BLADE HARDNESS GAUGE: SNOW HARDNESS MEASURING AND ANALYSIS TECHNIQUES

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ABSTRACT: The blade hardness gauge (BHG) is a promising technology for avalanche forecasters, technicians, and researchers. Designed and produced by Fraser Instruments Ltd., the BHG resembles and is based on the thin-blade tool introduced by Borstad and McClung in 2011. The BHG was designed to quantitatively measure snow hardness without the known biases of the hand hardness test. Research was carried out in the Canadian mountains of British Columbia and Alberta during the 2020-21 and 2021-22 winter seasons to test the reliability and integrity of the BHG. Side by side snow hardness profile comparison amongst avalanche practitioners shows that the BHG is more consistent for measuring snow hardness than the hand hardness test. A blade hardness to hand hardness comparative scale was developed to utilize the BHG as a teaching tool for the hand hardness test. This paper proposes refinements to standard data collection methods and techniques including the insertion rate and orientation of the thin-blade into the snowpack. These recommendations aim to increase consistency amongst users and highlight applications for avalanche practitioners to use in the field.

KEYWORDS: snow hardness, hand hardness, thin-blade, blade hardness gauge.

1. INTRODUCTION

A predictive measurement used in avalanche forecasting is snow hardness, which is a measure of the snow's resistance to penetration by an object (Fierz et al., 2009). The resistance is the combination of snow grain bonds and structures, bending, rupturing, and compacting along with the friction between the snow and the penetrating object (Borstad & McClung, 2011).

The first mechanical measurements of snow hardness were taken using the Swiss rammsonde, a metal probe driven into the snow by the observer dropping specified weights on the probe, in 1936 (Haefeli, 1954; Höller & Fromm, 2010). Although capable of measuring snow hardness, it is unable to detect thin weak layers associated with slab avalanches (Schneebeli & Johnson, 1998).

The current standard for measuring snow hardness in Canada is the hand hardness test, introduced by De Quervain in 1950 (Canadian Avalanche Association, 2016). The hand hardness test has the operator exert 10-15 N of force using physical objects of decreasing surface area (fist, 4 fingers, 1 finger, pencil and knife) into the snowpack. This standard has been set by "The International Classification for Seasonal Snow on the Ground" (Fierz et al., 2009). Furthermore, the Canadian Avalanche Association has operators add + and - indicators to illustrate variations in hardness (Canadian Avalanche Association, 2016). This test has shortcomings in accuracy: bias amongst users, failure to consistently apply 10-15 N, misusing ± as a classification and varying size of hand (Pogue et al., 2018).

The blade hardness gauge (BHG) is a promising technology to quantitatively measure snow hardness without the shortcomings of the hand hardness test. This work investigates the reliability and integrity of the BHG with respect to measuring snow hardness.

Figure 1: Blade Hardness Gauge

The BHGs used in this study were the 3rd and latest model of the BHG produced by Fraser Instruments

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Ltd. (Figure 1). The blade is stainless steel, 0.6 mm thick, width of 10.0 cm, has a force range of 0 – 50 N and is precise to 0.05 N. The BHG measures and displays the peak resistance hardness as the blade is inserted into the snowpack.

The BHG is based off the thin-blade tool introduced by Borstad and McClung (Borstad & McClung, 2011). The thin-blade device allows the avalanche practitioner to measure the hardness of thin weak layers over time (Pogue & McClung, 2016). A Parks Canada study comparing the use of the BHG, and the hand hardness test concluded that the ± indexes used have no meaning, that fist and 4 fingers hardness is basically the same and that further testing is needed for operator hand hardness bias (Pogue et al., 2018).

2. OBJECTIVES

Utilizing the BHG to quantitatively measure the hardness of snow this research explored the following objectives:

- Determine if there is a difference in recorded BHG measurements between fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates into the snowpack.
- Determine if there is a difference in recorded BHG measurements depending on the orientation of the BHG into the snowpack.
- Find a correlation between BHG measurements and the hand hardness test.
- Test the replication of the hand hardness test versus the BHG amongst avalanche technicians.

3. METHODS

This study occurred over the winter seasons of 2020/21 and 2021/22. The primary field sites were situated within the Kicking Horse Mountain Resort tenure and the surrounding backcountry in Golden, BC, Canada. Additional field data was gathered in the Canadian Rockies, Rogers Pass, Big White Ski Area, and Whistler Blackcomb. The snow profiles carried out in the designated study sites adhered to the observation and recording guidelines set forth by the Canadian Avalanche Association (Canadian Avalanche Association, 2016). Further observations were made using the BHG.

3.1 Insertion Rate

The BHG was inserted into the snowpack with a fast (≈ 10 cm/s) insertion rate while maintaining a slope parallel angle. Subsequently, the same BHG was inserted into the snowpack at the same depth of snow with a slow (≈ 1-3 cm/s) insertion rate at the same angle as the prior measurement (parallel with the slope). The insertions were spaced roughly 2 cm apart.

To determine the consistency of fast versus slow measurements, a second experiment was completed. In this experiment, layers of homogenous snow greater than 10 cm in height were utilized to take trials of ten fast versus ten slow measurements. The BHG was placed into the snow perpendicular to the slope angle to reduce spatial variability of the snowpack in relation to snow layering. This procedure was carried out in multiple layers of snow differing in snow hardness. Figure 2 illustrates the spacing of BHG measurements that were taken.

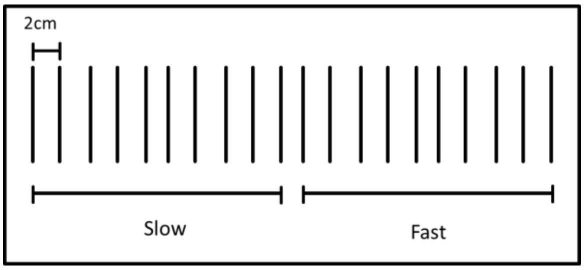

Figure 2: Schematic of the spacing of blade hardness measurements in relation to the consistency of insertion rate objective.

In both of the above experiments, the velocity of insertion rates was standardized through timer and ruler-based measurements, where velocity is the measure of the distance covered in a given amount of time. These calibrations were conducted inside by the researcher before venturing into the field. During fieldwork, the researcher subjectively assessed the insertion rates.

3.2 Orientation

Homogenous snowpack layers with a height of 10 cm or more (determined through a combination of visual and physical methods in excavated snow profiles) were subject to a comparison between six horizontal BHG measurements (blade aligned parallel to the slope) and one vertical BHG measurement (blade aligned perpendicular to the slope). For the horizontal measurements, intervals of 2 cm were employed vertically, resulting in a cumulative vertical height of 10 cm. When using the BHG in a vertical orientation, a measurement was obtained over the entire 10 cm vertical distance. Both horizontal and vertical measurements were spaced roughly 2 cm apart and their corresponding values were documented.

3.3 Hand hardness

Blade hardness measurements were conducted in conjunction with the respective hand hardness profiles, aiming to quantitatively gauge the hand hardness scale. An avalanche technician recorded hand hardness for each layer. The researcher, on the other hand, performed BHG measurements at approximately 2 cm intervals within the layers to ensure uniform BHG measurements. The insertion rate for all

BHG measurements was maintained at approximately 10 cm/s, with the researcher subjectively assessing the rate.

To assess the repeatability of both the hand hardness test and the BHG, avalanche technicians sequentially executed hand hardness and BHG measurements. Each technician was unaware of the measurements previously taken by others to ensure independence. The technicians were instructed to carry out BHG measurements with a consistent, rapid insertion rate of approximately 10 cm/s, every 2 cm within the layers. These sets of measurements were obtained from the same snow profile, with minimal time gaps between technicians to mitigate weather-related influences, and minimal spacing to mitigate spatial variability effects in the snowpack.

4. RESULTS

4.1 Insertion Rate

Pairs of BHG measurements were taken to test if there is a difference in BHG measurements with respect to fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates. A total of 136 in situ pairs were taken in snow profiles consisting of dry snow ranging in blade hardness 0.1 N to 36.2 N (Table 1). Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the distribution of differences between the fast and slow insertion rates (WS = 1938.00, $p < 0.01$). The data supports there is statistically significant difference between the median of the distribution of differences between the fast and slow insertion rates (Figure 3).

Table 1. Descriptive statistics comparing fast and slow insertion rates with the BHG (Difference = Fast – Slow).

Insertion Rate	Average (N)	Standard Deviation (N)	Standard Error (N)
Fast	6.47	7.54	0.65
Slow	8.01	9.00	0.77
Difference	-1.54	2.69	0.23

To test the consistency of the insertion rates, trials of ten fast versus ten slow measurements were taken in layers of homogenous snow greater than 10 cm in height. This procedure was carried out in multiple layers of snow differing in snow hardness resulting in 11 trials of 10 fast versus 10 slow BHG measurements.

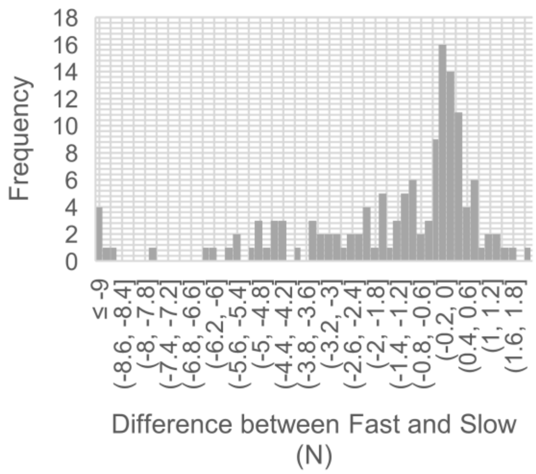

Figure 3: Histogram of the distribution of differences between the fast and slow insertion rates of the BHG into dry snow, n=136.

Comparing the standard deviations of the 11 trials (Figure 4) illustrates that using a fast insertion rate results in more consistent measurements without a high scatter of data. Using a slow insertion rate results in a higher scatter of data in each snow layer.

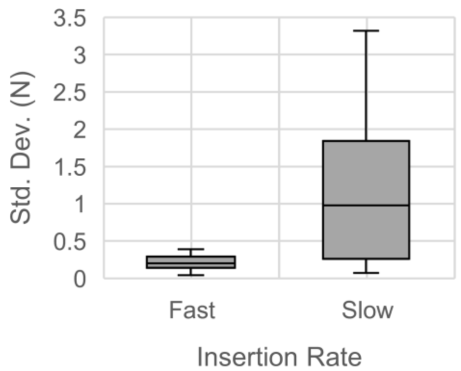

Figure 4: Box and whisker plot grouping the standard deviations of the 11 fast versus slow insertion rate trials.

Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the distribution of differences between the fast and slow standard deviations (WS = 1.50, $p < 0.01$). The data supports there is a statistically significant difference from zero in the median of the distribution of differences between the fast and slow insertion rates. With the fast insertion rate consistently having a smaller standard deviation.

4.2 Orientation

186 vertical (slope perpendicular) BHG measurements (height of 10 cm) were compared with 186 mean horizontal (slope parallel) measurements (mean of six horizontal measurements spaced 2 cm apart for total height of 10 cm) in homogenous layers

of dry snow greater than 10 cm in height (Table 2). Being paired and nonparametric, the Wilcoxon signed-rank test was used to compare the two gauges (WS = 6206.00, $p < 0.01$). The data supports there is a statistically significant difference from zero in the median of the distribution of differences between the two BHGs.

Table 2. Descriptive statistics comparing orientation of the BHG (Difference = Vertical – Mean Horizontal).

Orientation	Average (N)	Standard Deviation (N)	Standard Error (N)
Vertical	4.90	5.61	0.41
Mean Horizontal	5.19	6.01	0.44
Difference	-0.29	1.19	0.09

4.3 Hand Hardness

During the 2020/21 and 2021/22 winter field seasons a total of 68 hand hardness profiles by 33 different avalanche technicians were taken with corresponding BHG measurements. The avalanche technicians classified the hand hardness test with the five hand hardness indices (F, 4F, 1F, P and K) and with the ± indices. A total of 4229 BHG measurements were compared with the hand hardness indices (Figure 5).

To see if there is a difference in the hand hardness indices based on experience the data from 68 hand hardness profiles was split up based on the avalanche technician's certification. During the 2020/21 and 2021/22 winter field seasons a total of 36 hand hardness profiles by 20 different avalanche technicians with the CAA Operations Level 1 certification were taken with corresponding BHG measurements. During those field seasons a total of 19 hand hardness profiles by 13 different avalanche technicians with the CAA Operations Level 2 certification were taken with corresponding BHG measurements (Figure 6).

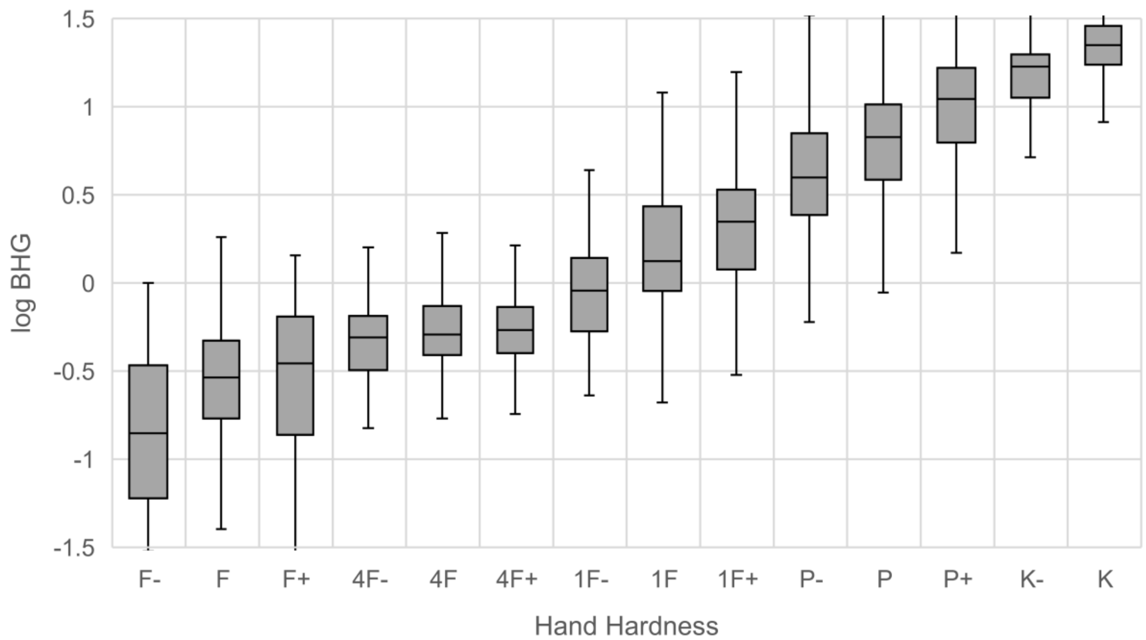

Figure 5: Log box plot comparing hand hardness indices with blade hardness gauge (BHG) measurements from 68 hand hardness profiles by 33 avalanche technicians. The grey boxes represent the 1st and 3rd quartiles, as a measure of spread. The vertical lines show the full spread of the data.

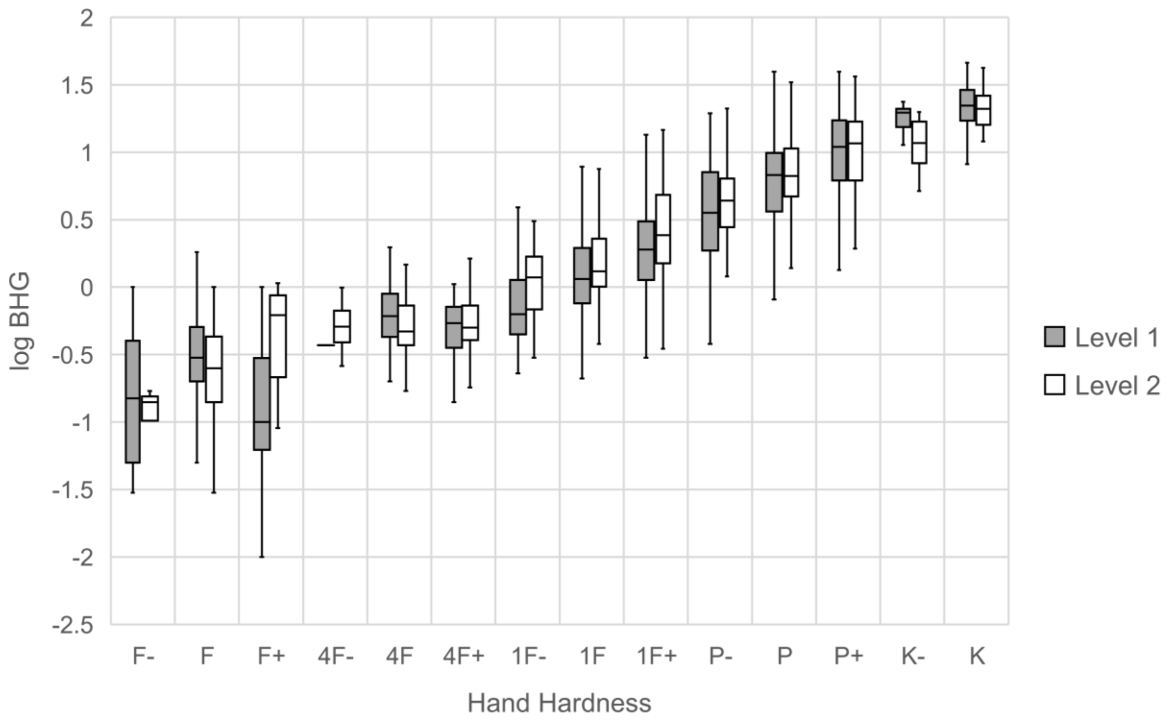

Figure 6: Log box plot comparing hand hardness indices with blade hardness gauge (BHG) measurements by CAA Level 1 and Level 2 operators.

Log box plots are seen in Figures 5 and 6 to visualize the overlap in the data between the hand hardness values. The shaded squares represent the interquartile ranges, the line in the shaded square represents the medians and the whiskers represent the minimum and maximum ranges found in the log BHG measurements. Comparing the blade hardness with the hand hardness shows significant overlap between the neighbouring hand hardness levels. The log scale of the blade hardness forms an almost linear relationship with the hand hardness as the surface area of each hand hardness level decreases.

Testing the reproducibility of the hand hardness test and the BHG, avalanche technicians took corresponding hand hardness and BHG measurements one after another. Throughout the research a total of 286 snow layers were compared with the hand hardness test and 208 snow layers were compared with the BHG. Results of the reproducibility of the hand hardness test and the BHG are seen in Figure 7.

Figure 7 indicates that the percentage of layers in agreement between avalanche technicians was 90.4% when utilizing the BHG, in contrast to 40.2% when employing the hand hardness test with the ± indices.

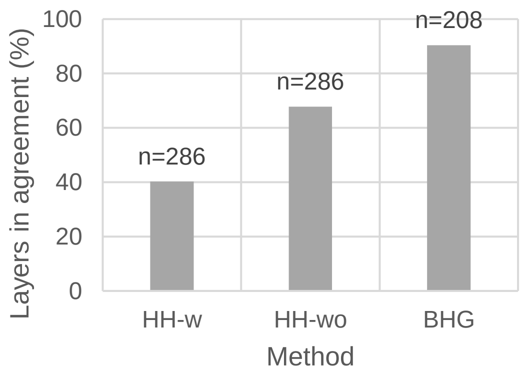

Figure 7: Side by side snow hardness replication of the hand hardness test with ± indices (HH-w), the hand hardness test without ± indices (HH-wo), and the BHG.

This comparison highlights the superiority of the BHG over the hand hardness test in measuring snow hardness amongst avalanche technicians. Excluding the ± notations, the consistency of the hand hardness test amongst avalanche technicians can significantly increase, as the percentage of layers in agreement rose to 67.8%.

5. DISCUSSION

The rate at which the BHG is inserted into the snowpack holds significance in achieving uniformity amongst users. This research investigated both fast (≈ 10 cm/s) and slow (≈ 1-3 cm/s) insertion rates. The analysis revealed a statistically significant disparity between the two rates, with slow insertion giving larger hardness values. Faster insertion rates also tend to give lower variability and better consistency. By comparing these findings with existing literature (Bradley, 1966; Fukue, 1977) it is advisable to employ an insertion rate of approximately 10 cm/s into the snowpack to ensure consistency amongst users. Adequate training should be provided to BHG users to maintain a consistent and fast insertion rate.

The natural snowpack is made up of different stratigraphic layers as the snowpack transforms throughout the winter season. Due to elevation, terrain, weather, and snow metamorphism there is a range of snow hardness throughout the snowpack. This research explored the orientation of the BHG with parallel or perpendicular to the snowpack insertions to measure the snow hardness. The data supports a statistical difference between one perpendicular BHG measurement to the average of six parallel BHG measurements (Wilcoxon signed-rank test, $p < 0.01$). There is variation amongst the measurements especially in non-homogenous snow layers. The recommendation is to insert the BHG parallel to the snowpack in two-centimeter increments with extra measurements taken at the location of persistent weak layers to gain the most precise hardness profile.

As the hand hardness test is the current standard for measuring snow hardness in Canada, this research set out to further correlate the BHG with the hand hardness test. The data from the 68 hand hardness profiles with correlating blade hard measurements, seen in Figure 5, resulted in no difference between the ± indices in the four fingers category. The data from the 19 hand hardness profiles from CAA Level 2 Operators, seen in Figure 6, resulted in no difference between F+, 4F-, 4F and 4F+ indices. This illustrates that avalanche technicians have a hard time distinguishing hardness difference in soft snow and that the ± indices do not have meaning in soft snow. These results are similar to what Pogue et al. found in 2018 (Pogue et al., 2018).

Comparing the replication of the hand hardness test and BHG amongst users resulted in 90.4% of layers agreeing with the BHG while only 40.2% of layers agree within current measurement precision with the hand hardness test amongst avalanche technicians. This supports the idea BHG measurements are more consistent amongst users than the hand hardness test.

Table 3: Hand Hardness and Blade Hardness Scale

Hand Hardness Index	Blade Hardness (N)
Fist	0 - 0.4
Four Fingers	0.4 - 1
One Finger	1 - 4
Pencil	4 - 14
Knife	14 - 45

Data from this research was used to create a blade hardness to hand hardness scale as seen in Table 3. The BHG can be used as a teaching tool to introduce and improve consistency of the hand hardness test amongst users. It offers the users the ability to feel what 10-15 N of force feels like, which is the insertion force of the hand hardness test. By measuring the blade hardness, the user can identify the corresponding hand hardness by utilizing the provided blade hardness to hand hardness scale. Continuous calibration of the hand hardness test with the BHG could lead to greater consistency amongst avalanche technicians.

The outcomes of this research suggest that the removal of the ± indices from the hand hardness test would enhance the reproducibility among avalanche technicians. However, within a single snow profile, a particular avalanche technician can utilize the ± indices to assess hardness discrepancies between snow layers in each snow profile. Those ± indices will overlap the other indices over time and will not necessarily be reproduced by another technician. For a more accurate and consistent assessment of snow layer hardness over time, it is recommended to measure the snow hardness with the BHG instead of the hand hardness test.

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