of the SP2 and they did not receive any related grants or patents.

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